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Applied Energy Systems - Rudimentary Thermodynamics

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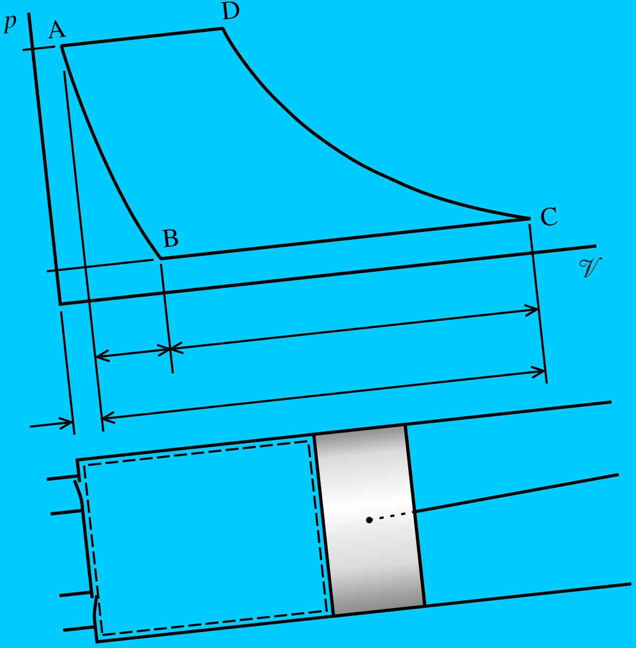
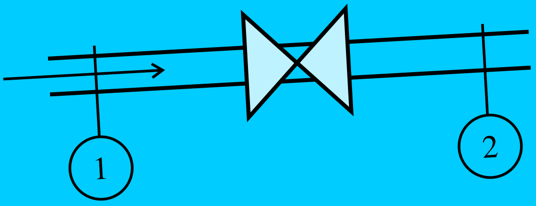
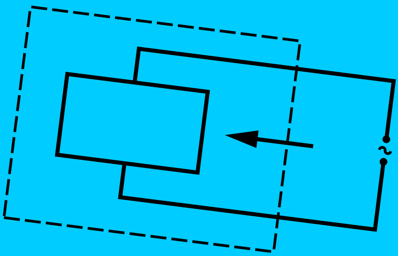
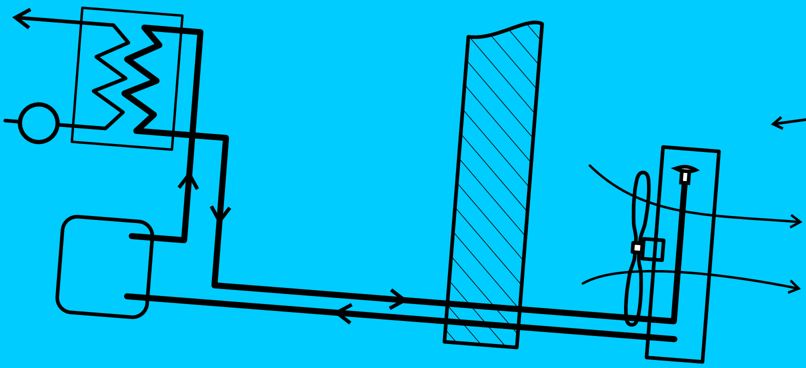
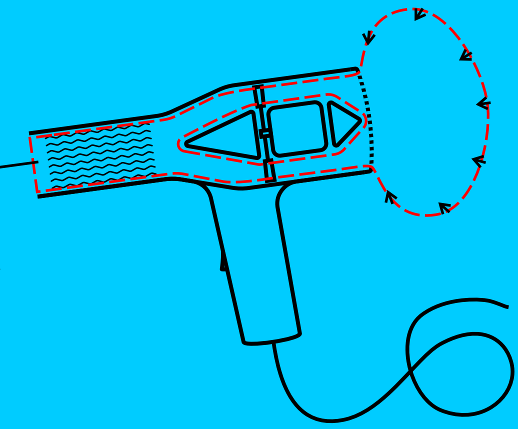










SI Units 2014 Edition

Applied Energy Systems — Rudimentary Thermodynamics

Jim McGovern

SI Units

2014 Edition

Jim McGovern
http://www.fun-engineering.net/aes

Table of Contents

Nomenclature

Symbol	Description	SI units
abs.	absolute	
A	area	m^2
a	acceleration	ms^{-2}
c	specific heat capacity	$\mathrm{Jkg}^{-1}\mathrm{K}^{-1}$
const.	constant	
COP	coefficient of performance	
d	diameter	m
E	energy	J
E_{pump}	pump overall efficiency	
E_{vol}	volumetric efficiency	
E_{th}	thermal efficiency	
$\dot{E}_{\text{in}}$	energy input rate	W
e	specific energy	Jkg^{-1}
F	force	N

Symbol	Description	SI units
f	function	
g	acceleration due to gravity	$\mathrm{m\,s^{-2}}$
h	specific enthalpy	$\mathrm{J\,kg^{-1}}$
L	length dimension	
M	mass dimension	
m	mass	kg
$\bar{m}$	molar mass	$\mathrm{kg\,mol^{-1}}$
$\dot{m}$	mass flow rate	$\mathrm{kg\,s^{-1}}$
N	amount of substance dimension	
n	polytropic exponent (or index)	
n	amount of substance	mol
p	pressure	$\mathrm{N\,m^{-2}}$ or Pa
Q	heat transfer	J
$\dot{Q}$	heat transfer rate	W

Symbol	Description	SI units
q	heat transfer per unit mass	$\mathrm{J\,kg^{-1}}$
R	specific gas constant	$\mathrm{J\,kg^{-1}K^{-1}}$
$\bar{R}$	universal gas constant	$\mathrm{J\,mol^{-1}K^{-1}}$
r	ratio	
S	entropy	$\mathrm{J\,K^{-1}}$
s	specific entropy	$\mathrm{J\,kg^{-1}\,K^{-1}}$
s	displacement	m
SI	(Système International), International System	
T	time dimension	
T	absolute temperature	K
t	conventional temperature	°C
$ŧ$	time	s
TEV	thermostatic expansion valve	

Symbol	Description	SI units	
U	internal energy	J	
u	specific internal energy	$\mathrm{J\,kg^{-1}}$	
V	velocity	$\mathrm{m\,s^{-1}}$	
V_n	velocity at position n	$\mathrm{m\ s^{-1}}$	
$\mathscr{V}$	volume	$\mathrm{m^3}$	
$\dot{\mathscr{V}}$	volume flow rate	$\mathrm{m^3 s^{-1}}$	
v	specific volume	$\mathrm{m^3 kg^{-1}}$	
W	work	J	
$\dot{W}$	power, rate of work	W	
w	work per unit mass	$\mathrm{J kg^{-1}}$	
x	dryness fraction		
x	arbitrary variable		
y	arbitrary variable		
z	elevation	m	
Greek letters			
γ	adiabatic index		(gamma)

Symbol	Description	SI units	
Δ	indicates an increment of the following variable e.g. Δy is a difference between two values of y		(uppercase delta)
δ	indicates a small amount of the following variable e.g. δQ is a small amount of heat transfer		(lowercase delta)
Θ	temperature dimension		(uppercase theta)
θ	angle	rad	(lowercase theta)
ρ	density	$\mathrm{kg\,m^{-3}}$	(rho)
Subscripts			
adiab	adiabatic		
avg	average		
cl	clearance		
comp	compressor		
cond	condenser		

Symbol	Description	SI units
const	constant	
elec	electrical	
evap	evaporator	
f	saturated liquid	
fg	increment from saturated liquid to dry saturated vapour	
g	dry saturated vapour	
gauge	identifies a gauge pressure	
H	higher temperature reservoir	
horiz	horizontal	
L	lower temperature reservoir	
ind	induced	
k	kinetic	
p	potential	
re	re-expansion	

Symbol	**Description**	**SI units**
refr	refrigerant	
refrig	refrigeration	
s	saturation	
s/h	superheat	
sw	swept	
turb	turbine	
vol	volumetric	
w	water	

Preface

Applied Energy Systems modules have developed and evolved at the Dublin Institute of Technology (DIT) within the framework of the Bachelor of Engineering Technology degree and the programmes that preceded it. The present work is a textbook for such a module addressing rudimentary thermodynamics. Specifically, it is an introduction to the thermodynamics of incompressible matter, ideal gases, steam power cycles and refrigeration cycles. To allow for learners of diverse backgrounds, the level of mathematics is kept simple. The book does not attempt to cover the principles of thermodynamics comprehensively. Rather, it provides a practical but theoretically sound foundation, linked to some key areas. Some familiarity with laws of mechanics and principles of physics and chemistry is assumed. Any gaps in knowledge can be filled on a need-to-know basis by using the Internet or a library.

‘Energy’ is often very topical. There is a widespread appreciation that energy must be used efficiently and a general willingness to make use of all forms of energy that are renewable and sustainable. Likewise there is a general desire to avoid, where possible, making use of forms of energy that are finite (i.e. already stored in limited quantities on the planet Earth) or that damage the environment when they are used. The underlying principles and scientific knowledge relating to energy utilization are common, whether energy is being used well or ineffectively and irrespective of the source of the energy. This present work fits into that general picture.

We live in an environment where air is always present. The same air plays a central role in many of the energy conversion processes used by mankind: from wind power, to boilers for space or process heating, to fuel-fired power plants, to air-conditioning in buildings or vehicles. An understanding of the energy-related properties of air is therefore essential to Applied Energy Systems. Water can exist in solid, liquid and vapour forms and it too plays a central role in many energy conversion processes: the steam power cycle continues to be highly important. Refrigeration cycles that involve a two-phase fluid, such as refrigerant 134a, are further good examples of how thermodynamics is employed in the service of mankind. The selection of topics treated in this textbook is sufficient for learners to appreciate the significance of thermodynamics and to apply it in a useful range of situations. In this way they are prepared for applying the same and similar principles to a much broader range of practical applications in the future.

Learners who have ambition to work with the most exciting and innovative ways of harnessing energy will find that what they learn through taking an Applied Energy Systems module in Rudimentary Thermodynamics will serve them well. Of course, not all applied technologists work at the forefront of technological development and innovation. The everyday work of society must go on. If that work touches upon energy conversions involving heat, work and the properties of substances in any way, the learner will find that their learning within the scope of such a module will have been relevant and worthwhile. However, the relevance of a module of this type is significantly broader yet. In common with other modules on an engineering programme, it involves engineering units (specifically the SI system) and important and generic engineering approaches such as experimentation, measurement, representation of practical problems in mathematical form, teamwork and communication. Learners are encouraged to make use of the Internet and library services for additional and supplementary information. They are also encouraged to discuss the topics among themselves and to participate as teams in performing associated laboratory assignments.

Chapter 1 Quantities, Units and Dimensions

Key Quantities in Thermodynamics

The word *energy* is part of everyday language, so most people have a good grasp of what it means. That everyday meaning might be encapsulated by a phrase such as ‘the capacity to bring about change’. For engineers and scientists, energy is quantified in terms of a mechanical effect that can be brought about, called work.

Work

Work is readily visualized as the occurrence wherein a force is applied to an object (e.g. a pebble) that undergoes a movement or displacement along the line of action of the force. If there is no displacement along the line of action of the force, there is no work, i.e. the work is zero.

Equally well, work can be visualized as the occurrence wherein an object undergoes a displacement while a force is applied to it along the line of the displacement. If there is no force acting along the line of the displacement, the work is zero.

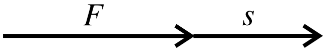


Figure 1-1 Work, where the point of action of force F moves through a displacement s, which is collinear with F.

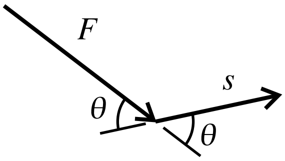


Figure 1-2 Work, where the point of action of force F moves through a displacement s, which is at an angle θ to F.

Force and displacement are both vector quantities, i.e. each has a magnitude and a direction. If the force F and the displacement s are in the same direction, as shown in Figure 1-1, then the work W is simply the product of the two magnitudes, i.e. $W = Fs$.

For a force at an angle to a displacement, as represented in Figure 1-2, the work is given by

$$W = F s \cos \theta \tag{1-1}$$

where

W	=	work	J
F	=	force	N
s	=	displacement	m
θ	=	angle	rad

In Equation (1-1) the expression $s \cos \theta$ represents the component of the displacement s in the direction of the force F. Similarly, $F \cos \theta$ represents the component of the force F in the direction of the displacement s. If the angle θ is zero, $\cos \theta$ equals 1 and the work equals Fs. If the angle θ is $\pi/2$ or 90°, $\cos \theta$ equals 0 and the work is zero.

While the SI unit for angle is the radian, many calculators, by default, require the angle to be entered in degrees in evaluating trigonometric functions such as cos.

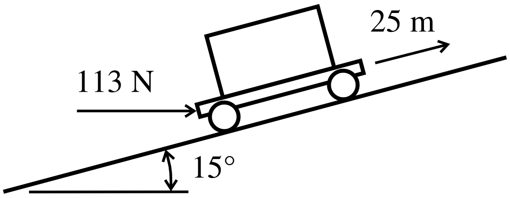
It is important to grasp that work is transient and exists only while it is occurring. Work is said to be done *on* an object when a force acts on the object and there is a displacement (or component of displacement) of the object in the same direction. Work is done *by* an object when the object exerts a force and moves (or has a component of displacement) in the direction of the force. The SI unit for work is the newton metre

(Nm), which is known as the joule (J). Work is not a property of an object, or of matter.

Example 1-1 Work on a Bogie

A constant horizontal force of 113 N is applied to push a loaded bogie up an inclined plane that is at an angle of 15° to the horizontal. What amount of work is done by the force if the distance travelled along the plane is 25 m?

Solution



The distance travelled in the direction of the force is given by

$$s_{\text{horiz}} = s\cos\theta = 25\ [\text{m}]\ \cos 15^\circ = 24.15\ \text{m}$$

Hence,

$$W = 113\ [\text{N}] \times 24.15\ [\text{m}] = 2729\ \text{J}$$

Energy

Energy is the capacity to do work, i.e. to apply a force (in newtons) through a distance (in metres). The unit of energy is therefore the same as the unit of work, the newton metre, Nm, or the joule, J. While work is transient, the capacity to do work, known as energy, endures and can be passed or transferred from one system to another. An object or system or amount of matter can possess energy in various ways. Energy is thus a property of an object, a system or an amount of matter.

Kinetic Energy

A speeding bullet or a speeding train has kinetic energy associated with its velocity. Part or all of that kinetic energy can be used to do mechanical work. Kinetic energy is calculated as

$$E_{\mathrm{k}} = \frac{m\,V^2}{2} \tag{1-2}$$

where

E_{k} = kinetic energy J

m = mass kg

V = velocity $\mathrm{m\,s^{-1}}$

Potential Energy

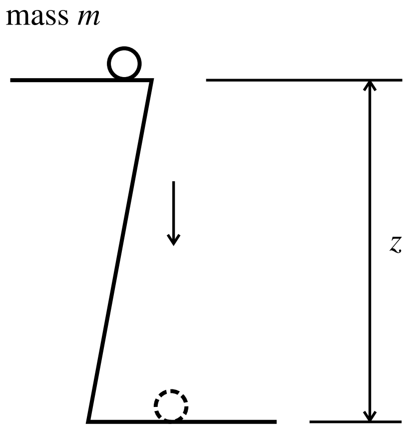


Figure 1-3 Diagram to illustrate potential energy of a boulder on a cliff.

A boulder on the top of a cliff, Figure 1-3, can be allowed to fall through a height in the Earth's gravitational field, thereby acquiring kinetic energy, which could be used to do mechanical work. Alternatively, by means of a rope and pulley system, the lowering of the boulder could be used to raise another object. The capacity for doing work that the boulder has due to its elevation is known as gravitational potential energy (or 'potential energy' for short).

Potential energy is calculated as

$$E_{\mathrm{p}} = mgz \tag{1-3}$$

where

E_p = potential energy J

m = mass kg

z = elevation m

g = acceleration due to gravity $\mathrm{m\,s^{-2}}$

Strain Energy

A coil spring may possess energy due to the fact that it has been pre-compressed or pre-extended. Mechanical work could be done as the spring returns to its original length. Such energy can be described as strain energy.

Internal Energy

Solids, liquids and gases possess energy, known as internal energy, which is associated with translation, rotation or vibration of the molecules or sub-molecular constituents that comprise matter and with the attractive or repulsive forces that bind matter together or determine its atomic and molecular level arrangement and configuration. While kinetic energy, potential energy or strain energy are fully available for the production of mechanical work at the macroscopic level, the availability of internal energy is more restricted, as there is no practical means of extracting all of the random energy possessed by individual molecules or sub-molecular constituents and converting it directly to macroscopic work.

For a given molecular configuration of matter (e.g. solid, liquid or gas) the internal energy increases with temperature. In other words, for a known substance as a solid, liquid or gas, the temperature is an indicator of the amount of internal energy possessed by the substance.

Both temperature and internal energy are properties that a system or an amount of matter can possess. Thus, internal energy is a property that characterizes the capacity of a system or an amount of matter to do work (whether at the sub-molecular, molecular or macroscopic level).

Heat

The word ‘heat’ as used by scientists and engineers in technical contexts has a more restricted and precise meaning than the same word as used in everyday language. The important aspect to grasp is that heat in the technical sense is energy transfer across a boundary due to a temperature difference between matter on one side of the boundary and matter on the other side of the boundary. There is no technical difference between ‘heat’ and ‘heat transfer’.

Heat transfer can occur between objects or systems that are separated by a vacuum—this is how the Earth receives energy from the Sun. Such heat transfer is known as radiant heat transfer, or radiation.

Heat transfer can also occur by direct contact between objects or systems, or amounts of substance. This is known as conduction. Where the conduction is also accompanied by relative movement between a solid and a fluid, or by differential velocities within a fluid, the heat transfer is described as convection.

Thus, whether the mode of heat transfer is radiation, conduction or convection, heat is the occurrence of energy transfer due to temperature difference. Heat is not a property of a system or of matter. Also, in the technical sense, heat is not something that can be possessed by matter.

In principle, the temperature difference may be extremely small, but heat, or heat transfer, cannot occur if there is no temperature difference between the ‘source’ and the ‘sink’ of internal energy i.e. the region that loses energy and the region that gains energy by heat transfer.

Frictional or Stirring Work

It is well known that friction causes a local increase in temperature. This occurs where one surface slides over another. For instance, a moving brake disc in a car slides over a fixed brake pad. Friction also occurs when mechanical energy is used to stir or mix a fluid. Thus, mechanical work can cause a direct increase in internal energy. The addition of energy to matter by surface friction or fluid friction is a one-way process: the energy transferred to the matter becomes random atomic and molecular level energy of the matter and there is no direct way that that energy can be ‘organized’ so that it yields back a work output, as if the original frictional work interaction had never taken place.

Figure 1-4 is a schematic representation of a device of the type originally used by James Prescott Joule for a famous experiment. The falling weight does work on the system due to fluid friction between the moving paddles and the fixed blades. The internal energy of the water is thereby increased.

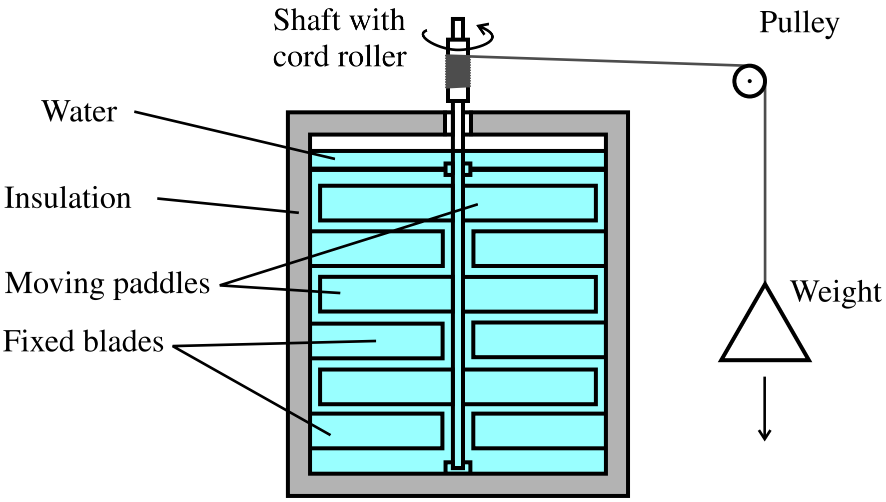


Figure 1-4 Work input causing an increase in internal energy.

Units

Table 1-1 lists SI and some non-SI units that are used in this text. A physical quantity such as an amount of heat transfer Q is represented as a pure number, such as 736, multiplied by a unit, such as kJ (kilojoule). Hence, an amount of heat transfer might be written as 736 kJ. If we divide the heat transfer by its unit we are left with just the pure number:

$$\frac{Q}{[\mathrm{kJ}]} = \frac{736\ [\mathrm{kJ}]}{[\mathrm{kJ}]} = 736$$

The same physical quantity may be expressed in terms of different units, for instance the Joule or the kJ for heat transfer. The relationship between different units for the same quantity can be expressed as an equation such as

$$1\ \mathrm{kJ} = 1000\ \mathrm{joule}.$$

Hence

$$1 = 1000\ \frac{\mathrm{joule}}{\mathrm{kJ}}$$

and

$$1 = 10^{-3}\,\frac{\mathrm{kJ}}{\mathrm{joule}}.$$

The right hand sides of the previous two equations are examples of conversion factors between different units. Table C-2, Appendix C, lists some common SI prefixes.

The SI unit for angle is the radian (abbreviation rad). The relationships between the degree (°) and the radian are

$$2\pi\ \mathrm{rad} = 360^\circ$$

$$1\ \mathrm{rad} = \frac{360^\circ}{2\pi}$$

$$1^\circ = \frac{2\pi}{360}\ \mathrm{rad}$$

Energy Conservation

The *principle of conservation of energy* states that energy is conserved, i.e. it can be transformed from one form to another, but cannot be created or destroyed.

First Law of Thermodynamics

The *first law of thermodynamics* states that if a system has undergone no net change after heat transfer and work interactions have taken place then the sum of the net heat transfer into the system plus the net work done on the system must be zero. It is a statement that recognizes that work and heat transfer are both forms of energy transfer and that energy is conserved.

Dimensions

Of all the physical quantities that are encountered, the units for these quantities are made up of five fundamental types of units, or dimensions. Symbols can be used to represent these fundamental unit types (or dimensions) as follows: mass M, length L, time T, temperature Θ and amount of substance N. Acceleration would have the fundamental units LT^{-2}. From Newton's second law[1] it can be deduced that force has the fundamental units MLT^{-2}. Pressure would therefore have the fundamental units $MLT^{-2}L^{-2}$, which is equivalent to $ML^{-1}T^{-2}$.

Table 1-1 Units

Physical quantity	SI base unit	Other units
mass	kg (kilogram)	$1\ g = 10^{-3}\ kg$ tonne: $1\ t = 10^{3}\ kg$
length	m (metre)	$1\ mm = 10^{-3}\ m$ $1\ km = 10^{3}\ m$ $1\ cm = 10^{-2}\ m$
time	s (second)	$1\ min = 60\ s$ $1\ h = 3600\ s$

---

[1] See Formulae and Glossary

Physical quantity	SI base unit	Other units
force	N (newton)	1 kN = 10^3 N 1 MN = 10^6 N
area	m^2	1 cm^2 = 10^{-4} m^2 1 mm^2 = 10^{-6} m^2
volume	m^3	1 cm^3 = 10^{-6} m^3 1 mm^3 = 10^{-9} m^3 litre: 1 L = 10^{-3} m^3 millilitre: 1 mL = 10^{-6} m^3
pressure	Pa (pascal)	1 Pa = 1 Nm^{-2} 1 kPa = 10^3 Pa 1 MPa = 10^6 Pa 1 GPa = 10^9 Pa 1 hPa = 10^2 Pa 1 bar = 10^5 Pa atmosphere: 1 atm = 101,325 Pa
amount of substance	mol (mole)	kilomole: 1 kmol = 10^3 mol

Physical quantity	SI base unit	Other units
velocity	$\mathrm{m\ s^{-1}}$	
acceleration	$\mathrm{m\ s^{-2}}$	
density	$\mathrm{kg\ m^{-3}}$	
energy, work, heat	J joule (= 1 Nm)	$1\ \mathrm{kJ} = 10^3\ \mathrm{J}$ $1\ \mathrm{MJ} = 10^6\ \mathrm{J}$
power	W (= $1\ \mathrm{J\,s^{-1}}$)	$1\ \mathrm{kW} = 10^3\ \mathrm{W}$ $1\ \mathrm{MW} = 10^6\ \mathrm{W}$ $1\ \mathrm{mW} = 10^{-3}\ \mathrm{W}$ $1\ \mu\mathrm{W} = 10^{-6}\ \mathrm{W}$
conventional or customary temperature	°C (degree Celsius)	
thermodynamic or absolute temperature	K (kelvin)	
torque (moment)	Nm	
angle	rad	$1^\circ = \frac{2\pi}{360}\ \mathrm{rad}$ revolution: $1\ \mathrm{rev} = 2\pi\ \mathrm{rad}$

Physical quantity	SI base unit	Other units
angular velocity	rad s^{-1}	revolutions per second: $1 \text{ r.p.s.} = 2\pi \text{ rad s}^{-1}$ revolutions per minute: $1 \text{ r.p.m.} = \dfrac{2\pi}{60} \text{ rad s}^{-1}$
angular acceleration	rad s^{-2}	
volume flow rate	$m^3 s^{-1}$	$1 \text{ L s}^{-1} = 10^{-3} \text{ m}^3 \text{ s}^{-1}$ $1 \text{ L min}^{-1} = \dfrac{10^{-3}}{60} \text{ m}^3 \text{ s}^{-1}$
mass flow rate	kg s^{-1}	

Problems

1-1 Indicate which of the following statements are true and which are false

A A know mass of a specified gas at a specified constant temperature and constant pressure within a container of a specified volume possesses internal energy that is constant.

B Kinetic energy and potential energy at the macroscopic level can be used directly to produce mechanical work.

C Heat and work are the same because they are both energy transfer.

D All of the internal energy of a system or substance can be used directly to produce mechanical work at the macroscopic scale.

E Work is a manner or occurrence by which energy can leave an amount of substance.

F Ice has less heat than liquid water.

G 1 kg of compressed air at ambient temperature has more work than 1 kg of air at ambient temperature and pressure.

H Heat transfer is a manner or occurrence by which energy can enter a system.

1-2 Match the physical quantities on the left with the base SI units on the right.

	Physical quantity		**SI base units**
A	power	1	$m^3 kg^{-1}$
B	volume per unit mass	2	K
C	angle	3	°C
D	energy per unit mass	4	mol
E	temperature (absolute)	5	$J kg^{-1}$
F	volume	6	$m^3 s^{-1}$
G	pressure	7	rad
H	volume flow rate	8	$kg m^{-3}$
I	density	9	Pa or $N m^{-2}$
J	mass flow rate	10	W or $N m s^{-1}$
K	mass	11	$kg s^{-1}$
L	amount of substance	12	kg
M	temperature (conventional)	13	m^3

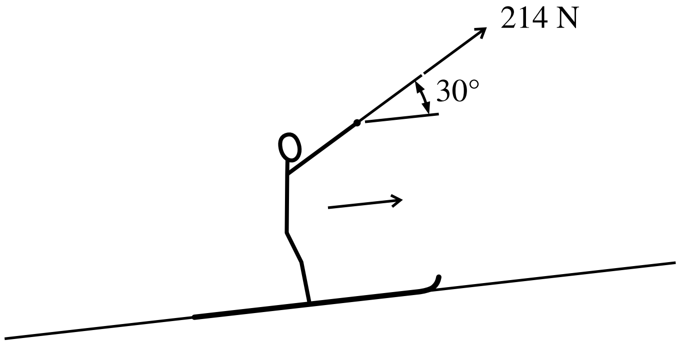
1-3 Match the symbols in the left column below with the numbers and units in the right column.

	Symbol		Number and unit
A	hPa or mbar	1	10^{-6} m^3
B	kPa	2	1,000,000 Pa
C	MPa	3	1000 J
D	bar	4	1000 Pa
E	kJ	5	10^5 Pa
F	MJ	6	100 Pa
G	L or litre	7	1,000,000 W
H	g or gram	8	1000 W
I	mL or millilitre or cc or cubic centimetre	9	10^9 W
J	MW	10	1,000,000 J
K	kW	11	10^{-3} kg
L	GW or gigawatt	12	10^{-3} m^3

1-4 Match the quantities in the left column below with dimensions in the right column.

	Quantity		Dimensions
A	pressure	1	$M L^2 T^{-3}$
B	temperature	2	L^3
C	volume	3	$M L^{-1} T^{-2}$
D	heat transfer	4	$L T^{-2}$
E	work per unit time	5	Θ
F	density	6	$M L T^{-2}$
G	acceleration	7	$M L^2 T^{-2}$
H	force	8	$M L^{-3}$

1-5



A skier advances up a smooth incline due to a pulling force from a ski tow of 214 N that is at an angle of 30° to the slope, as shown in the diagram. The skier covers a distance of 150 m up the slope in 43 seconds. Calculate the work done on the skier by the ski tow and the rate at which the work is done.

1-6 A mass of 2.3 kg is raised through a height of 3.7 m in the Earth's gravitational field and its original velocity of 1.2 m/s is increased by 1.6 m/s. By how much does the energy of the mass increase?

1-7 A boulder with a mass of 251 kg has fallen off a cliff. It has a velocity of 15 m/s and is at a height of 60 m from the ground below. Evaluate its kinetic energy and its potential energy. What is the maximum of kinetic plus potential energy that the rock could have when it hits the ground? Explain your answer.

1-8 Is there heat transfer between Venus and Earth and if so what is its direction? As a (big) simplification assume that Venus, which is 30% nearer the Sun than the Earth, has a higher effective temperature for radiation exchange than the Earth.

1-9 A cuckoo clock is powered by an elevated mass of 0.32 kg that descends 1.60 m in 24 hours. Calculate the average power provided to the clock in microwatts.

Chapter 2 Properties of Substances

Properties

Substance is matter of a particular chemical composition. Water substance, H_2O, can exist as solid ice, liquid water or as water vapour, which is also called steam. Within a refrigeration system, a refrigerant such as R134a, which has the chemical formula $C_2H_2F_4$, exists as a liquid and as a vapour. Air is a mixture of gases, principally nitrogen N_2 (about 78% by volume) and oxygen O_2 (about 21% by volume). In this chapter, information is provided in relation to some important thermodynamic properties of substances, e.g. pressure, temperature, volume and mass.

Water and R134a are examples of pure substances, whereas air is a mixture of pure substances: oxygen, nitrogen, a small amount of argon and very small amounts of carbon dioxide and other gases. As the relative amounts of the constituents of air are almost invariant, it can be regarded as a pseudo-substance for the purposes of engineering calculations. Most pure substances can exist in three principal phases, or molecular configurations: solid, liquid and gas (or vapour[2]).

A system, Figure 2-1, is a region in space, or the content of a real or virtual container. It is defined by a boundary that encloses volume. Within a system there may be substances or objects made of matter or even nothing at all (vacuum). A system can be described by its properties, some of which may be relevant in relation to energy or energy-interaction calculations. Such properties are known as thermodynamic properties.

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[2] A vapour is a gas at a temperature low enough that the substance could also be a solid-gas mixture or a liquid-gas mixture at the same temperature if the pressure were high enough.

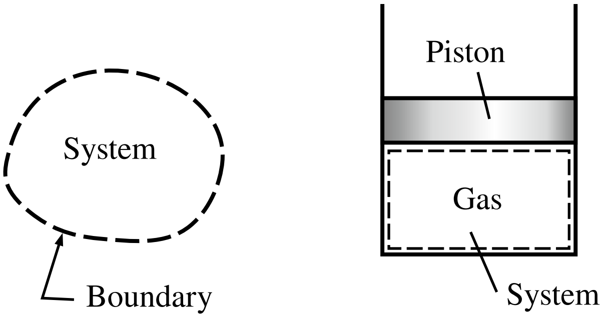

Figure 2-1 A general system and a specific example

In thermodynamics, the state of a system or substance is defined by giving the values of sufficient properties to describe it. For instance, a system containing just liquid water at a uniform temperature and pressure could be adequately described by giving the mass of water present, its temperature and its pressure. As water is a well-documented substance, all other thermodynamic properties could be determined from published information, given these three properties.

In general, the thermodynamic properties of a system may vary from place to place within the system. There may or may not be sufficient information to describe exactly how these properties vary within the system. However, if a system is in a special type of state, known as an equilibrium state, it is relatively easy to describe the thermodynamic state.

A system is said to be in an equilibrium state if none of its thermodynamic properties would change if the system were instantly enclosed by a boundary that prevented energy inputs from its surroundings and energy outputs to its surroundings.

If a system contains only a pure substance that is in equilibrium, then the number of independent thermodynamic properties required to describe the system is usually just three, e.g. mass, pressure and temperature. However, if the state of a system is described on a basis that does not depend on its extent or size, two independent properties are usually sufficient. In this case the independent properties must not depend on the extent or size of the system. Volume per unit mass

(m^3/kg), rather than volume, and internal energy per unit mass (J/kg), rather than internal energy, are examples of properties that are independent of the extent or size of a system: any fraction of the system would have the same properties.

Pressure

Pressure is force exerted per unit area in a direction that is normal to and towards the area. It is expressed as

$$p = \frac{F}{A} \tag{2-1}$$

where

p	=	pressure	Pa
F	=	force	N
A	=	area	m^2

Atmospheric pressure is the pressure of the atmosphere, which can be measured by a barometer.

$$1 \text{ standard atmosphere} = 1.01325 \times 10^5 \text{ Pa}$$

Gauge pressure is a relative pressure: it is the amount by which the pressure exceeds the pressure of the atmosphere.

Absolute pressure is the true pressure. This term is used when it is necessary to emphasize that the pressure being referred to is not a relative pressure, such as gauge pressure, or a differential pressure, such as the pressure drop across a valve. The lowest possible value of absolute pressure is zero (in any pressure units).

Unless otherwise stated it will be taken that pressure is absolute pressure. The pressure that a substance is at is a property of the substance.

Internal Energy

In this book the symbol U with the unit J (joule) is used to represent internal energy. For a given substance in a given state, much of this is kinetic energy associated with the movement of atoms and molecules. The atoms in solids vibrate and thus have stored energy associated with the vibrations. In liquids, molecules also have translational kinetic energy. In gases, molecules have kinetic energy associated with random translation. Multi-atomic gases also have kinetic energy that is associated with the rotation of each molecule about its centre of gravity. The internal energy of a substance also includes energy stored in association with electrostatic or nuclear forces that bind atoms and molecules together. Such energy can be released in chemical reactions or, much less commonly, atomic reactions. Within engineering thermodynamics it is not usually necessary to quantify, or work with, the absolute internal energy possessed by a substance and that magnitude is not important in itself. Rather, it is appropriate and necessary to calculate changes in internal energy associated with changes in the state of a substance, or substances. It is common to take the internal energy per unit mass as zero at a convenient reference state for each substance.

The ratio of the internal energy of a system or substance to its mass is known as the specific internal energy, which has the units J/kg.

$$u = \frac{U}{m} \tag{2-2}$$

Typically, in the calculations and problems presented in this book, a difference in specific internal energy between two states is evaluated, i.e. the increase from state 1 to state 2 would be written as

$$\Delta u_{1\rightarrow 2} = u_2 - u_1 .$$

The specific internal energy difference Δu is independent of the arbitrary reference state at which the specific internal energy is assigned the value zero.

Temperature

Temperature is the formal measure of the property that humans sense as ‘hotness’ or ‘coldness’. Objects that are at higher temperatures will lose energy to objects that are at lower temperatures if they are allowed to interact by being brought into contact or by the removal of anything that could block energy exchange by radiation between them.

The Celsius temperature scale is the everyday or conventional temperature scale, which has a zero value at the freezing point of water substance and a value of 100 at its boiling point, where the water is at atmospheric pressure in both cases. The symbol t will be used to denote conventional temperature.

Absolute Temperature

In thermodynamics it is often appropriate to make use of an absolute scale and this is taken to be the definitive temperature scale. No system or substance can be cooled down to a temperature that is lower than zero on the absolute scale. At absolute zero the thermal energy of a system (the part of the internal energy that the system can lose by heat transfer) is zero[3].

The absolute temperature scale requires one fixed reproducible temperature for its definition. Fortunately there exists a convenient and unique temperature, the triple point temperature of water, at which solid, liquid and vapour phases of water substance can co-exist in equilibrium. This reproducible reference temperature is used to define the Kelvin scale of absolute temperature and is assigned the value 273.16 kelvin (273.16 K).

The freezing temperature of water (273.15 K) at standard atmospheric pressure is slightly lower than the triple point temperature (273.16 K).

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[3] In fact the second law of thermodynamics implies that a refrigeration plant would require an infinite input of work to cool a finite amount of substance to absolute zero temperature.

One deliberate consequence of the way in which the absolute temperature scale is defined is that one degree of temperature difference on the conventional scale equals one unit of temperature difference on the absolute scale.

1 °C temperature difference = 1 K temperature difference

The symbol T will be used to denote absolute temperature and t to denote conventional temperature. The absolute temperature is got by adding 273.15 K to the Celsius temperature, e.g.

55 °C is equivalent to (55 + 273.15) K, i.e. 328.15 K.

While using t to represent conventional temperature and T to represent absolute temperature, the following equation can be written as a basis of converting from one scale to the other.

$$t = T - 273.15 \text{ [K]} \tag{2-3}$$

Volume and Mass

Volume $\mathscr{V}$ and mass m are two more properties that a system or a substance can have. The ratio of volume to mass is known as the specific volume v. It has the units of m^3/kg.

$$v = \frac{\mathscr{V}}{m} \tag{2-4}$$

Whereas density ρ is commonly used in fluid mechanics, specific volume is much more commonly used in thermodynamics.

$$v = \frac{1}{\rho} \tag{2-5}$$

Amount of Substance

'Amount of substance' is a measure and a property of a collection of specified entities of a substance (or mixture of substances) at the atomic or molecular level. The entities would typically be atoms, molecules or ions (ions are charged atoms or molecules). The SI unit for amount of substance is the mole, which can be abbreviated to mol.

A mole is an amount of substance with the same number of entities as there are atoms of carbon 12 in 0.012 kg (i.e. 12 g) of carbon 12. (The actual number of entities is known as Avogadro's number, $6.022 \times 10^{23}\ \text{mol}^{-1}$). The kilomole is often used and is abbreviated to kmol. The molar mass of carbon 12 is 0.012 kg/mol, which is commonly written as 12 kg/kmol.

Note that some carbon atoms have a higher molar mass because of additional neutrons in the nucleus, e.g. carbon 14 has 6 protons and 8 neutrons in its nucleus compared to 6 of each for carbon 12.

For a given substance, the molar mass, $\bar{m}$, is the mass per amount of substance. The SI base unit for molar mass is kg/mol, but in common usage it is usual to favour either kg/kmol (as in this text) or g/mol. For instance, oxygen has a molar mass of approximately 32 kg/kmol. The amount of substance, n, corresponding to a mass of a given substance can be calculated as follows:

$$n = \frac{\text{mass}}{\text{molar mass}} = \frac{m}{\bar{m}} \tag{2-6}$$

Example 2-1 Amount of Substance of CO_2

What amount of substance of CO_2 (in kmol) is present in 55 kg of the gas? The molar mass can be taken as approximately 44 kg ⁄kmol.

Solution

$$n = \frac{m}{\bar{m}} = \frac{55\ [\text{kg}]}{44\ [\text{kg/kmol}]} = 1.25\ \text{kmol}$$

Incompressible Substances

An incompressible substance is a substance whose volume does not change when it is subjected to changes in pressure while the temperature is held constant. Most substances are very nearly incompressible when in the solid or liquid phase. For example, it would require a pressure of 22 MPa to reduce the volume of liquid water by just 1%. For incompressible substances, pressure and temperature can be varied independently of one another and the main thermodynamic properties (other than pressure or any property that is defined to include pressure[4]) depend only on temperature and are not influenced by pressure. For most liquids and solids the following approximations apply:

$$v \approx \mathrm{f}(T)$$

$$u \approx \mathrm{f}(T).$$

That is, as an approximation, the specific volume and the specific internal energy of a substance that is considered incompressible can be written as a function of temperature only.

Specific Heat of Incompressible Solids or Liquids

In order to perform calculations that involve changes in internal energy it is useful to define the specific heat capacity (or specific heat, for short) of an incompressible substance as follows:

$$c = \left.\frac{\Delta u}{\Delta T}\right|_{\Delta T \to 0} \tag{2-7}$$

where

c = specific heat J/kgK

u = specific internal energy J/kg

---

[4] The product of pressure and specific volume pv is itself a property, but it clearly depends on pressure.

ΔT = increase in temperature K

In words, Equation (2-7) states that the specific heat of an incompressible substance is the ratio of the increase in specific internal energy to an increase in temperature for a small increase in temperature (that tends towards zero). The specific heat itself may vary with temperature, but a mean value over a temperature range can usually be used for calculation purposes. It follows therefore that the change in the specific internal energy of an incompressible substance corresponding to a change in temperature between two states is given by

$$\Delta u_{\text{incomp}} = u_2 - u_1 = c_{\text{avg}}(T_2 - T_1) \tag{2-8}$$

where

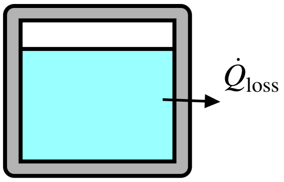
c_{avg} = average specific heat over temperature range J/kgK

In engineering calculations there are two main options when it is desired to calculate a difference in specific internal energy between two states of a solid or liquid substance. The first option is to find the specific internal energy at the initial and final states, whether from thermodynamic tables, from an empirical equation or from a software application. The second option is to use Equation (2-8), which only requires a value of the specific heat that is applicable for the temperature range.

Example 2-2 Energy Loss from a Storage Tank

A hot water storage tank in an industrial plant contains 4.63 m^3 of water. Over a period of 8 hours at night the temperature of the water drops by 3.77 K due to heat loss. During that period there is no energy addition and no flow of water in or out of the tank. Calculate the amount of energy that is lost from the water and the average rate of heat loss for the period. Take the specific volume of the water as 0.00103 m^3/kg and the specific heat as 4.12 kJ/kgK.

Solution



From the information provided it can be assumed that the energy loss comes entirely from a reduction in the internal energy of the water.

Calculate the mass of water.

$$m = \frac{\mathscr{V}}{v} = \frac{4.63\ [\text{m}^3]}{0.00103\ [\text{m}^3/\text{kg}]} = 4495\ \text{kg}$$

Calculate the energy loss.

$$E_{\text{loss}} = -\Delta U = -m\Delta u = mc(T_1 - T_2)$$

$$= 4495\ [\text{kg}] \times 4.12\ [\text{kJ/kgK}] \times 3.77\ [\text{K}]$$

$$= 69.82 \times 10^3\ \text{kJ}$$

$$= 69.8\ \text{MJ}$$

Calculate the average rate of heat loss by dividing the energy loss by the time, t.

$$\dot{Q}_{\text{loss}} = \frac{E_{\text{loss}}}{t} = \frac{69.82 \times 10^3\ [\text{kJ}]}{8\ [\text{h}] \times 3600\ [\text{s/h}]} = 2.42\ \text{kW}$$

Ideal Gases

Gases are highly compressible and their main thermodynamic properties depend on pressure and temperature. Just as an incompressible substance is an idealized but useful representation of solids and liquids, an ideal gas is a relatively uncomplicated representation of gases.

The Ideal Gas Equation

Many gases can be modelled as being ideal in the sense that the relationship between the properties p, $\mathscr{V}$, m and T can be described by a simple equation:

$$p\mathscr{V} = mRT \tag{2-9}$$

where R is a constant known as the specific gas constant. This equation is known as the ideal gas equation and the units of R can be established by rearranging it as follows:

$$R = \frac{p\mathscr{V}}{mT}.$$

Hence, the units of R are

$$\frac{\mathrm{N\,m^{-2}\,m^3}}{\mathrm{kg\,K}} \quad \text{or} \quad \frac{\mathrm{N\,m}}{\mathrm{kg\,K}} \quad \text{or} \quad \frac{\mathrm{J}}{\mathrm{kg\,K}}$$

By dividing both sides of Equation (2-9) by m, the ideal gas equation can also be written as:

$$pv = RT \tag{2-10}$$

The value of R depends on the particular gas, e.g. for air $R =$ 0.2871 kJ/kgK; for helium $R = 2.077$ kJ/kgK. Data for some selected ideal gases are listed in Table D-1, Appendix D.

Some Applications

(i) Find the mass of a particular gas (of known R) at known p and T in a container of known volume.

$$m = \frac{p\mathscr{V}}{RT}$$

(ii) Find the density of a known gas at a given temperature and pressure.

$$v = \frac{RT}{p}$$

Hence

$$\rho = \frac{1}{v} = \frac{p}{RT}$$

(iii) Describe how the pressure of a given mass of gas varies with volume if the temperature remains constant.

$$p\mathscr{V} = mRT = \text{constant}$$

Hence

$$p\mathscr{V} = \text{constant}$$

or

$$p \propto \frac{1}{\mathscr{V}} \tag{2-11}$$

This is known as Boyle's law. For two different states

$$p_1\mathscr{V}_1 = p_2\mathscr{V}_2$$

or

$$\frac{\mathscr{V}_2}{\mathscr{V}_1} = \frac{p_1}{p_2}.$$

(iv) Describe how the volume of a given mass of gas varies with temperature if the pressure remains constant.

$$\frac{\mathscr{V}}{T} = \frac{mR}{p} = \text{constant}$$

Hence

$$\mathscr{V} \propto T. \tag{2-12}$$

This is known as Charles' law. For two different states

$$\frac{\mathscr{V}_2}{T_2} = \frac{\mathscr{V}_1}{T_1}$$

or

$$\frac{\mathscr{V}_2}{\mathscr{V}_1} = \frac{T_2}{T_1}.$$

(v) Find the specific gas constant for a known mass of an unknown gas at known T and p in a container of known volume.

$$R = \frac{p\mathscr{V}}{mT}$$

(vi) If the pressure, volume and temperature of a closed system containing a gas are known and if two of these properties are changed while the system remains closed then the third property at the new state can be found, Figure 2-2.

$$\frac{p_1\mathscr{V}_1}{T_1} = mR = \frac{p_2\mathscr{V}_2}{T_2}$$

Hence, if $p_1, \mathscr{V}_1$ and T_1 are known and if p_2 and T_2 are also known, then

$$\frac{p_2\mathscr{V}_2}{T_2} = \frac{p_1\mathscr{V}_1}{T_1}$$

and so

$$\mathscr{V}_2 = \frac{p_1}{p_2}\frac{T_2}{T_1}\mathscr{V}_1.$$

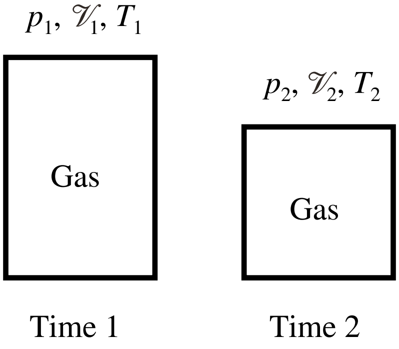
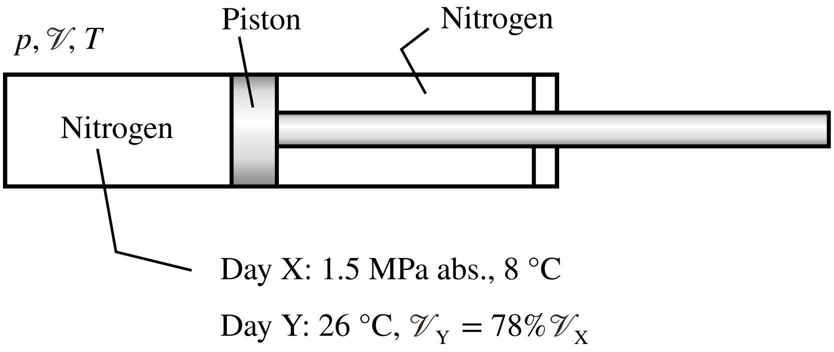


Figure 2-2 A closed system of variable volume at two different times

It is important to remember that T and p are both absolute in the ideal gas equation.

Example 2-3 Gas Spring



On a day when a hospital trolley is in a storeroom where the temperature is 8 °C a fixed amount of nitrogen within one end of a gas spring on the trolley is at a pressure of 1.5 MPa. On another day the trolley is in a hospital ward where the temperature is 26 °C and the gas spring is in a more compressed state such that the volume of the gas has been reduced to 78% of what it was at the previously described state. Calculate the pressure of the nitrogen under the second set of conditions. Assume the gas spring piston is leak-tight.

Solution

Note that only the volume of nitrogen on the left of the piston is involved in the problem.

$$\frac{p_1 \mathscr{V}_1}{T_1} = mR = \frac{p_2 \mathscr{V}_2}{T_2}$$

Hence

$$p_2 = \frac{\mathscr{V}_1}{\mathscr{V}_2} \frac{T_2}{T_1} \, p_1$$

The following are given:

$$p_1 = 1.5 \text{ MPa}$$

$$T_1 = (8 + 273.15) \text{ K} = 281.15 \text{ K}$$

$$T_2 = (26 + 273.15) \text{ K} = 299.15 \text{ K}$$

$$\frac{\mathscr{V}_1}{\mathscr{V}_2} = \frac{1}{0.78}$$

Hence

$$p_2 = \frac{1}{0.78}\,\frac{299.15}{281.15}\;1.5\text{ MPa} = 2.05\text{ MPa abs.}$$

Example 2-4 Find the Density of Air

Use the ideal gas equation to find the density of air at a pressure of 2 bar gauge and a temperature of 32 °C. Take atmospheric pressure as 999 hPa.

Solution

$$v = \frac{RT}{p}$$

$$\rho = \frac{1}{v} = \frac{p}{RT}$$

$$p = \left(2\times 10^5 + 999\times 10^2\right)\text{ Pa}$$

$$= 2.999\times 10^5\text{ Pa}$$

$$T = (32 + 273.15)\text{ K} = 305.15\text{ K}$$

From Table D-1

$$R = 287.1\text{ J/kgK}$$

Hence

$$\rho = \frac{2.999\times 10^5\text{ [Pa]}}{287.1\text{ [J/kgK]}\times 305.15\text{ [K]}}$$

$$= 3.424\left[\text{N m}^{-2}\,\text{N}^{-1}\,\text{m}^{-1}\,\text{kg K K}^{-1}\right]$$

$$3.424\text{ kg/m}^3$$

The Universal Gas Constant

For ideal gases (or real gases at low pressure) it is found that for a given temperature, pressure and volume the amount of substance present is the same irrespective of which gas or mixture of gases is involved.

Hence, as $m = p\mathscr{V}/RT$

$$n = \frac{m}{\bar{m}} = \frac{p\mathscr{V}}{\bar{m}\,RT} = \text{constant}$$

and this applies for different gases when p, $\mathscr{V}$ and T are fixed. Therefore $\bar{m}\,R$ is a constant for all ideal gases and is known as the universal or molar gas constant, $\bar{R}$. Thus

$$\bar{R} = \bar{m}\,R \tag{2-13}$$

and

$$R = \frac{\bar{R}}{\bar{m}}. \tag{2-14}$$

The ideal gas equation can be written using $\bar{R}$ as

$$p\mathscr{V} = \frac{m\bar{R}\,T}{\bar{m}}$$

or

$$p\mathscr{V} = n\bar{R}\,T. \tag{2-15}$$

The universal gas constant $\bar{R}$ has the value 8.3145 kJ/kmolK.

Example 2-5 Amount of Substance of Air

An industrial clean room contains 40 m^3 of air at a temperature of 21 °C and a pressure of 1030 hPa absolute. Calculate the amount of substance of air that is present in kilomoles. Hence, given that the molar mass of air is 28.97 kg/kmol, find the mass of air present.

Solution

$$n = \frac{p\mathscr{V}}{\bar{R}\,T} = \frac{1030 \times 100\ [\text{Pa}] \times 40\ \left[\text{m}^3\right]}{8314.5\ [\text{J/kmolK}] \times (21 + 273.15)[\text{K}]}$$

$$= \frac{1030 \times 100 \times 40}{8314.5 \times 294.15}\ \text{kmol} = 1.685\ \text{kmol}$$

$$m = n\bar{m} = 1.685\ [\text{kmol}] \times 28.97\ \left[\text{kg kmol}^{-1}\right] = 48.8\ \text{kg}$$

Specific Heat at Constant Volume

For substances in general, the specific internal energy depends on two independent properties, such as pressure and temperature or specific volume and temperature. It is useful to define the specific heat capacity at constant volume as follows:

$$c_v = \left.\frac{\Delta u}{\Delta T}\right|_{\Delta T \to 0,\ v = \text{const}} \tag{2-16}$$

where

c_v	=	specific heat at constant volume	J/kgK
u	=	specific internal energy	J/kg
ΔT	=	increase in temperature	K
v	=	specific volume	$\mathrm{m^3 kg^{-1}}$

In words, Equation (2-16) states that the specific heat at constant volume is the ratio of the increase in specific internal energy to an increase in temperature for a small increase in temperature (that tends towards zero), while the specific volume is held constant. The specific heat itself may vary with temperature, but a mean value over a temperature range can usually be used in calculations. It follows therefore that the change in the specific internal energy of a substance corresponding to a change in temperature between two states that have the same specific volume is given by

$$\left.\Delta u\right|_{v = \text{const}} = u_2 - u_1 = c_{v,\,\text{avg}}\,(T_2 - T_1). \tag{2-17}$$

where

$c_{v,\,\text{avg}}$ = average specific heat at constant volume
over temperature range
J/kgK

Fortunately, for ideal gases the specific internal energy depends only on the temperature of the gas, i.e.

$$u = \mathrm{f}(T).$$

Hence, for ideal gases, Equation (2-17) is much less restrictive. It applies between any two states of the ideal gas, whether or not the specific volume remains constant. Therefore, for an ideal gas

$$\Delta u = u_2 - u_1 = c_{v,\,\mathrm{avg}}\,(T_2 - T_1). \tag{2-18}$$

In many practical engineering calculations, gases can be taken as approximately ideal and Equation (2-18) is a convenient way of evaluating changes in specific internal energy. Values of c_v for various ideal gases are presented in Table D-1, Appendix D.

Example 2-6 Internal Energy Increase of Compressed Air

A rigid pressure vessel contains 1.32 kg of compressed air at an initial temperature of 18 °C. If the temperature of the gas is increased by 5 K, determine the corresponding increase in the internal energy of the gas. Assume the air can be regarded as an ideal gas with a constant specific heat at constant volume, c_v.

Solution

From Table D-1, $c_v = 0.7171$ kJ/kgK. Assume this value is valid over the temperature range 18 °C to 23 °C.

$$\Delta U = m\,c_v\,\Delta T$$

$$= 1.32\ [\mathrm{kg}] \times 0.7171\ \left[\frac{\mathrm{kJ}}{\mathrm{kg\,K}}\right] \times 5\ [\mathrm{K}] = 4.73\ \mathrm{kJ}$$

Safety and Environmental Issues Associated with Gases

Persons working with gases need to be aware of the associated safety issues. Because of their nature, whereby a gas will fully occupy any empty space, gases cannot be stored in open containers. They must be stored in sealed containers. In most cases, for the container to be of a reasonable size quite a high pressure must be used. Any such container is a pressure vessel and its construction and use are regulated to ensure public safety. If the valve of a pressurized gas container is suddenly opened or a puncture occurs in the container, the emerging jet of gas can cause physical injury or, for instance, could cause dirt or grit to be propelled into a person's eyes. If the temperature of a sealed container of gas is increased, the pressure within it will increase. This effect could possibly cause failure of the container or the escape of the gas. Some gases are toxic or harmful to health if inhaled. Gases may also be highly flammable or potentially explosive when mixed with air. Leaks of oxygen or mixtures of gases that are rich in oxygen can increase the risk of unintended or unexpected combustion within a region affected. Gases can also cause suffocation by displacing air and it is important to realize that such a potential danger would not be visible, as gases are usually transparent.

Some gases produced in combustion or in power plants are pollutants in the environment. Some of these gases and also some working fluids used in refrigeration, heat pump or air-conditioning equipment can cause ozone depletion in the upper atmosphere or can contribute to global warming through the greenhouse effect.

Knowledge of the nature of gases and the principles of thermodynamics is useful and relevant for mitigating the risks associated with gases.

Problems

2-1 Express 56 °C, 431.6 °C and −186.2 °C in absolute units.

2-2 Match the physical quantities on the left with the base SI units on the right.

	Physical Quantity		Base Unit
A	pressure	1	$\mathrm{kg\,mol^{-1}}$
B	molar mass	2	$\mathrm{J\,mol^{-1}\,K^{-1}}$

C	absolute temperature	3	Pa
D	specific heat	4	J
E	density	5	$\mathrm{Jkg^{-1}}$
F	conventional temperature	6	W
G	universal or molar gas constant	7	kelvin
H	rate of heat transfer	8	$\mathrm{Jkg^{-1}K^{-1}}$
I	work	9	°C
J	specific volume	10	$\mathrm{m^3kg^{-1}}$
K	amount of substance	11	$\mathrm{kgm^{-3}}$
L	specific energy	12	mole

2-3 If the atmospheric pressure is 1010 hPa and the pressure in a tyre is 240 kPa gauge what is the absolute pressure in the tyre?

2-4 An iron casting with a mass of 29.1 kg and at 156 °C is cooled to 18.2 °C by immersion in a tank that contains 1.62 $\mathrm{m^3}$ of water. If the specific heat of the iron is 0.448 kJ/kgK, calculate the energy loss from the casting. Also, assuming that all of the energy lost by the iron is gained by the water, calculate the increase in temperature of the water. Take the specific volume of water as 0.001 $\mathrm{m^3/kg}$ and take its specific heat as 4.18 kJ/kgK.

2-5 What is the mass of hydrogen in a balloon that has a volume of 90 $\mathrm{m^3}$ if the pressure is 0.0989 MPa absolute and the temperature is 14 °C? What would be the mass if air were to replace the hydrogen?

2-6 Find the mass of carbon dioxide in a container of volume $1.2 \times 10^{-3}\ \mathrm{m^3}$ if the pressure is 730 kPa and the temperature is -5 °C.

2-7 A fixed mass of an ideal gas has a volume of 5.2 m^3 at a pressure of 1 bar absolute. What volume will it have at the same temperature if the pressure is increased to 4 bar absolute?

2-8 A container of volume 4.2 m^3 holds an unknown gas at a pressure of 14 bar absolute and a temperature of 135 °C. If the mass of the gas is 69 kg, what is its specific gas constant?

2-9 A container holds a mixture of 2.3 kg of nitrogen gas and 2.7 kg of carbon dioxide gas. Determine the amount of substance of each gas present in kmol and in mol. Hence, briefly discuss the question 'is there more nitrogen or carbon dioxide in the container?'

2-10 In a vehicle repair garage, compressed air is stored in a pressure vessel, called an air receiver, at a pressure of 700 kPa gauge. The compressed air is used for inflating tyres and for operating pneumatic tools. Briefly describe four ways in which the compressed air within or coming from this vessel could cause failure, damage or personal injury.

Chapter 3 Non-flow Processes

The Non-Flow Energy Equation

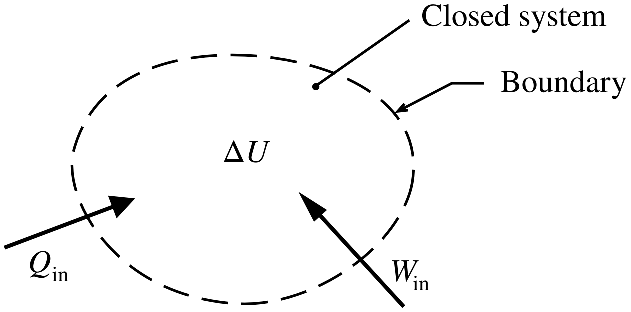


Figure 3-1 A general non-flow process for a closed system.

Figure 3-1 represents a general closed system. Energy crosses the boundary as heat and as work and, as a result, the internal energy of the system changes. The non-flow energy equation, Equation (3-1), expresses the fact that energy is conserved.

$$Q_{in} + W_{in} = \Delta U \tag{3-1}$$

where

Q_{in}	=	net heat transfer into system	J
W_{in}	=	net work into system	J
U	=	internal energy	J
ΔU	=	increase in internal energy	J

On a per-unit-mass basis, Equation (3-1) can be re-written as Equation (3-2).

$$q_{in} + w_{in} = \Delta u \tag{3-2}$$

where

q_{in} = net heat transfer into system per unit mass J/kg

w_{in} = net work into system per unit mass J/kg

Δu = increase in specific internal energy J/kg

It can be noted that for an incompressible substance, changes in specific internal energy can be calculated with Equation (2-8)[5], while for an ideal gas, changes in specific internal energy can be calculated with Equation (2-18), i.e. in both cases

$$\Delta u = c_v \Delta T \tag{3-3}$$

where

c_v = specific heat at constant volume J/kgK

ΔT = increase in temperature K

Two Types of Work Processes

The arrow representing 'net work into the system' in Figure 3-1 includes all work interactions. There are two main types: shaft work and displacement work.

Shaft Work

Shaft work is work done by a shear force in the plane of the system boundary, most commonly where a rotating shaft transmitting mechanical power passes through the boundary, as represented in Figure 3-2.

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[5] $c_v = c$ for an incompressible substance

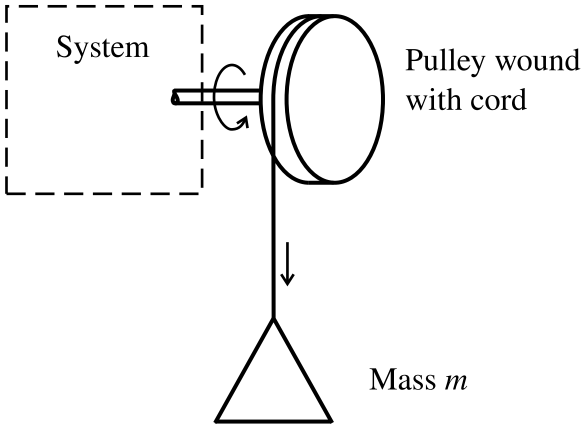

Figure 3-2 Shaft work being done on a system.

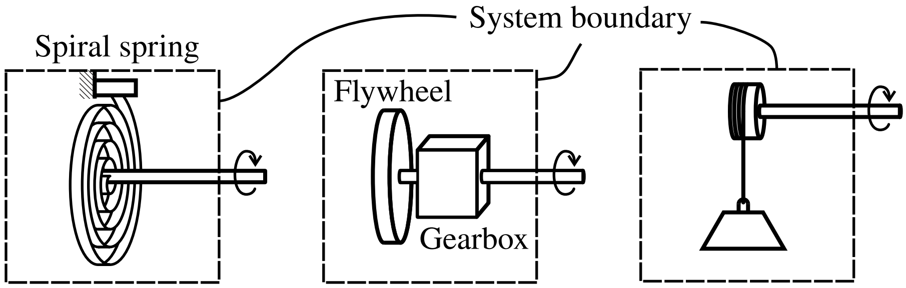

Figure 3-3 Systems that could store energy.

Figure 3-3 represents some systems that are capable of storing energy that enters as shaft work. In a system that contained a spring that could store energy, or a flywheel, or a mass that could be raised or lowered, an input of shaft work could increase the strain energy of the spring or the kinetic energy of the flywheel, or the potential energy of the movable mass within the system. Also, these types of stored energy could give rise to an output of shaft work from a system. However, if a system has a constant volume and comprises a simple incompressible or compressible fluid, an input of shaft work can only increase the energy of the system (in this case the internal energy) by friction within the fluid—see Figure 1-4. A system of constant volume comprising only a simple fluid cannot produce an output of shaft work.

Displacement Work

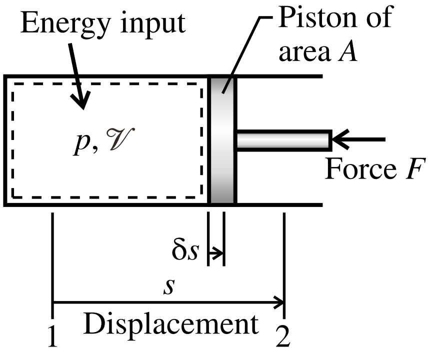

Figure 3-4 Displacement work.

Displacement work for a closed system involves a displacement of the system boundary, i.e. the boundary moves inwards or outwards and the volume of the system changes accordingly. Figure 3-4 illustrates a typical example of displacement work. Energy input to a closed system causes a displacement of the boundary against an externally imposed resisting force. If there is negligible acceleration of the piston and negligible friction, the pressure within the system, p, will equal the force F divided by the area A. The increase in volume for a small displacement δs is given by $A\,\delta s$.

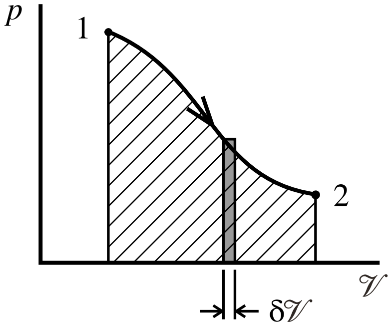

Figure 3-5 Variation of pressure with volume in a general displacement work process.

Figure 3-5 shows how the pressure might vary with volume in the course of a total displacement s from position 1 to position 2. For a small increase in volume, $\delta\mathscr{V}$, as shown in Figure 3-5, corresponding to a short displacement δs, as shown in Figure 3-4, the work done by the system on the piston would be given by

$$\delta W_{\text{out}} = F\delta s = pA\delta s = p\,\delta\mathscr{V}$$

where

δW_{out}	=	work done for a small displacement δs	J
F	=	Force exerted on piston	N
δs	=	small displacement	m
p	=	pressure	Pa
A	=	piston area	m^2
$\delta\mathscr{V}$	=	small increase in volume corresponding to δs	m^3

As the pressure variation would be negligible for a small displacement but, in general, would be significant over a large displacement, it is useful to visualize the overall displacement as a series of small displacements. It can be noted that δW_{out} or $p\,\delta\mathscr{V}$ equals the area of the strip shaded in grey in Figure 3-5. In calculus notation, the work output for the entire displacement is given by

$$W_{\text{out}} = \int_1^2 p\,\mathrm{d}\mathscr{V}$$

and this is equal to the hatched area under the process curve in Figure 3-5. This mathematical notation simply means that if the total displacement is visualized as being made up of a very large number of tiny displacements, the total work done equals the sum of the amounts of work done for all of the tiny displacements.

Electrical Work and Power

At this point it is appropriate to reflect on the thermodynamic nature of electrical work or electrical power. Electric generators are commonly used to convert mechanical power to electrical power, while motors are commonly used to convert electrical power to mechanical power. In principle, the laws of thermodynamics allow for direct conversion from mechanical power to electrical power or from electrical power to mechanical power. In practice, electric motors and generators have efficiencies less than 100%, but machines with very high efficiencies, e.g. 98% for generators and 95% for motors exist.

Keep in mind that transmitting shaft work through a gearbox involves inefficiency. Some of the driving shaft work is always used to overcome friction, so the power output is always less than the power input. Friction will give rise to temperature rise and heat loss from the gearbox to the surroundings. Thus, the conversion efficiency for mechanical power transmission through a gearbox might be a value such as 90%. However, the laws of thermodynamics do not require this efficiency to be less than 100% and it is always possible to devise a gearbox that would involve less friction and would come closer to the ideal efficiency of 100%. In an analogous way, electric motors and generators involve friction and electrical resistance that result in the output power being less than the input power. Of course, energy is conserved as the sum of the power output plus the rate of heat rejection (in steady state operation) equals the power input.

Figure 3-6 illustrates the transmission of electric power across a system boundary, while Figure 3-7 illustrates how, in principle, through the use of an ideal motor and an ideal generator, this could be replaced by an equivalent transmission of mechanical power across the same boundary. In principle, therefore, electric power transmission is thermodynamically equivalent to mechanical power transmission. Work is equivalent to power multiplied by time, so an amount of work done electrically, e.g. using energy that was stored in a battery, is equivalent to work done mechanically, e.g. using energy that was stored as the potential energy of an elevated mass in a gravitational field.

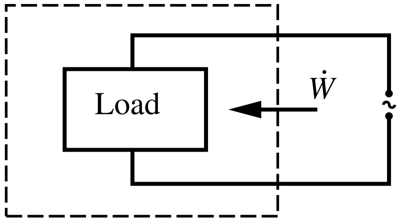

Figure 3-6 Electric power transfer across a system boundary

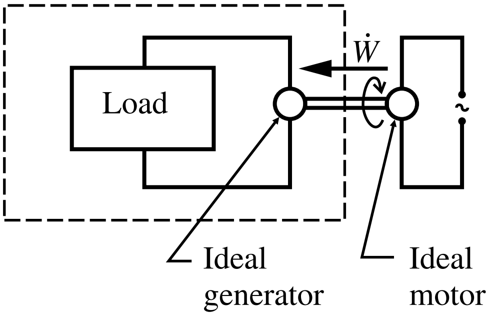

Figure 3-7 Equivalent mechanical power transfer across a boundary

Electrical Resistance Heating

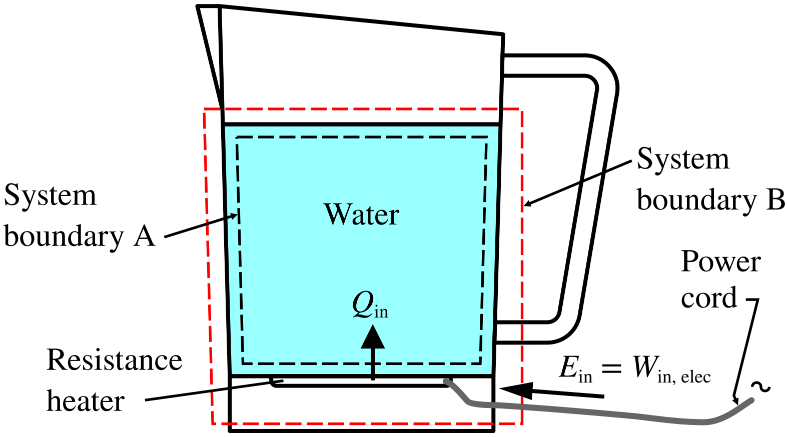

Figure 3-8 Energy transfer in a jug kettle.

Electrical energy is commonly used to provide energy transfer as heat, for instance to heat water in a jug kettle, Figure 3-8. In this figure, system boundary A is drawn to include all the water in the kettle. The energy transfer to the water is thus in the form of heat. However, if system boundary B (which includes part of the jug kettle and intersects the power cord) is used instead, energy crosses it as electrical work. A conversion of electrical work to internal energy and then to heat transfer occurs within the electrical resistance heater. If losses from the base are negligible then the heat transfer is approximately equal to the electrical work.

Constant Volume Processes

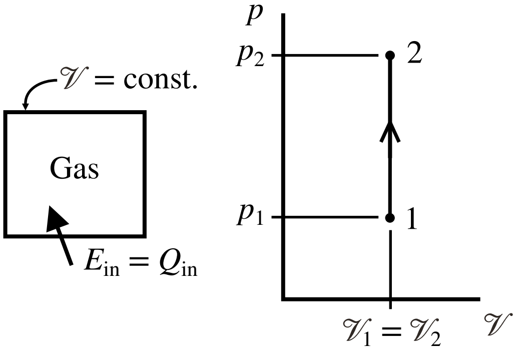

Figure 3-9 Constant volume process of a gas

Figure 3-9 illustrates a constant volume process for an ideal gas. In order to achieve this process, in which the volume remains constant as the pressure increases, energy must be added to the gas, e.g. by heat transfer, which will cause its temperature to increase. If there was heat rejection from the system at constant volume, rather than heat transfer inwards, then both the temperature and the pressure would decrease.

From the ideal gas equation the following relationship applies:

$$\frac{p}{T} = \text{const.} = \frac{p_1}{T_1} = \frac{p_2}{T_2}. \tag{3-4}$$

It can be noted that no work is done on or by the system in the heating process at constant volume illustrated in Figure 3-9.

Constant Pressure Processes

A constant pressure process for an ideal gas is illustrated in Figure 3-10. It is assumed that the piston is frictionless and leak-tight. The sum of the mass of the piston and the mass of the load it carries is constant and therefore the pressure remains constant. In order for the volume to increase, energy must be added to the gas, e.g. by heat transfer, which will cause its temperature to rise.

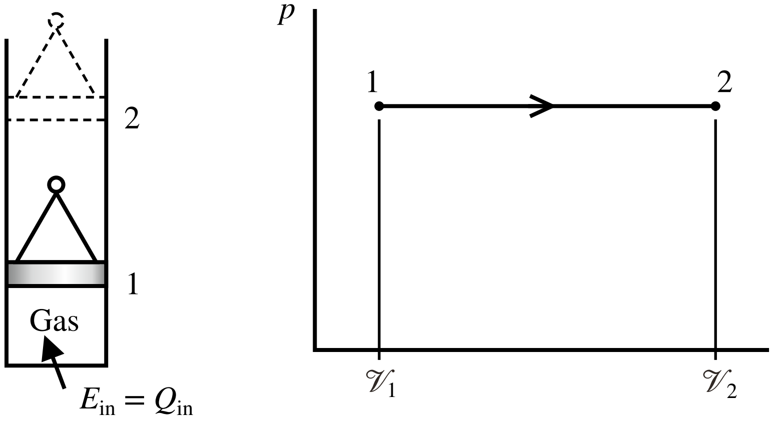

Figure 3-10 Constant pressure process of a gas

From the ideal gas equation, the following relationship applies:

$$\frac{v}{T} = \text{const.} = \frac{v_1}{T_1} = \frac{v_2}{T_2} \tag{3-5}$$

For the constant pressure heating process illustrated in Figure 3-10 work is done on the piston by the system. This work equals the area underneath the horizontal line, which can be expressed as

$$W_{\text{out},1\to 2}\Big|_{p\,=\,\text{const}} = p\,(\mathscr{V}_2 - \mathscr{V}_1).$$

Specific Heat at Constant Pressure

Constant Volume and Constant Pressure Heat Transfer Processes

In order to understand the meaning of specific heat at constant pressure, c_p, it is useful to compare the constant volume process of Figure 3-9 with the constant pressure process of Figure 3-10, both of which involve heat transfer to an ideal gas. Suppose the two systems contain the same mass of the same gas. Suppose also that the temperature rise for a process 1 → 2 is the same in both cases. Which process, the one at constant volume or the one at constant pressure, will require the greater amount of heat input?

The non-flow energy equation, Equation (3-1), is the basis for the correct answer. It can be re-written as indicated below

$$\begin{aligned} Q_{\text{in}} &= \Delta U - W_{\text{in}} \\ &= \Delta U + W_{\text{out}} \end{aligned}$$

For the constant volume process and the constant pressure process the increase in internal energy will be the same, but the constant volume process has zero work. Hence,

$$Q_{\text{in},1\to 2}\Big|_{V=\text{const}} = U_2 - U_1 = m\,(u_2 - u_1). \tag{3-6}$$

However, from the non-flow energy equation, the constant pressure process will require a greater heat input, because W_{out} is greater than zero for it. In this case the energy input as heat goes to increase the internal energy *and* to do work:

$$Q_{\text{in},1\to 2}\Big|_{p\,=\,\text{const}} = U_2 - U_1 + p\,(\mathscr{V}_2 - \mathscr{V}_1).$$

As $p_2 = p_1$ for the constant pressure process, the above expression can also be written as

$$Q_{\text{in},1\to 2}\Big|_{p\,=\,\text{const}} = (U_2 + p_2\mathscr{V}_2) - (U_1 + p_1\mathscr{V}_1). \tag{3-7}$$

The combination of properties $U + p\mathscr{V}$ arises frequently and has the name enthalpy, with the symbol H and the unit J. Enthalpy is a thermodynamic property that depends on the state of the substance or system. Specific enthalpy is the enthalpy per unit mass. It is given the symbol h and has the unit J/kg. The following expressions formally define the properties enthalpy and specific enthalpy:

$$H = U + p\mathscr{V} \tag{3-8}$$

$$h = u + pv \tag{3-9}$$

where

H	=	enthalpy	J
h	=	specific enthalpy	J/kg

Hence, from Equations (3-7) and (3-8), for a constant pressure heat transfer process of a closed system, as shown in Figure 3-10, the following expressions apply

$$Q_{\text{in},1\to 2}\Big|_{p\,=\,\text{const}} = H_2 - H_1 = m(h_2 - h_1) \tag{3-10}$$

$$q_{\text{in},1\to 2}\Big|_{p\,=\,\text{const}} = h_2 - h_1 \tag{3-11}$$

Definition of Specific Heat at Constant Pressure

It is useful to define the specific heat capacity at constant pressure as follows:

$$c_p = \frac{\Delta h}{\Delta T}\bigg|_{\Delta T\to 0,\ p\,=\,\text{const}} \tag{3-12}$$

where

c_p	=	specific heat at constant pressure	J/kgK
Δh	=	increase in specific enthalpy	J/kg
ΔT	=	increase in temperature	K

p = pressure Pa

In words, Equation (3-12) states that the specific heat at constant pressure is the ratio of the increase in specific enthalpy to an increase in temperature for a small increase in temperature (that tends towards zero), while the pressure is held constant. The specific heat itself may vary with temperature, but a mean value over a temperature range can usually be used for calculation purposes. It follows therefore that the change in the specific enthalpy of a substance corresponding to a change in temperature between two states that have the same pressure is given by

$$\Delta h \Big|_{p\,=\,\text{const}} = h_2 - h_1 = c_{p,\,\text{avg}}\,(T_2 - T_1). \tag{3-13}$$

where

$c_{p,\,\text{avg}}$ = average specific heat at constant pressure over temperature range J/kgK

For substances in general, the specific enthalpy depends on two independent properties, such as pressure and temperature. Fortunately, for ideal gases the specific enthalpy depends only on the temperature of the gas, i.e.

$$h = \mathrm{f}(T).$$

The reason for this is that the two additive terms that make up specific enthalpy, $u + pv$, each depend on temperature only:

$$u = \mathrm{f}(T)$$

$$pv = RT = \mathrm{f}(T)$$

Hence, for ideal gases, Equation (3-13) is much less restrictive. It applies between any two states of the ideal gas, whether or not they are at the same pressure. Therefore, for an ideal gas

$$\Delta h = h_2 - h_1 = c_{p,\,\mathrm{avg}}\,(T_2 - T_1). \tag{3-14}$$

In many practical engineering calculations, gases can be taken as approximately ideal and Equation (3-14) is a convenient way of evaluating changes in specific enthalpy.

Example 3-1 Differences in Internal Energy and Enthalpy

A leakproof, variable volume closed system contains 2 kg of argon at state 1, at which the pressure is 2 MPa and the temperature is 278 K. The system is then brought to state 2, at which the pressure is 4 MPa and the temperature is 315 K. Evaluate the increase in internal energy and the increase in specific enthalpy of the gas from state 1 to state 2. The argon can be regarded as an ideal gas with constant specific heats c_v and c_p of 0.3122 kJ/kgK and 0.5203 kJ/kgK respectively.

Solution

For an ideal gas, both the internal energy and the enthalpy depend on temperature only.

$$\Delta U = m\,c_v\,(T_2 - T_1)$$

$$= 2\ [\mathrm{kg}] \times 0.3122\ \left[\frac{\mathrm{kJ}}{\mathrm{kg\,K}}\right] \times (315\text{-}278)\ [\mathrm{K}] = 23.10\ \mathrm{kJ}$$

$$\Delta h = c_p\,(T_2 - T_1)$$

$$= 0.5203\ \left[\frac{\mathrm{kJ}}{\mathrm{kg\,K}}\right] \times (315\text{-}278)\ [\mathrm{K}] = 38.5\ \mathrm{kJ/kg}$$

Isothermal, Polytropic and Adiabatic Processes

Isothermal, polytropic and adiabatic non-flow processes for an ideal gas are of the general type illustrated in Figure 3-11.

The Isothermal Process

In an isothermal process the temperature is constant. Therefore, from the ideal gas equation, Equation (2-10), the following relationship applies:

$$pv = \text{const.} = p_1v_1 = p_2v_2 \tag{3-15}$$

or, if the mass is constant, as is the case for a closed system, Equation (2-9) yields:

$$p\mathscr{V} = \text{const.} = p_1\mathscr{V}_1 = p_2\mathscr{V}_2. \tag{3-16}$$

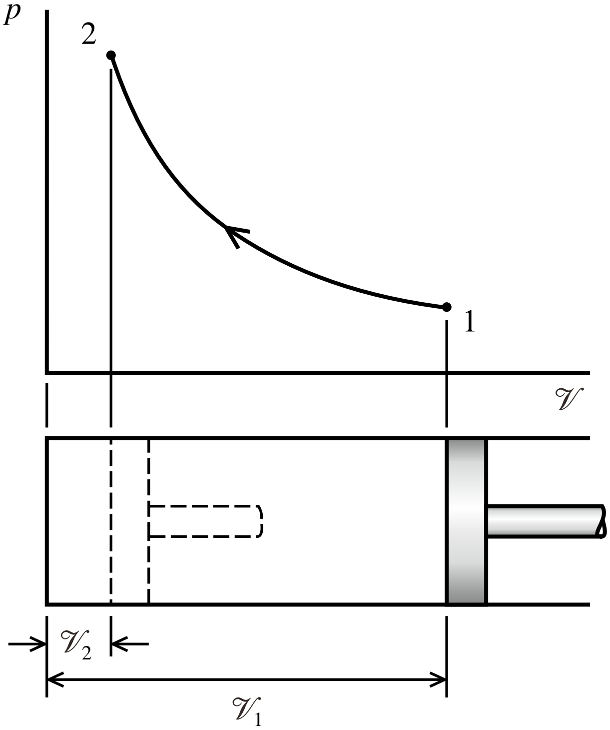

Figure 3-11 Diagram for isothermal, polytropic or adiabatic changes for an ideal gas

A hyperbola is any curve that has the form $xy = \text{const.}$ Therefore an isothermal process of an ideal gas can also be described as a hyperbolic process. In order to achieve isothermal compression of an ideal gas, the gas must reject heat as it is compressed. Likewise, in order to achieve isothermal expansion the gas must accept heat as it expands.

Example 3-2 Isothermal Compression

If an ideal gas is compressed at constant temperature from a pressure of 0.1 MPa absolute and a volume of 50 litres to a pressure of 0.9 MPa, determine the volume of the gas when the pressure reaches 0.3 MPa, 0.6 MPa and 0.9 MPa.

Solution

$$p\mathscr{V} = \text{const.} = p_1\mathscr{V}_1 = 0.1\ [\text{MPa}]\ 50\ [\text{L}] = 5\ \text{MPa L}$$

Hence,

$$\mathscr{V} = \frac{5\ [\text{MPa}]}{p}\ [\text{L}]$$

when $p = 0.3$ MPa $\quad \mathscr{V} = \dfrac{5}{0.3}\ \text{L} = 16.7\ \text{L}$

when $p = 0.6$ MPa $\quad \mathscr{V} = \dfrac{5}{0.6}\ \text{L} = 8.33\ \text{L}$

when $p = 0.9$ MPa $\quad \mathscr{V} = \dfrac{5}{0.9}\ \text{L} = 5.56\ \text{L}$

The Polytropic Process

A polytropic process is a change in the state of a system or substance that can be described by an equation of the form

$$p\mathscr{V}^{\,n} = \text{const.} \tag{3-17}$$

where p is absolute pressure, $\mathscr{V}$ is volume and n is a real number that is typically within the range 1 to 1.7. It is found experimentally that certain real processes can be represented accurately in this way. The isothermal process is a special case where $n = 1$. More generally, the polytropic process can represent the compression or expansion of a gas in a non-isothermal way. Where n is greater than 1, the temperature of the gas will rise during compression and fall during expansion.

For a polytropic process that takes place from state 1 to state 2, Equation (3-17) can be written as Equation (3-18)

$$p_1\mathscr{V}_1^{\,n} = p_2\mathscr{V}_2^{\,n}. \tag{3-18}$$

On a 'per-unit-mass' basis this can also be written in the form[6]

$$p_1 v_1^n = p_2 v_2^n \tag{3-19}$$

where

p	=	pressure	Pa
v	=	specific volume	$\mathrm{m^3\,kg^{-1}}$
$\mathscr{V}$	=	volume	$\mathrm{m^3}$
n	=	polytropic exponent	

i.e. either volume or specific volume can be used in the polytropic relationship.

Temperature Ratios for the Polytropic Process

It is often useful to express the ratio of the start and finish temperatures of a polytropic process of an ideal gas as a function of the ratio of the start and finish volumes or pressures, as follows.

From the polytropic relation

$$p_1\mathscr{V}_1^{\,n} = p_2\mathscr{V}_2^{\,n}.$$

Hence

$$\frac{p_2}{p_1} = \left(\frac{\mathscr{V}_1}{\mathscr{V}_2}\right)^n$$

and

$$\frac{\mathscr{V}_2}{\mathscr{V}_1} = \left(\frac{p_1}{p_2}\right)^{1/n}.$$

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[6] See Appendix G for an explanation.

For a closed system the ideal gas equation gives

$$\frac{p_1\mathscr{V}_1}{T_1} = \frac{p_2\mathscr{V}_2}{T_2}.$$

Hence

$$\frac{T_2}{T_1} = \frac{p_2\mathscr{V}_2}{p_1\mathscr{V}_1}.$$

Substituting $(\mathscr{V}_1/\mathscr{V}_2)^n$ for the pressure ratio p_2/p_1,

$$\frac{T_2}{T_1} = \left(\frac{\mathscr{V}_1}{\mathscr{V}_2}\right)^{n-1}. \tag{3-20}$$

Substituting $(p_1/p_2)^{1/n}$ for the volume ratio $\mathscr{V}_2/\mathscr{V}_1$,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{(n-1)/n}. \tag{3-21}$$

Equations (3-20) and (3-21) show that the higher the value of the polytropic exponent, the higher will be the gas temperature after a polytropic compression process.

Example 3-3 Polytropic Expansion

An ideal gas is expanded polytropically from 350 kPa absolute to 115 kPa absolute. The initial temperature of the gas is 35 °C and the polytropic exponent is 1.2. If the initial volume is 2.7×10^{-3} m^3, find the final volume and temperature.

Solution

$$p_1\mathscr{V}_1^{1.2} = p_2\mathscr{V}_2^{1.2}$$

Hence

$$\mathscr{V}_2 = \mathscr{V}_1\left(\frac{p_1}{p_2}\right)^{1/1.2}$$

$$= 2.7 \times 10^{-3}\ [\mathrm{m}^3] \left(\frac{350}{115}\right)^{1/1.2} = 6.83 \times 10^{-3}\ \mathrm{m}^3$$

$$T_1 = 35 + 273.15\ \mathrm{K} = 308.15\ \mathrm{K}$$

From Equation (3-21)

$$T_2 = T_1 \left(\frac{p_2}{p_1}\right)^{(n-1)/n}$$

$$= 308.15\ [\mathrm{K}] \left(\frac{115}{350}\right)^{0.2/1.2}$$

$$= 255.98\ \mathrm{K}$$

Hence,

$$t_2 = (255.98 - 273.15)\ [^\circ\mathrm{C}] = -17.2\ ^\circ\mathrm{C}$$

The Ideal Adiabatic Process for an Ideal Gas

The word adiabatic means ‘without heat transfer’. An ideal adiabatic process for an ideal gas is a change of state of the gas in which the pressure, volume and temperature of the gas change without any friction effects being present and without any heat transfer occurring to or from the gas.

It is found experimentally that a closed system containing a gas at low pressure obeys the polytropic rule with a characteristic exponent when it undergoes an ideal adiabatic process. The exponent is known as the adiabatic index, γ.

$$p\mathscr{V}^{\gamma} = \text{ const.} = p_1\mathscr{V}_1^{\gamma} = p_2\mathscr{V}_2^{\gamma} \tag{3-22}$$

Thus, an ideal adiabatic process of an ideal gas is a special case of a polytropic process where $n = \gamma$. The value of γ depends on the particular gas, e.g. for air and also for nitrogen the adiabatic index is 1.4. Values of the adiabatic index γ for several ideal gases are tabulated in Table D-1, Appendix D.

Example 3-4 Diesel Engine Compression

Within the cylinder of a diesel engine, 500×10^{-6} m^3 of air at a temperature of 27 °C and a pressure of −15 hPa gauge is compressed to a volume of 24×10^{-6} m^3. Assuming the compression takes place adiabatically as the piston moves towards the cylinder head and given that the adiabatic index for air is 1.4, find the pressure and the temperature at the end of compression. Take the atmospheric pressure as 1019 hPa.

Solution

$$p_1 = (1019 - 15) \times 100 \text{ Pa abs.} = 100{,}400 \text{ Pa abs.}$$

$$p_2 = p_1 \left(\frac{\mathscr{V}_1}{\mathscr{V}_2}\right)^{1.4}$$

$$= 100{,}400 \text{ [Pa]} \left(\frac{500}{24}\right)^{1.4} = 7.047 \times 10^6 \text{ Pa abs.}$$

$$T_1 = 27 + 273.15 \text{ K} = 300.15 \text{ K}$$

$$\frac{T_2}{T_1} = \left(\frac{\mathscr{V}_1}{\mathscr{V}_2}\right)^{n-1}$$

Hence

$$T_2 = 300.15 \text{ [K]} \left(\frac{500}{24}\right)^{0.4}$$

$$= 1011.21 \text{ K.}$$

Hence,

$$t_2 = (1011.21 - 273.15) \text{ [°C]} = 738 \text{ °C.}$$

Various Non-Flow Process Diagrams

Figure 3-12 illustrates some non-flow processes on diagrams of pressure versus specific volume for an ideal gas. In each case the direction of the process is indicated by means of an arrowhead. The processes are described as follows:

(a) Constant pressure (with volume increase)

(b) Constant volume (with pressure reduction)

(c) Polytropic expansion

(d) Isothermal and adiabatic processes, both starting from the same pressure and specific volume and both involving a reduction in volume

(e) Constant volume with cooling followed by constant pressure with heating followed by polytropic expansion

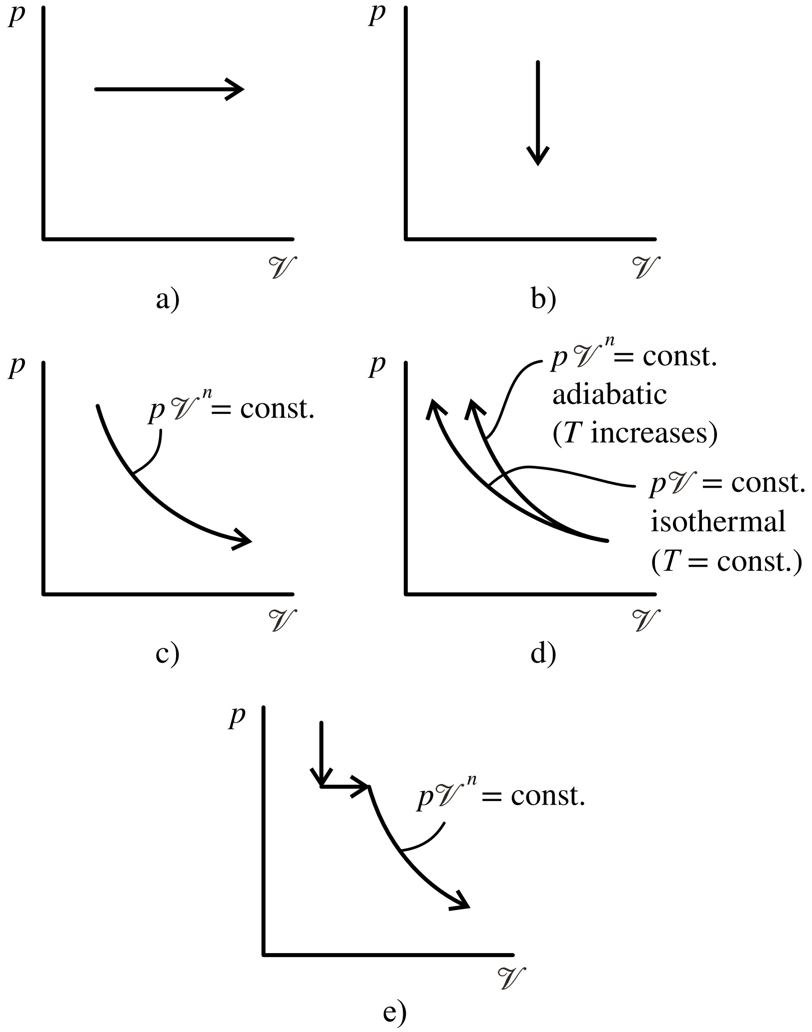


Figure 3-12 Processes of an ideal gas.

Problems

3-1 Given that for a polytropic process

$$T_2 = T_1 \left(\frac{p_2}{p_1} \right)^{(n-1)/n}$$

calculate the final temperature of a gas if it is compressed from atmospheric pressure of 1013 hPa and a temperature of 25 °C to 3 bar gauge with a polytropic index of 1.6.

3-2 A 15 kg mass of carbon dioxide gas ($R = 188.9$ J/kgK) is compressed from 200 kPa gauge and 20 °C to 20% of its original volume and 1700 kPa gauge. It is then cooled back to 20 °C at constant volume. Take atmospheric pressure as 100 kPa. Determine:

a) the temperature after compression.

b) the pressure drop due to the cooling.

c) the final specific volume of the gas.

3-3 Dry air within a closed system is compressed from a temperature of 300 K and a pressure of 0.100 MPa to one tenth of its original volume. Assuming the process is polytropic, calculate the final temperature of the air if the polytropic exponent is (a) 1.2 and (b) 1.4. The following equation can be used:

$$\frac{T_2}{T_1} = \left(\frac{\mathscr{V}_1}{\mathscr{V}_2} \right)^{n-1}.$$

3-4 Sketch the following processes on diagrams of pressure versus specific volume for a closed system containing an ideal gas. In each case indicate the directions of the processes by means of arrowheads.

(i) Constant pressure with volume increase followed by constant volume with pressure increase

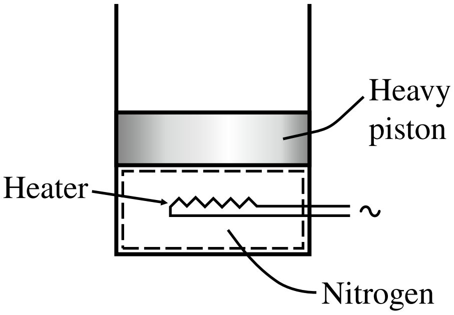
(ii) Polytropic compression followed by constant volume heat addition, followed by polytropic expansion, followed by constant volume heat rejection thereby arriving at the original state

(iii) Isothermal and adiabatic processes, both ending at the same pressure and specific volume and both involving a reduction in volume

(iv) Constant pressure with cooling followed by constant volume with heating followed by polytropic expansion

3-5 Calculate the increase in the enthalpy and the increase in the specific enthalpy of 3.2 kg of air when it is brought from 0.11 MPa and 18 °C to 0.17 MPa and 43.5 °C.

3-6



The volume occupied by 0.1 kg of nitrogen in the system shown above is to be increased by 25% through the use of an electric heater. The gas system is assumed to be perfectly insulated and the piston is assumed to be leak-tight and frictionless. The initial temperature of the gas is 17 °C and the pressure is 0.121 MPa absolute. What amount of work is done on the piston? What energy input must be supplied to the electric heater? The following equations can be used:

$$p\mathscr{V} = mRT$$

$$W_{\text{out, displ},1\to2}\Big|_{p\,=\,\text{const}} = p\,(\mathscr{V}_2 - \mathscr{V}_1)$$

$$W_{\text{in, elec},1\to2} = m(u_2 - u_1) + p\,(\mathscr{V}_2 - \mathscr{V}_1)$$

$$= m(h_2 - h_1) = mc_p\,(T_2 - T_1).$$

Chapter 4 The Reciprocating Compressor

A compressor is a machine in which a gas is compressed from one pressure to another. The gas enters the compressor through an inlet or suction pipe and leaves through a discharge pipe. The reciprocating compressor, Figure 4-1, is commonly used for providing compressed air in industry or compressing refrigerant vapour in a refrigeration system.

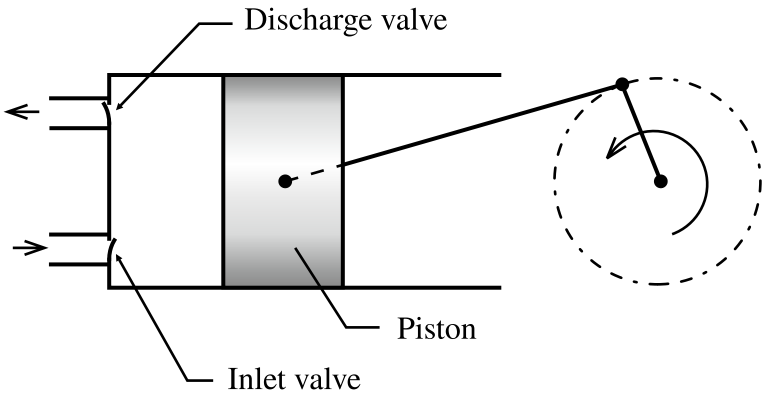


Figure 4-1 Schematic diagram of a reciprocating compressor

The reciprocating compressor belongs to a class of compressors known as positive displacement compressors. In all positive displacement compressors a quantity of gas is taken in at low pressure, compressed by the reduction of the volume of the space in which it is enclosed and then discharged at high pressure. Thus, mechanical work is done on the gas to increase its pressure. In the reciprocating compressor, one-way valves control the admission and discharge of the gas.

Pressure-Volume Diagram

Figure 4-2 illustrates the processes that occur within a reciprocating compressor, assuming no pressure losses through the ideal one-way valves. It can be noted that the system, bounded by the dashed line in the figure, is closed for process AB and for process CD on the p-$\mathscr{V}$

diagram. For the other two processes, BC and DA, mass is entering and leaving the system respectively.

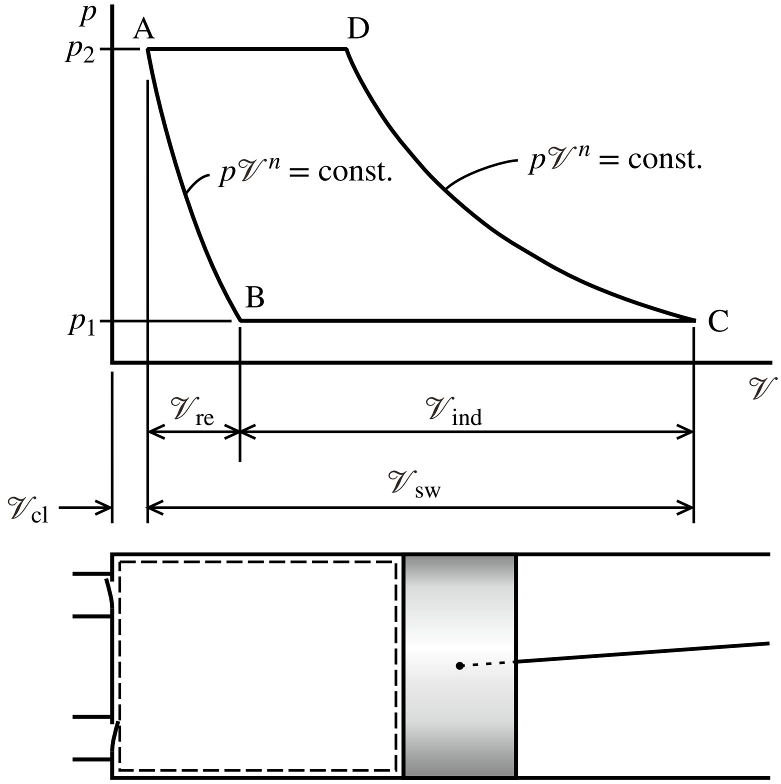


Figure 4-2 p-$\mathscr{V}$ diagram for a reciprocating compressor and a schematic representation of the piston in the cylinder.

At position A the piston is at top-dead-centre and the volume within the cylinder is at a minimum (the clearance volume, $\mathscr{V}_{\text{cl}}$). From A to B the piston moves down the cylinder (away from the cylinder head that contains the valves) and the pressure reduces according to the polytropic relationship. As the pressure within the cylinder is below the discharge pressure p_2 the discharge valve remains closed. The suction valve also remains closed because the pressure within the cylinder is higher than the suction pressure p_1. At point B the pressure within the cylinder reaches the suction pressure. It can be noted that the mass of gas in the cylinder at point B is the same as it was at point A, but the volume of this mass has increased by an amount known as the re-expansion volume, $\mathscr{V}_{\text{re}}$.

As the piston moves from B to C, the inlet valve allows gas to enter the cylinder. The volume of gas which enters is known as the induced volume, $\mathscr{V}_{\text{ind}}$. At point C the piston reaches bottom-dead-centre, which corresponds to the maximum volume within the cylinder (the sum of the clearance volume and the swept volume, $\mathscr{V}_{\text{sw}}$).

As soon as the piston begins to move up the cylinder again, from C to D, the inlet valve closes and the pressure rises according to the polytropic relationship. At point D the pressure within the cylinder reaches the discharge pressure p_2.

As the piston moves from D to A, the discharge valve allows the gas to exit. The mass of gas discharged is the same as the mass of gas that was induced from B to C.

Volumetric Efficiency

The volumetric efficiency of a reciprocating compressor, Equation (4-1), is the ratio of the induced volume (the volume of gas taken in at the suction pressure and temperature) to the swept volume (the volume through which the piston face sweeps). It can be seen in Figure 4-2 that the induced volume $\mathscr{V}_{\text{ind}}$ is less than the swept volume $\mathscr{V}_{\text{sw}}$ due to the re-expansion of gas that remains in the clearance volume $\mathscr{V}_{\text{cl}}$ when the piston is at the top-dead-centre position.

$$E_{\text{vol}} = \frac{\mathscr{V}_{\text{ind}}}{\mathscr{V}_{\text{sw}}} \tag{4-1}$$

where

E_{vol}	=	volumetric efficiency	
$\mathscr{V}_{\text{ind}}$	=	induced volume	m^3
$\mathscr{V}_{\text{sw}}$	=	swept volume	m^3

By applying the polytropic relationship to the processes shown in Figure 4-2 it can be shown[7] that the volumetric efficiency of an ideal reciprocating compressor is given by

$$E_{\text{vol, ideal}} = 1 - r_{\text{cl}}\left[\left(\frac{p_2}{p_1}\right)^{1/n} - 1\right] \tag{4-2}$$

$$r_{\text{cl}} = \frac{\mathscr{V}_{\text{cl}}}{\mathscr{V}_{\text{sw}}} \tag{4-3}$$

where

$E_{\text{vol, ideal}}$	=	ideal volumetric efficiency	
p_2	=	discharge pressure	Pa
p_1	=	suction pressure	Pa
$\mathscr{V}_{\text{cl}}$	=	clearance volume	m^3
$\mathscr{V}_{\text{sw}}$	=	swept volume	m^3
n	=	polytropic index	
r_{cl}	=	clearance ratio	

For maximum volumetric efficiency it is therefore important that the clearance ratio should be kept as small as possible. For a given clearance ratio, the volumetric efficiency depends on the ratio of the discharge pressure to the suction pressure. At high pressure ratios, the volumetric efficiency and the induced volume will be less than at lower pressure ratios.

Example 4-1 Volumetric Efficiency

Use the expression for the volumetric efficiency of an ideal reciprocating compressor to calculate the volumetric efficiency at a

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[7] See Appendix G

pressure ratio of four and at a pressure ratio of eight if the clearance ratio is 3%. The polytropic exponent is 1.35.

Solution

With a pressure ratio of 4

$$E_{\text{vol, ideal}} = 1 - r_{\text{cl}} \left[\left(\frac{p_2}{p_1} \right)^{1/n} - 1 \right]$$

$$= 1 - 0.03 \left[(4)^{1/1.35} - 1 \right]$$

$$= 94.6\%$$

With a pressure ratio of 8

$$E_{\text{vol, ideal}} = 1 - 0.03 \left[(8)^{1/1.35} - 1 \right]$$

$$= 89.0\%$$

Compression Processes

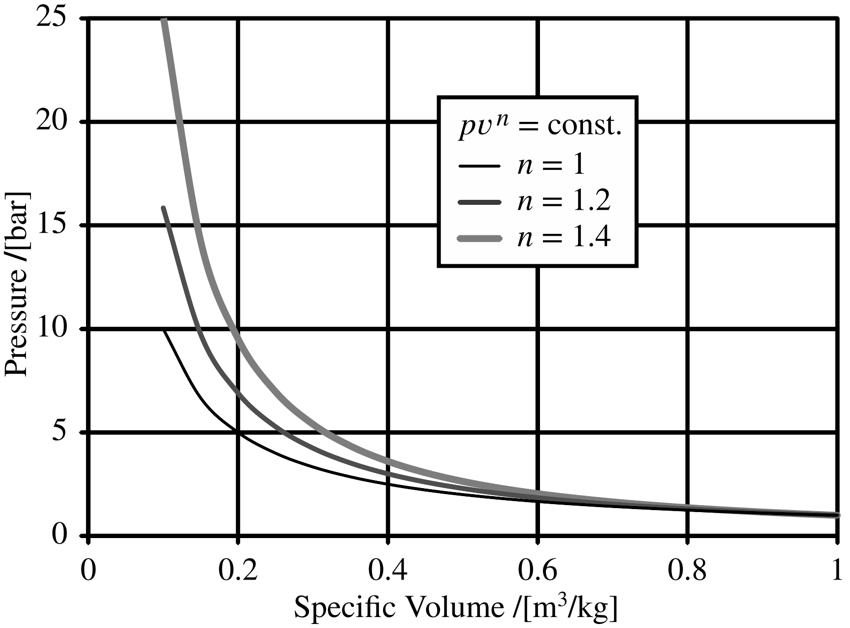


Figure 4-3 A comparison of three polytropic compression processes

In Figure 4-3 three polytropic compression processes are shown. All three have the same initial pressure and specific volume. The polytropic indices for the processes are 1, 1.2 and 1.4. The first process ($n = 1$) is the isothermal case, with heat rejection to keep the gas at its initial temperature. If the gas is air, the third process ($n = \gamma = 1.4$) is the adiabatic case with no heat rejection and the second ($n = 1.2$) is a case where there is some heat loss from the gas during compression.

It is found that compressors that operate with a low polytropic index require less work for compression than those in which the index is high. In practical terms, isothermal compression would require the least amount of work (but is impractical as it is difficult to achieve a high rate of heat rejection from a compact compressor), while adiabatic compression requires the most work. In situations where the purpose of a compressor is simply to increase the pressure of a gas, arrangements are usually made to reject as much heat as possible during compression.

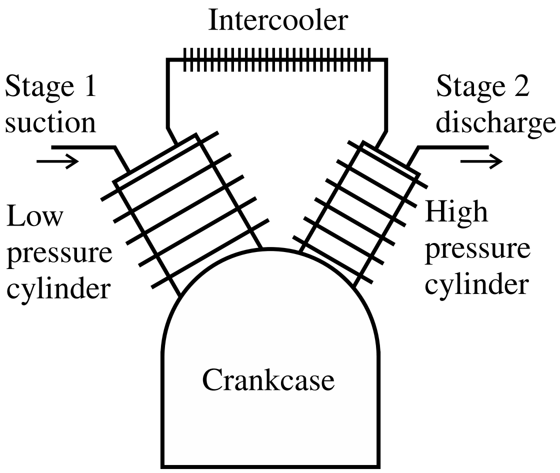


Figure 4-4 Schematic diagram of a two stage reciprocating compressor with an intercooler

Compressors may therefore have cooling fins to keep the gas as cool as possible during compression. Where high pressures are to be produced, energy can be saved by compressing a gas in several stages, with cooling of the gas between successive stages, as in Figure 4-4. Note that the high pressure cylinder is smaller than the low pressure cylinder.

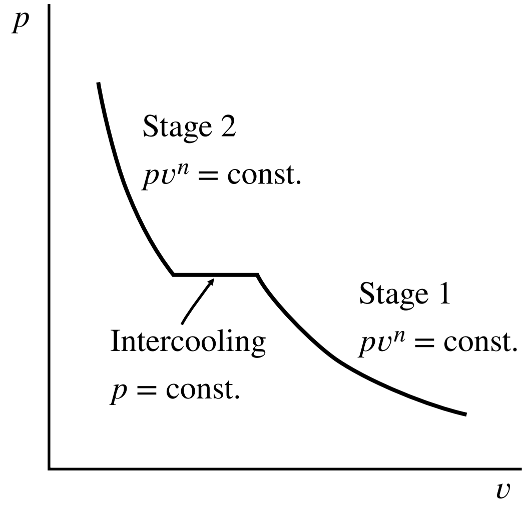


Figure 4-5 Two stage compression with intercooling shown on a *p*-*v* diagram

Figure 4-5 shows how the processes for 2-stage compression with intercooling appear on a pressure versus specific volume diagram. For the polytropic compression parts of the overall process the fluid is contained within closed systems (the stage 1 and stage 2 cylinders, with inlet and discharge valves closed). Otherwise, the fluid is entering or leaving one of the cylinders or passing through the intercooler.

Example 4-2 Volume of Gas after Compression and Cooling

An initial volume of 17.5 litre of gas is compressed from a pressure of 210 kPa gauge and 18.2 °C to 1250 kPa gauge. The gas is then cooled, at constant pressure, to 23 °C. Determine the final volume of the gas. Take atmospheric pressure as 1010 hPa.

Solution

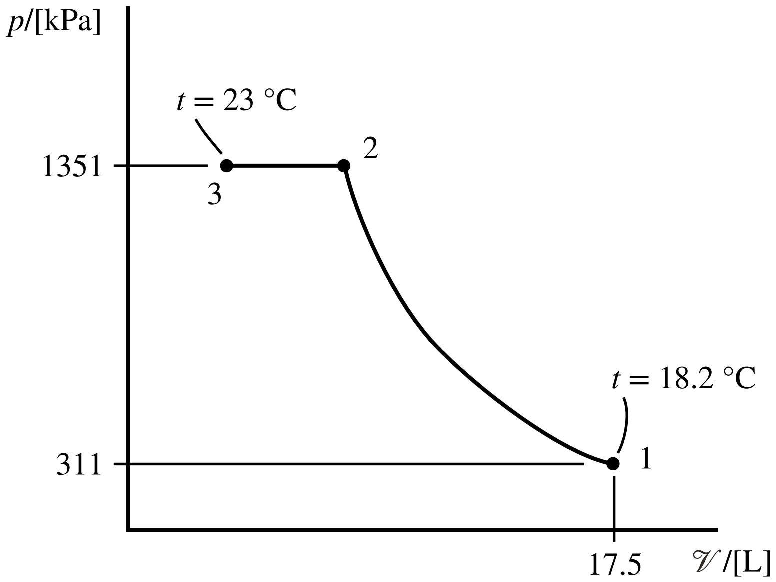
$$p_1 = (210 + 101.0) \text{ kPa abs.} = 311 \text{ kPa}$$

Similarly

$$p_2 = p_3 = (1250 + 101.0) \text{ kPa abs.}$$

$$= 1351 \text{ kPa}$$

The information given is shown on the following diagram. Note that there is insufficient information to determine the volume or temperature at state 2, but there is sufficient to find the volume at state 3.



$$T_1 = (18.2 + 273.15)\ \text{K} = 291.35\ \text{K}$$

$$T_3 = (23 + 273.15)\ \text{K} = 296.15\ \text{K}$$

$$\mathscr{V}_1 = 17.5 \times 10^{-3}\ \text{m}^3$$

The final volume can be found from

$$\frac{p_1 \mathscr{V}_1}{T_1} = \frac{p_3 \mathscr{V}_3}{T_3}.$$

Hence

$$\mathscr{V}_3 = \frac{p_1 T_3}{p_3 T_1} \mathscr{V}_1 = \frac{311 \times 296.15}{1351 \times 291.35}\ 17.5\ \text{L} = 4.09\ \text{L}$$

Problems

4-1 Within the cylinder of a reciprocating air compressor 1.26 L of air at a pressure of 1.35 bar gauge is compressed to a volume of 0.17 L, at which point the pressure is measured as 30 bar gauge. Atmospheric pressure is 1.020 bar. If the temperature of the air is 18 °C at the first state, what is it at the second state?

4-2 An ideal reciprocating compressor has a bore of 75 mm and a stroke of 70 mm and operates at 1450 cycles per minute. Air is taken in at 17 °C and 0.1 MPa and discharged at 0.9 MPa. The clearance ratio is 2% and the polytropic exponent is 1.35. Determine the average volume flow rate of air in the inlet pipe in L/min.

4-3 If a compressor takes in oxygen at 101.3 kPa absolute and 11 °C at the rate of 92.6×10^{-3} m^3/s, determine the intake mass flow rate in kg/s.

4-4 Nitrogen at a pressure of 0.11 MPa and a temperature of 12 °C is to be compressed to 2 MPa in an ideal compressor for which the polytropic index is 1.29. Determine the final temperature of the air (a) if it is compressed in a single stage and (b) if it is compressed to 0.47 MPa, cooled to 30 °C and then compressed to 2 MPa in a second stage.

Chapter 5 The Steady Flow Energy Equation

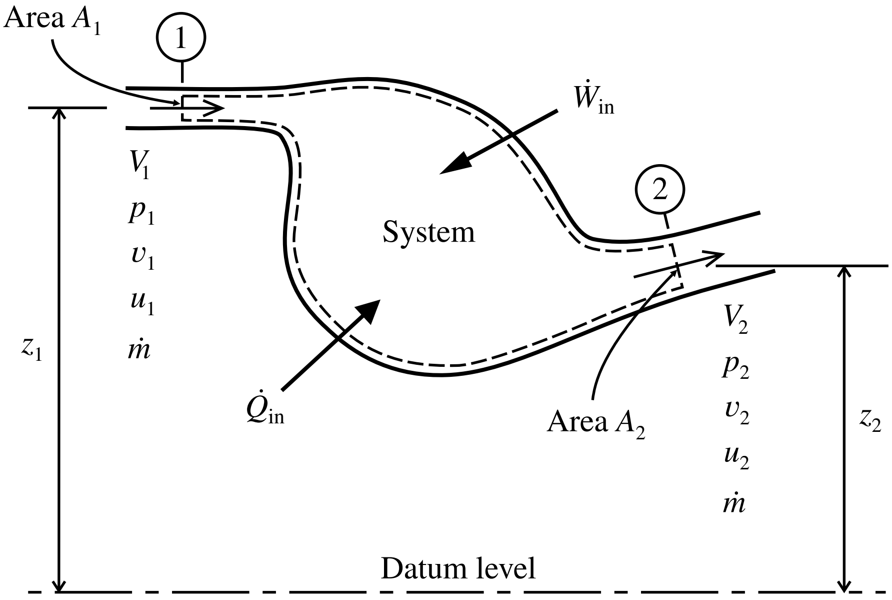


Figure 5-1 A general steady-flow process for an open system.

Figure 5-1 represents a system through which a fluid flows at a steady mass flow rate $\dot{m}$. The system is said to be open, as matter passes through its boundary, which is represented schematically by the dashed line in the figure. This very general diagram could represent real devices or components such as a pump, boiler, condenser, evaporator, length of pipe, nozzle, etc. It can be noted that, as conditions are steady, i.e. invariant in time, the energy of the system itself is not changing. For such a steady flow open system, the energy balance equation is summarized in words in Equation (5-1).

$$\text{Rate of energy input} = \text{Rate of energy output.} \tag{5-1}$$

The net rate of heat transfer into the system across the boundary is represented by $\dot{Q}_{\text{in}}$, while $\dot{W}_{\text{in}}$ represents the net rate of shaft work input across the boundary. A number of other modes of energy input are also involved and are described below. As a simplification, it is assumed that the fluid velocities V_1 and V_2 are constant over cross sections 1 and 2 and are equal to the average actual velocities at the respective positions.

Flow Work

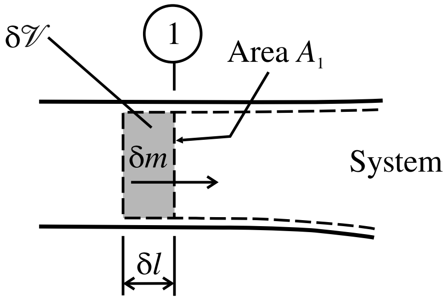


Figure 5-2 A small element of mass entering the system boundary.

Figure 5-2 is useful to explain how a rate of flow work is done *on* the system at flow position 1 and a rate of flow work is done *by* the system at flow position 2 in Figure 5-1. The shaded region represents a small fluid mass δm that is about to enter the system at position 1. In order for this small mass to enter the system it must travel through the small distance δl. The force exerted on the system boundary at 1 is $p_1 A_1$ and from Equation (1-1), as the force and the displacement are in the same direction, the flow work (which is a form of displacement work) is given by

$$W_{\text{flow, 1}} = p_1 A_1 \delta l.$$

The product of the area A_1 and the small length δl equals the volume of the small mass, $\delta \mathscr{V}$, so

$$W_{\text{flow, 1}} = p_1 \delta \mathscr{V}.$$

Also, the small volume $\delta \mathscr{V}$ can be expressed in terms of the small mass δm and the specific volume of the fluid at position 1:

$$\delta \mathscr{V} = \delta m \, v_1.$$

Hence, the work done on the system when mass δm enters is given by

$$\delta W_{\text{flow, 1}} = p_1 \delta m\, v_1$$

and so the flow work done *on* the system per unit mass at cross section 1 is

$$w_{\text{flow, 1}} = \frac{\delta W_{\text{flow, 1}}}{\delta m} = \frac{p_1 \delta m\, v_1}{\delta m}$$

or

$$w_{\text{flow, 1}} = p_1 v_1 . \tag{5-2}$$

Similarly the flow work per unit mass done *by* the system at position 2 is

$$w_{\text{flow, 2}} = p_2 v_2 . \tag{5-3}$$

Depending on the pressure and specific volume values, the flow work input per unit mass at position 1 can be greater than or less than the flow work output at position 2 per unit mass. As will be seen below, the flow work terms of Equations (5-2) and (5-3) are usually taken into account through the use of the property specific enthalpy in the steady flow energy equation.

The Steady Flow Energy Equation

Equation (5-1) can be written in terms of the parameters shown in Figure 5-1 as Equation (5-4). This is known as the steady flow energy equation.

$$\dot{m}\left(u + pv + \frac{V^2}{2} + gz\right)_{\text{in}} + \dot{Q}_{\text{in}} + \dot{W}_{\text{in}} = \dot{m}\left(u + pv + \frac{V^2}{2} + gz\right)_{\text{out}} \tag{5-4}$$

where

$\dot{Q}_{\text{in}}$	=	net heat transfer rate into system	W
g	=	acceleration due to gravity	m s^{-2}
$\dot{W}_{\text{in}}$	=	net shaft work rate into system	W
u	=	specific internal energy	J kg^{-1}
p	=	pressure	Pa
v	=	specific volume	m^3kg^{-1}
V	=	velocity	m s^{-1}
$\dot{m}$	=	mass flow rate	kg s^{-1}

In Equation (5-4) the term pv represents flow work per unit mass of fluid at inlet or outlet. The term u represents the specific internal energy of the fluid, i.e. the molecular level energy it possesses per unit mass. The term $V^2/2$ represents the kinetic energy per unit mass of fluid that crosses the boundary of the system at a specified position. The term gz represents the potential energy per unit mass of fluid that crosses the boundary of the system at a specified position.

The combination of properties $u + pv$ is the specific enthalpy, as defined by Equation (3-9). Hence, Equation (5-4) can be rewritten for steady flow from position 1 to position 2 as Equation (5-5)

$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) + \dot{Q}_{\text{in}} + \dot{W}_{\text{in}} = \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right)$$

(5-5)

or, on a per unit mass basis, as Equation (5-6)

$$h_1 + \frac{V_1^2}{2} + gz_1 + q_{\text{in}} + w_{\text{in}} = h_2 + \frac{V_2^2}{2} + gz_2$$

(5-6)

where

q_{in} = net heat transfer into system per unit mass J/kg

w_{in} = net shaft work into system per unit mass J/kg

Steady Flow of an Incompressible Fluid

Liquids passing through a steady flow system can usually be regarded as incompressible. Therefore if the inlet and outlet temperatures are known the change in specific internal energy can be calculated from Equation (2-8):

$$\Delta u_{\text{incomp}} = u_2 - u_1 = c_{\text{avg}}(T_2 - T_1) \qquad \text{(repeated) (2-8)}$$

Hence, as $v_1 = v_2 = v$,

$$\Delta h_{\text{incomp}} = h_2 - h_1 = c_{\text{avg}}(T_2 - T_1) + (p_2 - p_1)v \qquad (5\text{-}7)$$

For an incompressible fluid, temperature changes can arise because of heat transfer into or out of the system. Furthermore, temperature *increases* can arise because of fluid friction.

Pumps

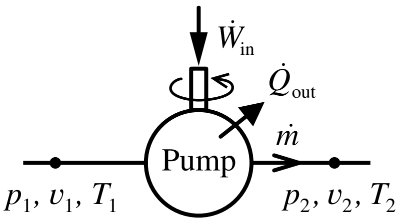


Figure 5-3 Symbolic representation of a pump

Figure 5-3 represents a general pump, such as an oil pump or a water pump. There is an input of shaft power and a rate of heat transfer to the surroundings. The elevation at outlet is the same as the elevation at inlet. Also, the velocity of the water in the outlet pipe is the same as that in the inlet pipe. The temperature of the surroundings is the same as the temperature of the water entering the pump.

The pressure at outlet is higher than that at inlet. Also, because of friction (including fluid friction) within the pump, the outlet temperature of the water is a little higher than the inlet temperature. If the pump were ideal, without any such friction, the exit temperature would be the same as the inlet temperature for an incompressible fluid. Also, the specific internal energy would be the same at exit as at inlet.

Applying the steady flow energy equation

$$\dot{m}\,h_1 + \dot{W}_{\text{in}} - \dot{Q}_{\text{out}} = \dot{m}\,h_2$$

Therefore

$$\dot{W}_{\text{in}} = \dot{m}\,(h_2 - h_1) + \dot{Q}_{\text{out}}. \tag{5-8}$$

Making the common assumption that the fluid is incompressible, this can be written using Equation (5-7) as

$$\dot{W}_{\text{in}} = \dot{m}\left[c_{\text{avg}}(T_2 - T_1) + (p_2 - p_1)v\right] + \dot{Q}_{\text{out}}. \tag{5-9}$$

Most commonly, the power input to a pump is measured directly, but it can be calculated from Equation (5-8) if the values of all the terms on the right hand side are known.

Ideal Pumping Power

In order to calculate the ideal power we assume the fluid is incompressible and the pump is ideal, involving no mechanical or fluid friction and no leakage. We also assume that there is no heat transfer to or from the surroundings. Subject to these assumptions the temperature of the fluid remains unchanged as it passes through the pump, the specific volume is the same at outlet as at inlet ($v_2 = v_1 = v$) and the specific internal energy is the same at outlet as at inlet ($u_2 = u_1$). Hence,

$$\begin{aligned}\dot{W}_{\text{in, ideal}} &= \dot{m}\,(h_2 - h_1)\\ &= \dot{m}\left[(u_2 + p_2v_2) - (u_1 + p_1v_1)\right]\end{aligned}$$

$$= \dot{m}\,[0 + (p_2 - p_1)v].$$

Thus

$$\dot{W}_{\text{in, ideal}} = \dot{m}\,v\,(p_2 - p_1). \tag{5-10}$$

That is, for an ideal frictionless and adiabatic pump the power input equals the product of the mass flow rate, the specific volume and the pressure rise. The ideal power can also be expressed in terms of the volume flow rate as

$$\dot{W}_{\text{in, ideal}} = \dot{\mathscr{V}}\,(p_2 - p_1). \tag{5-11}$$

where

$\dot{\mathscr{V}}$	=	volume flow rate	m^3/s

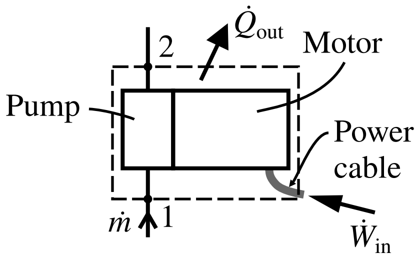
The overall efficiency of a pump is defined as

$$E_{\text{pump}} = \frac{\dot{W}_{\text{in, ideal}}}{\dot{W}_{\text{in}}}. \tag{5-12}$$

Example 5-1 Water Pump

A water circulator consists of an integrated permanent magnet motor and a centrifugal pump. The pressure increase across the pump is 24.3 kPa when the flow rate is $1.09\,m^3/h$, while the electric power consumption is 26.1 W. If the temperature increase of the water as it passes through the pump is 0.01 K, calculate the rate of heat loss from the circulator to the surroundings. Also calculate the overall efficiency of the circulator based on the electric power input.

Solution



Using Equation (5-9),

$$\dot{W}_{\text{in}} = \dot{m}\left[c_{\text{avg}}(T_2 - T_1) + (p_2 - p_1)v\right] + \dot{Q}_{\text{out}}.$$

Hence,

$$\dot{Q}_{\text{out}} = \dot{W}_{\text{in}} - \dot{m}\,[c_{\text{avg}}(T_2 - T_1) + (p_2 - p_1)v].$$

From Appendix E, for water

$$v = 0.001\,\frac{\text{m}^3}{\text{kg}}$$

$$c = 4180\,\frac{\text{J}}{\text{kg}\,\text{K}}$$

$$\dot{m} = \frac{\dot{\mathscr{V}}}{v} = \frac{1.09\ [\text{m}^3/\text{h}]}{3600\ [\text{s/h}] \times 0.001\,[\text{m}^3/\text{kg}]} = 0.3028\,\frac{\text{kg}}{\text{s}}$$

$$\dot{Q}_{\text{out}} = 26.1\ [\text{W}] - 0.3028\left[\frac{\text{kg}}{\text{s}}\right]\left\{4180\left[\frac{\text{J}}{\text{kg}\,\text{K}}\right] \times 0.01\ [\text{K}]\right.$$

$$\left. + 24.3 \times 10^3\left[\frac{\text{N}}{\text{m}^2}\right] \times 0.001\left[\frac{\text{m}^3}{\text{kg}}\right]\right\}$$

$$= 6.1\ \text{W}$$

$$\dot{W}_{\text{in, ideal}} = \dot{\mathscr{V}}\,(p_2 - p_1).$$

$$= \frac{1.09\ [\text{m}^3/\text{h}]}{3600\ [\text{s/h}]} \times 24.3 \times 10^3\left[\frac{\text{N}}{\text{m}^2}\right]$$

$$= 7.358\ \text{W}$$

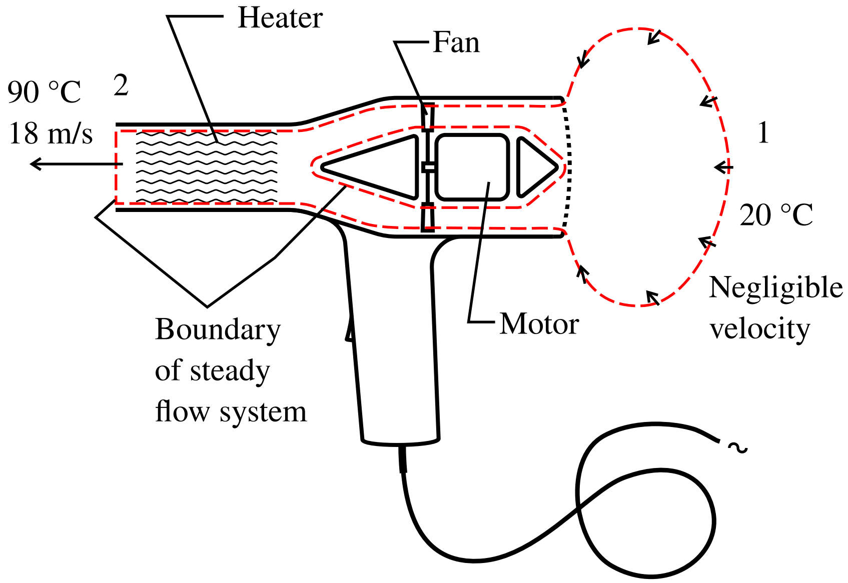
$$E_{\text{circulator}} = \frac{\dot{W}_{\text{in, ideal}}}{\dot{W}_{\text{in}}} = \frac{7.358\ \text{W}}{26.1\ \text{W}} = 28.2\%$$

Steady Flow of an Ideal Gas

A gas passing through a steady flow system can often be regarded as ideal. Therefore if the inlet and outlet temperatures are known the change in specific enthalpy can be calculated from Equation (3-14):

$$\Delta h = h_2 - h_1 = c_{p,\,\text{avg}}\,(T_2 - T_1). \qquad \text{(repeated) (3-14)}$$

Example 5-2 Electric Hair Drier



The diagram above is a schematic representation of a hair drier. An appropriate boundary for a steady flow system is also shown[8]. Ambient air has a temperature of 20 °C. It can be assumed that the average velocity over the inlet surface of the boundary, position 1, is negligible. At the exit surface of the boundary, position 2, the air has a temperature of 90 °C and a velocity of 18 m/s. The total electric power consumption is 1796 W (of which 47 W goes to the motor and the balance to the

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[8] Note that the inlet surface of the system boundary is drawn some distance from the back of the hair drier so that the average velocity is very low and the pressure equals ambient pressure. At the back of the hair drier the velocity is not known, although it would be significantly lower than the discharge velocity because of the larger area and the lower density of the intake air.

heater). Heat losses through the outer casing of the hair drier can be neglected. Use ideal gas properties of air from Table D-1, Appendix D.

(a) Determine the mass flow rate of air through the hair drier for the conditions described.

(b) Compare the overall rate of kinetic energy transfer to the air to the power that goes to the motor.

Solution

$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) + \dot{Q}_{\text{in}} + \dot{W}_{\text{in}} = \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right)$$

The kinetic energy term at inlet can be neglected and the potential energy terms cancel because the inlet and outlet are at the same level. Therefore

$$\dot{E}_{\text{in, total}} = \dot{Q}_{\text{in}} + \dot{W}_{\text{in}} = \dot{m}\left(h_2 - h_1 + \frac{V_2^2}{2}\right) = 1796\ [\text{W}].$$

Also

$$h_2 - h_1 = c_p(t_2 - t_1)$$

and $c_p = 1.0042 \times 10^3$ J/kgK.

Hence

$$\dot{m} = \frac{1796\ [\text{W}]}{1.0042 \times 10^3\ [\text{J/kgK}] \times (90 - 20)[\text{K}] + (18^2)/2\ [\text{m}^2/\text{s}^2]}$$

$$= \frac{1796\ [\text{W}]}{(70{,}294 + 162)\ [\text{J/kg}]}$$

$$= 25.49 \times 10^{-3}\ \text{kg/s}$$

The overall rate of kinetic energy transfer to the air is given by

$$\dot{E}_{\Delta e_{\text{k}}} = \dot{m}\ \Delta e_{\text{k}}$$

$$= 25.49 \times 10^{-3} \left[\frac{\text{kg}}{\text{s}}\right] \times 162 \text{ [J/kg]}$$

$$= 4.13 \text{ W.}$$

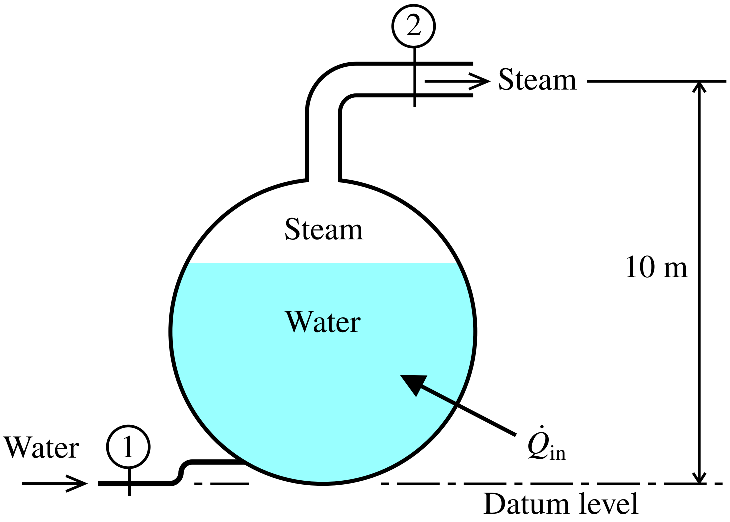
In comparison, the power that goes to the motor is 47 W.

Steady Flow with Phase Change

A common area of application of the steady flow energy equation is where a fluid evaporates, as in a boiler, or condenses, as in a condenser. In such cases the required specific enthalpy values can be found from tables such as those for water substance in Appendix E or for refrigerant 134a in Appendix F. The procedures for looking-up such tables are addressed in Chapter 7 and Chapter 10.

Example 5-3 Steam Boiler

Water enters a boiler at ground level at a rate of 1.7 kg/s, with a velocity of 1.3 m/s and with a specific enthalpy of 58.8 kJ/kg (corresponding to its temperature of 14 °C). Steam leaves the boiler at the same mass flow rate with a specific enthalpy of 2271 kJ/kg (saturation temperature 276 °C, pressure about 6 MPa absolute). The elevation of the outlet is 10 m relative to the inlet and the exit velocity is 3 m/s. Calculate the rate of heat transfer to the water substance in the boiler.



Solution

$$\dot{m}\left(h_1+\frac{V_1^2}{2}+gz_1\right)+\dot{Q}_{\text{in}}+\dot{W}_{\text{in}}=\dot{m}\left(h_2+\frac{V_2^2}{2}+gz_2\right)$$

$$1.7\left[\frac{\text{kg}}{\text{s}}\right]\left(58.8\times10^3+\frac{1.3^2}{2}+0\right)\left[\frac{\text{J}}{\text{kg}}\right]+\dot{Q}_{\text{in}}$$
$$=1.7\ \left[\frac{\text{kg}}{\text{s}}\right]\left(2271\times10^3+\frac{3^2}{2}+9.81\times10\right)\left[\frac{\text{J}}{\text{kg}}\right]$$

It can be noted that the potential energy and kinetic energy terms are negligible in comparison the specific enthalpy terms. The net rate of work input is zero. Hence,

$$\begin{aligned}\dot{Q}_{\text{in}}&=1.7\ (2271-58.8)\times10^3\ [\text{W}]\\&=3761\times10^3\ \text{W}\\&=3761\ \text{kW or }3.76\ \text{MW}\end{aligned}$$

Problems

5-1 $\dot{m}\left(h_1+\frac{V_1^2}{2}+gz_1\right)+\dot{Q}_{\text{in}}+\dot{W}_{\text{in}}=\dot{m}\left(h_2+\frac{V_2^2}{2}+gz_2\right)$

With regard to the equation above, match the correct meaning and the correct base SI units to each symbol in the table below.

Symb.		Meaning		Base Units
$\dot{m}$	A	elevation	1	J kg^{-1}
h	B	mass flow rate	2	m s^{-2}
V	C	specific enthalpy	3	kg s^{-1}
g	D	net heat transfer rate	4	m
$\dot{Q}$	E	velocity	5	W
z	F	acceleration due to gravity	6	m s^{-1}

5-2 Water enters a boiler at ground level at a rate of 4.6 kg/s, with a velocity of 3.7 m/s and with a specific enthalpy of 81.5 kJ/kg. Steam leaves the boiler at the same mass flow rate with a specific enthalpy of 2571 kJ/kg. The elevation of the outlet is 20 m relative to the inlet and the exit velocity is 9.2 m/s. Calculate the rate of heat transfer to the water substance in the boiler. Comment on the significance of the kinetic and potential energy terms in this case.

5-3 Water passes through a steady-flow electric water heater at the rate of 2.16 L/min and its temperature increases from 18 °C to 55 °C. The average specific heat of the water is 4.2 kJ/kgK and the average specific volume is 0.001007 m^3/kg. Calculate the electric power input to the heater and state any assumptions made.

5-4 Water enters a pressure washer machine with negligible velocity at atmospheric pressure and 14.5 °C. It exits from a nozzle with a velocity of 81 m/s at atmospheric pressure and at a temperature of 14.8 °C. The mass flow rate of the water is 0.106 kg/s. Estimate the electric power consumption of the machine on the assumption that all electric energy supplied to the machine is transferred to the water. If the machine were to be fitted with a heater to raise the temperature of the water to 45 °C, how much additional electric power would be required? Take the specific heat of water as 4.2 kJ/kgK.

Chapter 6 Properties of Water Substance

Subcooled, Saturated and Superheated Water Substance

Figure 6-1 is a schematic representation of three states of a closed system that contains only water substance. The pressure within the system is the same in each of the three states.

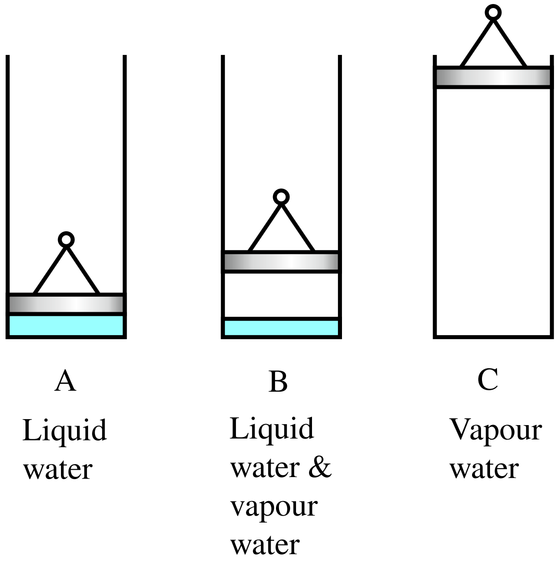


Figure 6-1 Three states of a closed system, all at the same pressure

In state B, liquid water and vapour water co-exist in equilibrium. This is known as a saturated state and, for a given pressure, the temperature is unique: it is known as the saturation temperature corresponding to the pressure. Conversely, the pressure can be described as the saturation pressure corresponding to the temperature.

In state A, the temperature of the water substance is below its saturation value and there is no vapour present. The water is said to be subcooled.

In state C the temperature is above the saturation value and there is no liquid present. The steam is said to be superheated. In reality the volume of the system in state C can be tens, hundreds or even thousands of times greater than the volume in state A. For instance, at atmospheric pressure dry saturated steam occupies about 1600 times as much volume as saturated liquid water and superheated steam occupies greater volume, which continues to increase as the amount of superheat increases.

In order to bring the system in Figure 6-1 from state A to state C energy must be provided to it, usually as heat transfer. There are three distinct stages to such a heating process:

1. The subcooled liquid is heated to the saturation temperature. There is a continuous temperature increase as energy is added.
2. While liquid and vapour are both present, the heat transfer to the system causes the amount of liquid to decrease and the amount of vapour to increase. There is no temperature change.
3. When there is only vapour present, heat transfer to the system increases the amount of superheat, i.e. there is a temperature increase.

The Dryness Fraction or Vapour Fraction or Quality

In state B, as shown in Figure 6-1, the relative amounts of liquid water and steam can vary. As long as both phases of water substance co-exist at the saturation temperature and pressure, the state or condition is described as saturated. The dryness fraction (or vapour fraction or quality) is defined as follows:

$$x = \frac{\text{mass of vapour}}{\text{total mass of liquid and vapour}} = \frac{m_\mathrm{g}}{m} \tag{6-1}$$

where

x = dryness fraction

m_g = mass of vapour kg

m = total mass of liquid and vapour kg

For a saturated mixture of liquid water and steam the dryness fraction or vapour fraction can vary from 0% (known as 'saturated liquid') to 100% (known as 'dry saturated vapour'). If only dry saturated vapour exists in a closed, constant pressure system then any net heat transfer to the system will cause the vapour to become superheated. If only saturated liquid exists in a closed constant pressure system then any net heat loss will cause the liquid to become subcooled.

For a closed, constant pressure system that contains a saturated mixture and where the dryness fraction is between zero and unity, heat transfer to or from the system takes place without any change in temperature. Heat gain causes the mixture to become drier, while heat loss causes the mixture to become wetter.

Property Tables

A set of tables of thermodynamic properties of water substance is provided in Appendix E. The set consists of three tables entitled 'Saturation properties', 'Superheat properties' and 'High and supercritical pressure properties'. In the tables, subscripts are used to represent properties at the saturation condition. These are listed in Table 6-1.

Table 6-1 Subscripts used in property tables

Subscript	Meaning	Example	
f	saturated liquid	u_f	specific internal energy of saturated liquid
g	dry saturated vapour	v_g	specific volume of dry saturated vapour
fg	difference	h_{fg}	$= h_g - h_f$ specific enthalpy difference

Principal Properties Listed in the Tables

The following properties are listed:

p = absolute pressure MPa

t = conventional temperature °C

v = specific volume $\mathrm{m^3/kg}$

u = specific internal energy kJ/kg

h = specific enthalpy kJ/kg

In addition there is one further property, which is useful in performing calculations relating to components such as compressors or turbines. This is known as specific entropy.

s = specific entropy kJ/kg K

Entropy

Entropy, with the symbol S (upper-case letter) and units of J/K, is a thermodynamic property of a system or an amount of substance, just as internal energy, temperature, mass and pressure are thermodynamic properties. Entropy quantifies the thermodynamic disorder of a system at the atomic and molecular level. In a pure crystalline solid at absolute zero temperature (0 K) there is no disorder: molecules retain their arrangement and have no chaotic motions or vibrations.

Entropy is increased when there is net heat transfer to a system and is decreased when net heat transfer occurs from a system. In fact, if a system can be considered to be in equilibrium, if a small amount of heat transfer δQ occurs to it slowly, the corresponding change in its entropy is $\delta Q/T$, where T is the absolute temperature of the system as the heat transfer occurs, Figure 6-2.

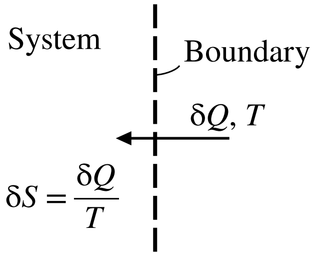


Figure 6-2 Entropy change due to heat transfer to a system. This figure illustrates the entropy increase of a system in quasi-equilibrium at temperature *T* when a tiny amount of heat transfer occurs to it at the same temperature.

In an ideal equilibrium process that involves no heat transfer (known as an adiabatic equilibrium process) the entropy of a system or a quantity of substance remains unchanged. Values of specific entropy for water substance at different states can be found from thermodynamic tables. Perhaps the most distinctive aspect of entropy is that, unlike mass and energy, entropy can be created. However, entropy cannot be destroyed.

The Temperature versus Specific Entropy Diagram

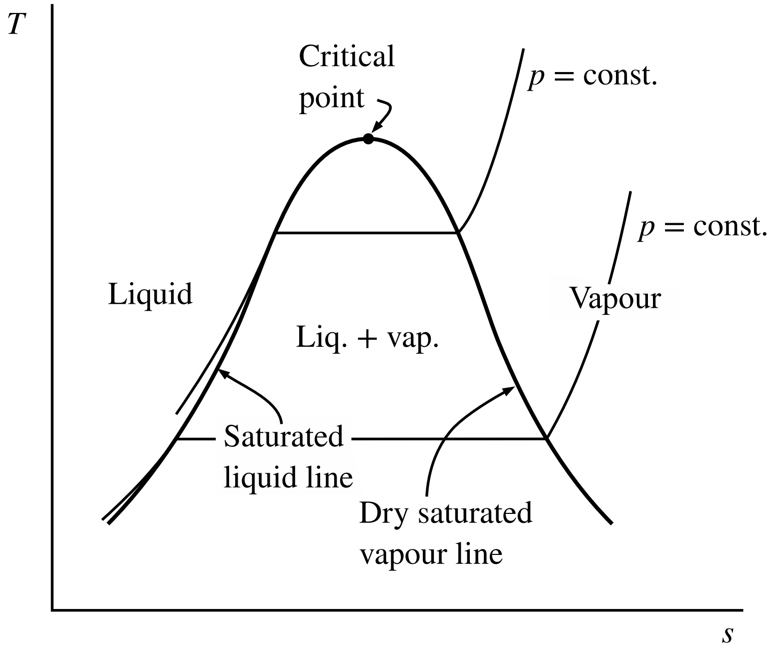


Figure 6-3 The *T*-*s* diagram for liquid water and steam

The constant pressure lines shown on the T-s diagram in Figure 6-3 could correspond to the constant pressure heating process of a closed system as shown in Figure 6-1. They could also correspond to a steady flow, constant pressure heating process that occurs in a boiler. Starting at the left hand side of one of the constant pressure lines, the temperature of the subcooled liquid water increases until the saturated liquid line is reached. The temperature remains unchanged from the saturated liquid state to the dry saturated vapour state, but increases again in the superheat region.

Problems

6-1 Match the physical quantities on the left in the table below with the SI units on the right.

	Quantity		SI Units
A	entropy	1	°C
B	specific entropy (also specific heat capacity, specific gas constant)	2	no units
C	specific volume	3	K
D	pressure	4	$\mathrm{kJkg^{-1}}$
E	conventional temperature	5	$\mathrm{kJK^{-1}}$
F	dryness fraction	6	$\mathrm{kJkg^{-1}K^{-1}}$
G	enthalpy, internal energy	7	MPa
H	specific enthalpy, specific internal energy	8	J
I	absolute temperature, temperature difference	9	$\mathrm{m^3kg^{-1}}$

6-2 (a) Find the specific volume of dry saturated steam at 700 kPa absolute.

(b) Find the specific internal energy of saturated liquid water at 190 °C.

(c) Find the specific enthalpy of dry saturated steam at 165 °C.

(d) Find the specific entropy of saturated liquid water at 1 MPa absolute.

(e) What is the saturation temperature of steam at 20 bar?

(f) What is the saturation pressure of water substance at 190 °C?

6-3 Calculate the specific enthalpy of saturated water and steam at 1 MPa if the dryness fraction is 82%.

6-4 A saturated mixture of liquid water and steam at 900 kPa has a specific enthalpy of 1574 kJ/kg. What is its dryness fraction?

6-5 A steady flow of water substance passes through a boiler drum in which the pressure is 0.8 MPa gauge at the rate of 1.74×10^{-2} kg/s. If it enters as saturated liquid and leaves as wet steam with a vapour fraction of 98%, calculate the rate of heat transfer to the water substance within the boiler. Take atmospheric pressure to be 0.1 MPa. The steady flow energy equation, below, applies.

$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) + \dot{Q}_{\text{in}} + \dot{W}_{\text{in}} = \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right)$$

Chapter 7 Use of Tables for Water Substance

Traditionally tables, often referred to as steam tables, have been used to look up the thermodynamic properties of liquid water and steam. Software is now commonly used for this purpose, but an understanding of using thermodynamic tables provides a sound basis for the correct use of such software.

Saturation Properties

Properties of saturated liquid water and of dry saturated vapour can be found in the saturation properties table, Table E-1, Appendix E. The tabulated saturation properties are

saturation pressure p_s/[MPa]

saturation temperature t_s/[°C]

specific internal energy (u_f, u_g) /[kJ/kg]

specific enthalpy (h_f, h_{fg}, h_g) /[kJ/kg]

specific entropy (s_f, s_{fg}, s_g) /[kJ/kgK]

and specific volume (v_f, v_{fg}, v_g) /[m^3/kg].

For most calculations it is sufficient to take v_f for liquid water as 0.001 m^3/kg, but precise values are available in the tables if required.

Example 7-1 Saturation Properties of Liquid Water and Steam

Use the water substance tables in Appendix E to find the following:

	Solutions
Saturation pressure at 28 °C:	0.00378 MPa (or 0.0378 bar)
Saturation pressure at 290 °C:	7.442 MPa

	Solutions
Saturation temperature at 0.2 bar:	60.1 °C
Specific volume of dry saturated vapour at 40 °C	19.515 m^3/kg
Specific internal energy of saturated liquid at 40 °C	167.5 kJ/kg
Specific internal energy of dry saturated steam at 25 bar	2602.1 kJ/kg
Specific internal energy of saturated liquid at 1.6 MPa	856.6 kJ/kg
Specific enthalpy of saturated liquid at 32 °C	134.1 kJ/kg
Specific enthalpy of dry saturated vapour at 32 °C	2559.2 kJ/kg
Specific enthalpy of dry saturated vapour at 22 MPa	2173.1 kJ/kg
Specific enthalpy difference ($h_g - h_f$) at 22 MPa	161.8 kJ/kg
Specific entropy of saturated liquid at 50 bar	2.921 kJ/kgK
Specific entropy of dry saturated steam at 4 MPa	6.070 kJ/kgK
Specific entropy difference ($s_g - s_f$) at 120 bar	1.997 kJ/kgK

Properties of Saturated Mixtures or Wet Steam

If the dryness fraction (vapour fraction) x is known then an equation of the same form as Equation (7-1) can be used to find v, u, h or s where these properties are average values per unit mass of the mixture as a whole.

$$h = h_\mathrm{f} + x h_\mathrm{fg} \tag{7-1}$$

e.g.

$$u = u_\mathrm{f} + x u_\mathrm{fg}$$

$$s = s_\mathrm{f} + x s_\mathrm{fg}$$

Sometimes the property value for the mixture is known and it is required to find the dryness fraction. This can be done by rearranging the appropriate equation, of the form of Equation (7-1), so that the dryness fraction is on the left hand side, e.g.

$$x = \frac{h - h_\mathrm{f}}{h_\mathrm{fg}} \tag{7-2}$$

Example 7-2 Properties of Saturated Mixtures or Wet Steam

a) Use the Properties of Water Substance tables to find the specific internal energy and the specific volume of a saturated mixture of water and steam at 0.45 MPa if the dryness fraction is 0.237.

b) Use the tables to find the vapour fraction of wet steam that has a specific enthalpy of 2650 kJ/kg at a pressure of 2.5 bar.

Solution

a) At 0.45 MPa

$$u_\mathrm{f} = 622.6\ \mathrm{kJ/kg}$$

$$u_\mathrm{fg} = 1934.5\ \mathrm{kJ/kg}$$

$$\upsilon_\mathrm{f} = 0.001088\ \mathrm{m^3/kg}$$

$$\upsilon_\mathrm{fg} = 0.4128\ \mathrm{m^3/kg}$$

Hence

$$u = (622.7 + 0.237 \times 1934.4)\ \mathrm{kJ/kg} = 1081.1\ \mathrm{kJ/kg}$$

$$\upsilon = (0.001088 + 0.237 \times 0.4128)\ \mathrm{m^3/kg} = 0.0989\ \mathrm{m^3/kg}$$

b) At 2.5 bar

$$h_{\mathrm{f}} = 535.3 \text{ kJ/kg}$$

$$h_{\mathrm{fg}} = 2181.2 \text{ kJ/kg}$$

Hence

$$x = \frac{2650 - 535.3}{2181.2} = 0.970$$

Properties of Subcooled Liquid Water

Subcooled liquid is liquid that is at a temperature below the saturation value corresponding to its pressure. For instance, at a pressure of 1.4 MPa the saturation temperature is 195.0 °C and so water at a lower temperature will be subcooled.

For subcooled liquid the properties specific volume, specific internal energy and specific entropy depend on the temperature and are quite insensitive to pressure. Therefore the saturation values at the same temperature can be used for subcooled liquid, e.g. for liquid water at 1.5 MPa and 85 °C the values for u and s are: 356.0 kJ/kg and 1.135 kJ/kgK—these values are read from the saturation table for water substance at 85 °C for liquid water. It can be noted that the specific volume of liquid water is about 0.001 m^3/kg at low temperatures.

From the definition of specific enthalpy, Equation (3-9), it is clear that the value depends on the pressure:

$$h = u + pv$$

(repeated) (3-9)

For low values of pressure the pv term in Equation (3-9) is often negligible in comparison to the u term. This is why at low pressures the u_{f} and h_{f} values can appear the same.

One way to find the specific enthalpy of subcooled liquid is to look up the specific internal energy in the saturation table at the temperature of the subcooled liquid and add on the pv term, Equation (7-3). It is important to ensure that both additive terms have the same units.

$$h_{\text{subcooled liquid}} = u_{\text{f @ }T} + pv_{\text{f @ }T} \,. \tag{7-3}$$

In some cases it is more convenient to look up the specific enthalpy of saturated liquid at the temperature of the subcooled liquid and apply a pv term correction, as follows:

$$h_{\text{subcooled liquid}} = h_{\text{f @ }T} + (p - p_{\text{s @ }T})v_{\text{f @ }T} \,. \tag{7-4}$$

Example 7-3 Properties of Subcooled Liquid Water

Find the specific enthalpy of water substance at 1.4 MPa and 150 °C using Equation (7-3) and also using Equation (7-4).

Solution

At 1.4 MPa t_s = 195.0 °C. Therefore the water is subcooled.

p [MPa]	t_s [°C]	v_f [m^3/kg]	u_f [kJ/kg]	h_f [kJ/kg]
0.4762	150	0.001091	631.7	632.2

Using Equation (7-3), the specific enthalpy of water at 150 °C and 1.4 MPa is therefore

$$h = 631.7 \left[\frac{\text{kJ}}{\text{kg}}\right] + 1.4 \times 10^3 \text{ [kPa] } \times 0.001091 \left[\frac{\text{m}^3}{\text{kg}}\right]$$

$$= 631.7 \left[\frac{\text{kJ}}{\text{kg}}\right] + 1.527 \left[\frac{\text{kJ}}{\text{kg}}\right] = 633.2 \,\frac{\text{kJ}}{\text{kg}}.$$

Using Equation (7-4), the specific enthalpy of water at 150 °C and 1.4 MPa is

$$h = 632.2 \left[\frac{\text{kJ}}{\text{kg}}\right] + (1.4 - 0.4762) \times 10^3 \text{ [kPa] } \times 0.001091 \left[\frac{\text{m}^3}{\text{kg}}\right]$$

$$= 632.2 \left[\frac{\text{kJ}}{\text{kg}}\right] + 1.008 \left[\frac{\text{kJ}}{\text{kg}}\right] = 633.2 \ \frac{\text{kJ}}{\text{kg}}.$$

Example 7-4 Properties of Subcooled Liquid Water

Find the specific entropy and the specific enthalpy of water at 8 MPa and 36 °C.

Solution

At 8 MPa t_s = 295.0 °C. Therefore the water is subcooled.

$\frac{t_s}{[°\text{C}]}$	$\frac{p}{[\text{MPa}]}$	$\frac{v_f}{[\text{m}^3/\text{kg}]}$	$\frac{h_f}{[\text{kJ/kg}]}$	$\frac{s_f}{[\text{kJ/kgK}]}$
36	0.00595	0.001006	150.8	0.519

$$s = s_f \ \text{at } 36\ °\text{C} = 0.519 \ \text{kJ/kg K}$$

h_f at 36 °C = 150.8 kJ/kg

p_s at 36 °C = 0.00595 MPa

Hence

$$h = 150.8 \ \left[\frac{\text{kJ}}{\text{kg}}\right] + (8 - 0.00595) \times 10^3 \ [\text{kPa}] \ \times 0.001006 \left[\frac{\text{m}^3}{\text{kg}}\right]$$

$$= 150.8 \left[\frac{\text{kJ}}{\text{kg}}\right] + 8.04 \left[\frac{\text{kJ}}{\text{kg}}\right] = 158.8 \ \frac{\text{kJ}}{\text{kg}}.$$

Properties of Superheated Steam

The properties of superheated steam are found in the ‘Superheat properties’ table. In this particular table, regular steps of saturation pressure and of saturation temperature are used. At each pressure, values are tabulated for a range of superheat temperatures. The tabulated properties in the superheat region are

pressure p/[MPa]

specific internal energy u/[kJ/kg]

specific enthalpy h/[kJ/kg]

specific entropy s/[kJ/kgK]

and specific volume v/[m^3/kg].

At each pressure the properties of dry saturated steam are also presented within a column headed ‘Dry sat.’ (Separate symbols with the subscript ‘s’ are not used.):

saturation temperature t_s/[°C]

specific internal energy u_g/[kJ/kg]

specific enthalpy h_g/[kJ/kg]

specific entropy s_g/[kJ/kgK]

and specific volume v_g/[m^3/kg].

Example 7-5 Properties of Superheated Steam

Use the ‘Properties of Water Substance’ tables, Appendix E, to find the specific enthalpy and the specific volume of superheated steam at 16 MPa and 500 °C. Also find the saturation temperature at the same pressure.

From the tables:

$$h = 3297.3 \text{ kJ/kg}$$

$$v = 0.01932 \text{ m}^3\text{/kg}$$

$$t_s = 347.4 \text{ °C}$$

Interpolation

Linear interpolation is used to find properties where the exact values of the known properties are not listed in the tables. The principle of the technique is illustrated in Figure 7-1. It can be seen by inspection of this figure that the estimated value of y_3 corresponding to x_3 when the coordinates (x_1, y_1) and (x_2, y_2) are known is given by Equation (7-5). It is not advisable to try to memorize this equation, but rather to understand it and then apply it in an intuitive way. Linear interpolation from the tables becomes routine with a little practice.

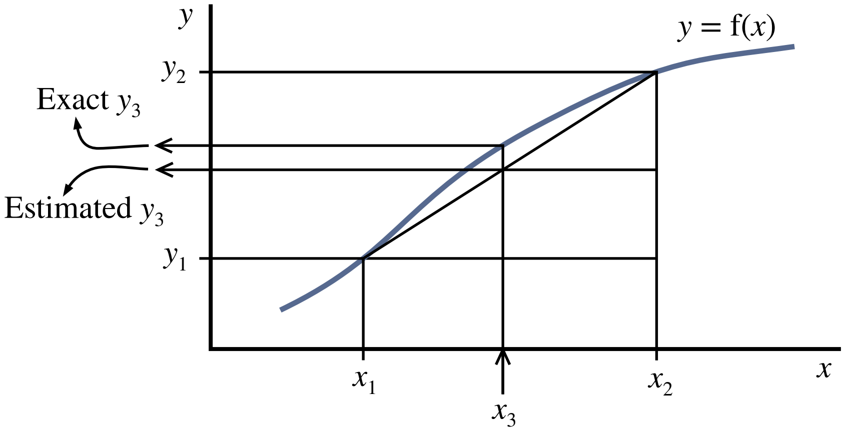


Figure 7-1 Interpolation

$$y_3 = y_1 + \frac{x_3 - x_1}{x_2 - x_1}(y_2 - y_1) \tag{7-5}$$

Example 7-6 Interpolation

(a) What is the saturation temperature of water at a pressure of 151.8 bar?

(b) What is the specific enthalpy of steam at a pressure of 11 MPa and a temperature of 512 °C?

Solution

(a)

At 150 bar $t_s = 342.2$ °C

At 160 bar $t_s = 347.4$ °C

Hence, at 151.8 bar

$$t_s = \left[342.2 + \frac{151.8 - 150}{160 - 150}(347.4 - 342.2)\right] \text{°C}$$

$$= 343.1 \text{ °C}$$

(b)

At 11 MPa and 500 °C $h = 3362.7$ kJ/kg

At 11 MPa and 550 °C $h = 3491.9$ kJ/kg

Hence, at 512 °C

$$h = \left[3362.7 + \frac{512 - 500}{550 - 500}(3491.9 - 3362.7)\right] \text{kJ/kg}$$

$$= \left[3362.7 + \frac{12}{50}(129.3)\right] \frac{\text{kJ}}{\text{kg}}$$

$$= 3393.7 \; \frac{\text{kJ}}{\text{kg}}$$

Problems

7-1 If wet steam has a specific enthalpy of 2762 kJ/kg and a pressure of 10 bar what is its quality? ($h = h_\text{f} + x h_\text{fg}$)

7-2 Calculate the specific volume of a saturated mixture of water and steam at 1.5 MPa given that the vapour fraction is 6.2%.

7-3 Calculate the specific volume of wet steam at 190 °C, given that the dryness fraction is 98.5%.

7-4 Find (a) the saturation pressure for water at 160 °C and (b) the specific enthalpy of steam at 1.5 MPa and 362.5 °C.

7-5 Find the specific internal energy, the specific entropy and the specific enthalpy of liquid water at 15 bar and 165 °C. ($h = h_{\text{f @ } T} + (p - p_\text{s})v_{\text{f @ } T}$)

7-6 (a) Find the specific volume of steam at 2 MPa and 350 °C.

(b) Find the specific internal energy of superheated steam at 250 °C and 3 MPa.

(c) If superheated steam has a specific enthalpy of 2924 kJ/kg and a pressure of 15 bar, what is its temperature?

Chapter 8 The Steam Power Plant

A Boiler and Superheater Plant for a Power Station

Figure 8-1 is a schematic diagram of a gas fired boiler and superheater plant, which might be part of a power station for generating electricity. For instance, it might produce 900 kg of steam per second at a pressure of up to 16 MPa gauge and at a temperature of up to 560 °C. It could well be as tall as a twelve storey building. In boilers such as this the entire chamber (within which combustion occurs and the economizer and superheater tube bundles are suspended) is lined with tubes containing boiling water. The heat transfer to these tubes (particularly those with a line of sight to the combustion flames) is largely by radiation, while the heat transfer to the feed water in the economizer and to the steam in the superheater tubes is mainly by convection.

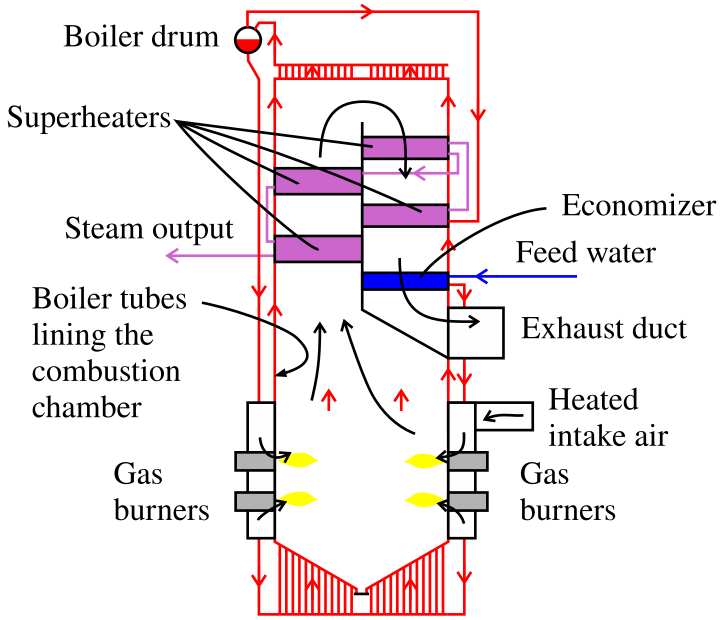


Figure 8-1 Schematic of a radiant steam boiler with superheaters and economizer

Figure 8-2 is a simplified schematic diagram of a generic economizer, boiler and superheater arrangement. It incorporates less detail than Figure 8-1, but the flow path of the water and steam is easier to follow in it.

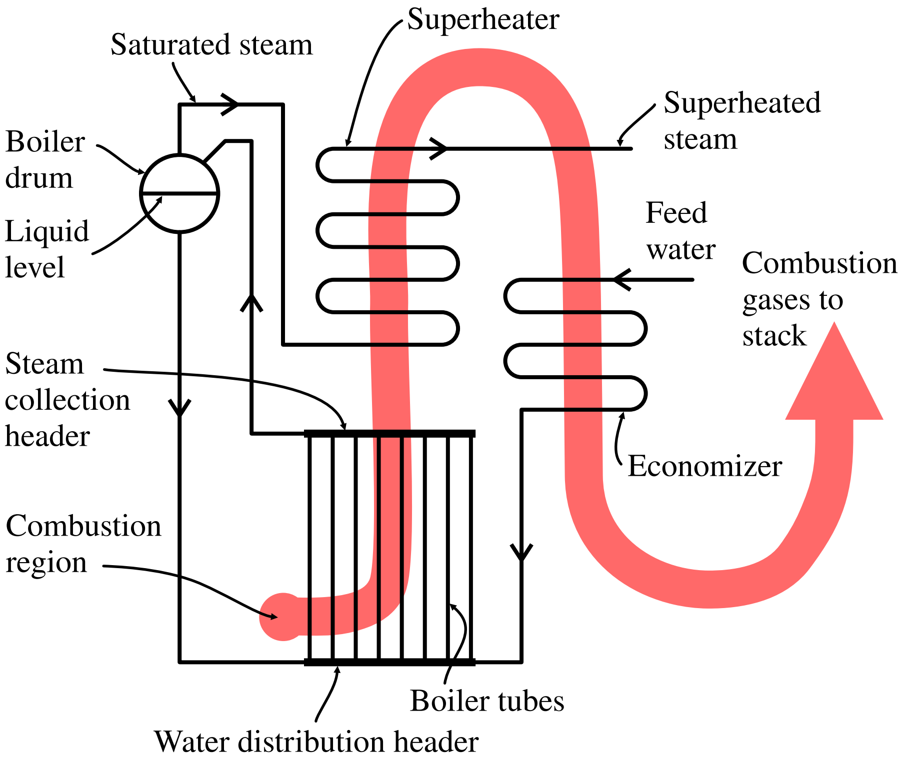


Figure 8-2 Schematic arrangement of a boiler with an economizer and a superheater

Block Diagram of a Steam Power Plant

Figure 8-3 shows the main components of a typical steam power plant. The feed pump pumps water into the boiler where it is heated to its saturation (boiling) temperature and evaporated to form steam. Point A in Figure 8-3 represents the position within the boiler at which the liquid water reaches the saturation temperature. The steam that leaves the boiler passes through the superheater where its temperature is increased further, leaving it at position 3. The pressure at positions 2, A, B and 3 is perhaps 8 MPa gauge and the temperature at point 3 could be 470 °C. The steam that leaves the superheater enters the turbine where it expands and provides mechanical power output in the turbine shaft. The steam leaves the turbine at position 4 at the condenser pressure and at the saturation (or condensing) temperature that corresponds to that pressure. The condenser operates under vacuum (at a pressure of perhaps 4 kPa abs.) and liquid water condensate leaves it at position 1.

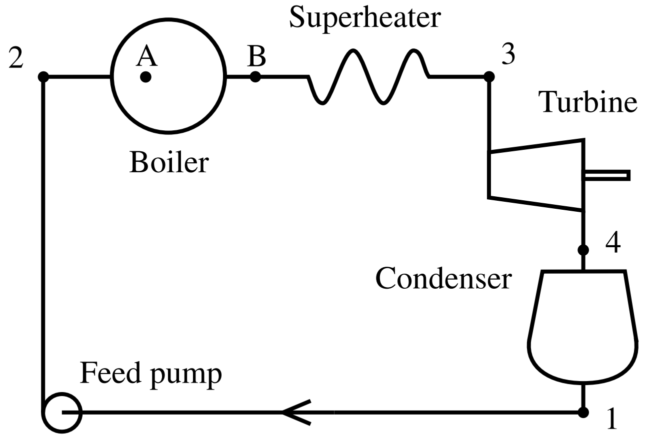


Figure 8-3 Block diagram of a steam power plant

To summarize, between positions 2 and 3 heat transfer occurs to the water and steam, e.g. from the combustion of a fuel. Between positions 4 and 1 heat rejection occurs from the steam to the surroundings, e.g. to cooling water that is at ambient temperature. There is power output from the turbine and a relatively small amount of power is required to drive the feed pump.

The Steam Power Plant as a Heat Engine

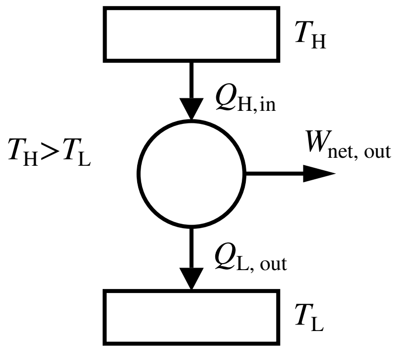


Figure 8-4 Schematic diagram of a heat engine

A steam power plant is a good example of what is known as a heat engine, Figure 8-4. In thermodynamics a heat engine is a system that undergoes a cycle in the course of which heat transfer is accepted from a heat source and heat rejection occurs to a heat sink at lower temperature, while a net work output is produced.

A cycle is a series of processes as a result of which a system or amount of substance that starts off at a given state is brought through other states and back to the initial state. After each cycle the system or amount of substance has undergone no net change.

It is possible for a substance to undergo a cycle as it passes around a flow circuit in steady flow. This is what happens in the steam power plant, Figure 8-3. Water enters the feed pump at state 1 and passes through the feed pump, the boiler and superheater, the turbine and the condenser to arrive back at its original state.

The thermal efficiency of a heat engine is defined as

$$E_{\mathrm{th}} = \frac{W_{\mathrm{net,\ out}}}{Q_{\mathrm{H,\ in}}} \tag{8-1}$$

where

E_{th} = thermal efficiency

$Q_{\mathrm{H,\ in}}$ = heat input from the thermal reservoir at the higher temperature J

$W_{\mathrm{net,\ out}}$ = net work output J

Also,

$$E_{\mathrm{th}} = \frac{W_{\mathrm{net,\ out}}/\Delta t}{Q_{\mathrm{H,\ in}}/\Delta t}$$

where Δt is a time interval during which the net work output and the net heat input occur.

Hence, if the net power output and the net heat input rate are constant,

$$E_{\text{th}} = \frac{\dot{W}_{\text{net, out}}}{\dot{Q}_{\text{H, in}}} \tag{8-2}$$

where

$\dot{Q}_{\text{H, in}}$ = heat input rate from the thermal reservoir at the higher temperature W

$\dot{W}_{\text{net, out}}$ = net work output rate (net power output) W

Note: sometimes the heat input is supplied at multiple temperatures or over ranges of temperature. Likewise, heat rejection can occur at multiple temperatures or over ranges of temperatures.

Example 8-1 Steam Power Plant Thermal Efficiency

The rate at which energy is supplied as heat transfer to the circuit of a steam power plant is 27.3 MW, while the net electric power produced is 11.3 MW. What is the thermal efficiency of the plant based on these values?

Solution

The electric power output can be regarded as a rate of work output. The thermal efficiency can be written in terms of the heat input and net work output rates as follows:

$$E_{\text{th}} = \frac{\dot{W}_{\text{net, out}}}{\dot{Q}_{\text{H, in}}}.$$

Hence,

$$E_{\text{th}} = \frac{11.3\ \text{MW}}{27.3\ \text{MW}} = 41.4\%$$

The Temperature versus Specific Entropy Diagram for an Ideal Steam Power Plant

Figure 8-5 illustrates the cycle for an ideal steam power plant, the Rankine cycle, on a *T*-*s* diagram. The processes undergone by the water substance are as follows:

1 → 2 Water at the saturated liquid state is pumped from the condenser pressure to the boiler pressure. This is taken to be an ideal adiabatic process, i.e. there are no friction effects and there is no heat transfer, so the specific entropy remains unchanged. The temperature rise from 1 to 2 is greatly exaggerated on the diagram and can be neglected in practice. Work input is required.

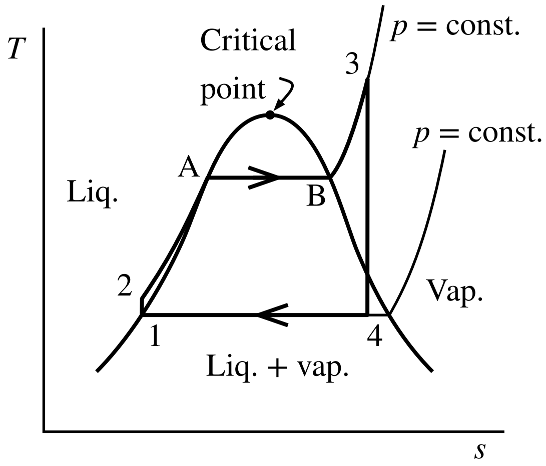


Figure 8-5 The ideal Rankine cycle for a steam power plant shown on a *T*-*s* diagram for water substance

2 → A The water is heated at constant pressure until it reaches the saturation temperature. This may occur within the boiler, but a separate heat exchanger known as an economizer is often used.

A → B Boiling (evaporation accompanied by considerable vapour bubble formation) occurs at constant pressure within the boiler.

B → 3 The steam is superheated at constant pressure in the superheater.

3 → 4 The steam is expanded in the turbine, producing work. This is taken to be an ideal adiabatic process so the specific entropy remains unchanged.

4 → 1 The steam is condensed at constant pressure in the condenser.

The Steady Flow Energy Equation for the Steam Power Plant

The steady flow energy equation, Equation (5-5), can be applied to the main components of the steam power plant. Changes in kinetic energy and potential energy between positions 1, A, B, 2, 3 and 4 in Figure 8-3 are usually negligible. Therefore, when applied to the feed pump, the boiler and superheater, the turbine and the condenser the steady flow energy equation usually involves only the heat transfer, work and specific enthalpy terms. These equations are examined in more detail for each of the main steam power plant components.

Feed Pump Work or Power

For a given mass flow rate $\dot{m}$ of water through the feed pump the rate of energy transfer to the pump as work is given by Equation (5-8), which is presented here as two variants, Equations (8-3) and (8-4).

$$\dot{W}_{\text{pump, in}} = \dot{m}\,(h_{\text{out}} - h_{\text{in}}) + \dot{m}\,q_{\text{pump, out}} \tag{8-3}$$

or

$$\dot{W}_{\text{pump, in}} = \dot{m}\,(h_{\text{out}} - h_{\text{in}}) + \dot{Q}_{\text{pump, out}} \tag{8-4}$$

where

$\dot{W}_{\text{pump, in}}$	=	net rate of work input	W
$\dot{Q}_{\text{pump, out}}$	=	net rate of heat output	W
$q_{\text{pump, out}}$	=	pump net heat output per unit mass	J/kg

$\dot{m}$	=	mass flow rate	kg/s

For an adiabatic pump, or one where the net heat transfer is negligible, Equation (8-3) for the net work input per unit mass of fluid can be written as

$$w_{\text{pump, in, adiab}} = h_{\text{out}} - h_{\text{in}}$$

and the rate of work input, or power, is given by

$$\dot{W}_{\text{pump, in, adiab}} = \dot{m}\,(h_{\text{out}} - h_{\text{in}}).$$

Ideal Feed Pump Power

For an incompressible fluid passing through an ideal pump without fluid friction, mechanical friction or heat transfer, the specific internal energy would be the same at the outlet as at the inlet. The ideal pump power input is given by Equation (5-9), which is written here as Equation (8-5) using 'in' and 'out' subscripts.

$$\dot{W}_{\text{pump, in, ideal}} = \dot{m}\,v\,(p_{\text{out}} - p_{\text{in}}) \tag{8-5}$$

where

$\dot{W}_{\text{pump, in, ideal}}$	=	net rate of work input of an ideal frictionless pump	W
v	=	specific volume of incompressible fluid (water)	m^3/kg
p	=	pressure	Pa

That is, for an ideal feed pump the power input equals the product of the mass flow rate, the specific volume and the pressure rise.

Calculation of Heat Transfer Rates in a Boiler

In a boiler, or boiler and superheater, a steady rate of heat transfer occurs to a steady flow stream of water substance and causes an increase in specific enthalpy from inlet to outlet. Within the boiler, liquid water changes to steam. Within the superheater, further heat transfer occurs to the steam in the absence of liquid water. The general heat transfer rate equation for a boiler (or boiler and superheater) has the form of Equation (5-4), which is written here as Equation (8-6).

$$\dot{Q}_{\text{boiler}} = \dot{Q}_{\text{in}} = \dot{m}\,(h_{\text{out}} - h_{\text{in}}). \tag{8-6}$$

where

$\dot{Q}_{\text{boiler}}$	=	rate of heat transfer that occurs into the system in a boiler	W
$\dot{Q}_{\text{in}}$	=	rate of heat transfer into the system	W
$\dot{m}$	=	mass flow rate of the water substance	kg/s
h_{out}	=	specific enthalpy of the water substance coming out of the system	J/kg
h_{in}	=	specific enthalpy of the water substance going into the system	J/kg

Equation (8-6) can be applied to the economizer, boiler and superheater taken as a whole, or to part of this flow system, e.g. to the superheater alone.

Example 8-2 Boiler and Superheater Heat Transfer Rate

In a Rankine steam cycle, water leaves the feed pump at 40 °C and 8 MPa. Steam leaves the superheater at 400 °C at the same pressure. If the mass flow rate of the steam is 98.3 kg/s, calculate the rate of heat transfer to the water substance in the integrated boiler and superheater.

Solution

Find h_{in} at 40 °C and 8 MPa:

h_{f} at 40 °C = 167.5 kJ/kg

p_{s} at 40 °C = 0.00738 MPa

v_f at 40 °C = 0.001008 m^3/kg

Therefore

$$h_{in} = 167.5\left[\frac{kJ}{kg}\right] + (8 - 0.00738) \times 10^3\ [kPa] \times 0.001008 \left[\frac{m^3}{kg}\right]$$

$$= (167.5 + 8.1)\ \frac{kJ}{kg} = 175.6\ \frac{kJ}{kg}$$

Find h_{out} at 400 °C and 8 MPa:

$h_{out} = 3139.4$ kJ/kg

Therefore

$$\dot{Q}_{in} = \dot{m}\,(h_{out} - h_{in})$$

$$= 98.3\left[\frac{kg}{s}\right] \times (3139.3 - 175.6)\left[\frac{kJ}{kg}\right]$$

$$= 291.3 \times 10^3\ kW = 291.3\ MW$$

Turbine Work or Power

For the turbine, the steady flow energy equation can be written as

$$w_{turb,\,in} + q_{turb,\,in} = h_{out} - h_{in}$$

where

h = specific enthalpy J/kg

$w_{turb,\,in}$ = turbine net work input per unit mass J/kg

$q_{turb,\,in}$ = turbine net heat input per unit mass J/kg

As net energy transfer as work is from the fluid during expansion, and as heat transfer is normally negligible in steam turbines, the equation can also be written as

$$w_{\text{turb, out}} = h_{\text{in}} - h_{\text{out}} \tag{8-7}$$

where

$w_{\text{turb, out}}$ = turbine net work output per unit mass J/kg

h = specific enthalpy J/kg

Thus Equation (8-7) can be used to calculate the net work output per unit mass if the specific enthalpy values at inlet and outlet are known.

With reference to Figure 8-5 it can be noted that for an ideal turbine (assumed adiabatic and without fluid friction) the specific entropy of the steam at exit would be the same as that of the steam at entry. In actual turbines (which are approximately adiabatic) there is always an increase in the specific entropy, which is caused by fluid friction. Equation (8-7) still applies, but the specific enthalpy at exit will be higher than for the ideal case.

The rate of work output, or the power, of the turbine is given by

$$\dot{W}_{\text{turb, out}} = \dot{m}\,(h_{\text{in}} - h_{\text{out}}) \tag{8-8}$$

where

$\dot{W}_{\text{turb, out}}$ = net rate of work output W

$\dot{m}$ = mass flow rate kg/s

Calculation of Heat Transfer Rate in a Condenser

In a condenser, Figure 8-6, a steady rate of heat transfer occurs from a steady flow stream of water substance and causes a decrease in specific enthalpy from inlet to outlet. The water substance condenses from steam to liquid water. The steady flow energy equation for a condenser can be written as

$$\dot{Q}_{\text{condenser}} = \dot{Q}_{\text{out}} = \dot{m}\,(h_{\text{in}} - h_{\text{out}}).$$

(8-9)

where

$\dot{Q}_{\text{condenser}}$ = rate of heat transfer that occurs out of the system in a condenser W

$\dot{Q}_{\text{out}}$ = rate of heat transfer out of the system W

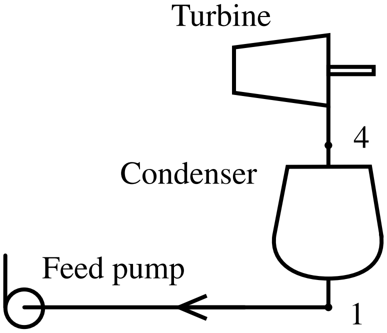


Figure 8-6 Condenser within a steam power plant

Figure 8-6 shows a condenser, situated between the turbine and the feed pump in a steam power plant. The condenser is cooled by ambient air or water and thereby rejects heat to the surroundings. As ambient temperature is well below 100 °C (the condensing temperature of water vapour at atmospheric pressure), the condenser normally operates at a pressure below atmospheric pressure. This ensures that the pressure drop across the turbine is as large as possible. The exact saturation pressure within the condenser is determined by the temperature of the surroundings *and* the effectiveness of heat rejection. Once the steam has been condensed to liquid water, it is returned to the boiler via a feed pump.

Why is a Condenser Required?

Modern steam power plants normally operate on a closed cycle, i.e. water substance is recirculated continuously through the plant. The water substance that leaves the turbine as steam will be required to pass through the boiler and superheater where energy will be added to it. It might therefore seem like a good idea to let the water substance, as steam, pass directly from the turbine outlet to the boiler. However, the turbine exhaust steam is at a very low pressure (perhaps about 4 kPa), while the pressure in the boiler is high (perhaps 8 MPa) and a compressor would be needed to bring about the required flow. The work to drive the compressor would have to come from the turbine. In fact, if there was no heat rejection from the steam before it was compressed, and allowing for inefficiency in both the turbine and compressor, it would take more work to compress the steam than the work produced in the turbine. Rejecting heat from the water substance in the condenser has the effect of reducing its volume to a tiny fraction of what it has at the turbine outlet. When the water substance is fully condensed to liquid water, at near ambient temperature, very little work is required to pump it into the boiler.

From a practical perspective, the condenser allows the water substance to be recirculated for the expenditure of relatively very little pumping power. From another perspective there is a law called the *second law of thermodynamics* that states that heat transfer cannot be converted completely to work at the macroscopic level. A machine that accepts heat transfer and produces a net work output without undergoing any net change in its own state must also reject heat. The condenser of a steam power plant allows for such heat rejection.

Example 8-3 Condenser

Wet steam, dryness fraction 0.95, is fed into a condenser at 0.2 bar absolute. Determine:

(a) the temperature of the steam,

(b) the amount of latent heat per unit mass given up by the condensing steam.

Solution

(a) At 0.2 bar (0.02 MPa) absolute the saturation temperature is found from the water substance tables to be 60.1 °C.

(b) $h_\mathrm{f} = 251.4$ kJ/kg and $h_\mathrm{fg} = 2357.5\ \mathrm{kJ/kg}$. The amount of latent heat given up by the condensing steam per unit mass is

$$q_\mathrm{cond} = h_\mathrm{in} - h_\mathrm{out} = (h_\mathrm{f} + xh_\mathrm{fg}) - h_\mathrm{f} = xh_\mathrm{fg}$$

$$= 0.95 \times 2357.5\ \frac{\mathrm{kJ}}{\mathrm{kg}} = 2239.6\ \frac{\mathrm{kJ}}{\mathrm{kg}}$$

Example 8-4 Condenser Heat Transfer Rate

Steam with a vapour fraction of 98.1% enters a condenser at a pressure of 0.0040 MPa absolute. If the flow rate of the steam is 13.9 kg/s and if it leaves the condenser as saturated liquid, calculate the rate of heat rejection in the condenser. Also calculate the volume flow rate of the steam at entry to the condenser and the volume flow rate of the condensate leaving the condenser.

Solution

At 0.004 MPa

$h_\mathrm{f} = 121.4$ kJ/kg

$h_\mathrm{fg} = 2432.3$ kJ/kg

$v_\mathrm{f} = 0.001004\ \mathrm{m^3/kg}$

$v_\mathrm{fg} = 34.790\ \mathrm{m^3/kg}$

$v_\mathrm{g} = 34.791\ \mathrm{m^3/kg}$

$$h_\mathrm{in} - h_\mathrm{out} = h_\mathrm{f} + x\ h_\mathrm{fg} - h_\mathrm{f} = x\ h_\mathrm{fg}$$

$$= 0.981 \times 2432.3\ \frac{\mathrm{kJ}}{\mathrm{kg}} = 2386.1\ \frac{\mathrm{kJ}}{\mathrm{kg}}$$

Therefore

$$\dot{Q}_{\text{out}} = \dot{m}\,(h_{\text{in}} - h_{\text{out}})$$

$$= 13.9 \left[\frac{\text{kg}}{\text{s}}\right] \times 2386.1 \left[\frac{\text{kJ}}{\text{kg}}\right] = 33{,}167 \text{ kW} = 33.17 \text{ MW}$$

To find the volume flow rate at inlet:

$$v_{\text{in}} = v_{\text{f}} + x\, v_{\text{fg}}$$

$$= (0.001004 + 0.981 \times 34.790)\ \frac{\text{m}^3}{\text{kg}}$$

$$= 34.13\ \frac{\text{m}^3}{\text{kg}}$$

Hence the volume flow rate at entry to the condenser is given by

$$\dot{\mathscr{V}}_{\text{in}} = \dot{m}\,v_{\text{in}} = 13.9 \left[\frac{\text{kg}}{\text{s}}\right] \times 34.13 \left[\frac{\text{m}^3}{\text{kg}}\right] = 474.4\ \frac{\text{m}^3}{\text{s}}$$

Also

$$\dot{\mathscr{V}}_{\text{out}} = \dot{m}\,v_{\text{out}} = 13.9 \left[\frac{\text{kg}}{\text{s}}\right] \times 0.001004 \left[\frac{\text{m}^3}{\text{kg}}\right] = 13.96 \times 10^{-3}\ \frac{\text{m}^3}{\text{s}}$$

Safety and Environmental Aspects

Persons working within steam power plants, or responsible for them, require training relating to the safe use and operation of the equipment. Safety topics to be aware of include the presence of water and steam at high temperatures and pressures, rotating machinery, noisy equipment, combustion of fuels and combustion products, safe fuel storage, movement of heavy loads, and risk of electric shock.

Environmental issues associated with power production in steam power plant installations include emissions from combustion, environmental impact of condenser heat rejection, radiation issues associated with nuclear-fuelled steam power plants, and safe disposal or storage of waste, whether ash from combustion or radioactive waste.

Problems

8-1 In a steam power plant operating with a thermal efficiency of 39% the net electric power production is 105 MW. Calculate the rate of heat transfer in the boiler and superheater, stating any assumptions made.

8-2 Feed water enters a boiler at 3 MPa and 150 °C. It leaves as superheated steam at a temperature of 450 °C. Determine the heat transfer per unit mass of steam and the rate of heat transfer if the mass flow rate is 23.2 kg/s. The formula below can be used in calculating the specific enthalpy of the feed water.

$$h_{\text{subcooled liquid}} = h_{\text{f @ }T} + (p - p_{\text{s @ }T})\, v_{\text{f @ }T}$$

8-3 Wet steam, with a quality of 0.985 condenses at 0.045 MPa absolute. Determine:

(a) the absolute temperature of the steam,

(b) the rate of heat rejection in the condenser if the mass flow rate of the condensate is 4.23 tonne/hour.

8-4 Dry saturated steam enters a superheater at 3 MPa at the rate of 22.1 kg/s and leaves as superheated steam at 500 °C. Determine the rate of heat transfer to the steam in the superheater.

8-5 Liquid water enters a boiler at a pressure of 9 MPa and a temperature of 200 °C. Steam leaves the boiler and flows through a superheater, leaving with a temperature of 550 °C. Calculate the specific enthalpy of the liquid water that enters the boiler and that of the superheated steam that leaves the superheater. The following expression may be used to find the specific enthalpy of subcooled liquid water:

$$h_{\text{subcooled liquid}} = h_{\text{f @ }T} + (p - p_{\text{s @ }T})\, v_{\text{f @ }T}.$$

If the rate of heat transfer in the boiler and superheater is 47.3 MW, calculate the mass flow rate of the water substance. State any assumptions made.

8-6 Water enters a boiler at ground level at a rate of 3.1 kg/s, with a velocity of 4 m/s. The boiler operates at a pressure of 4 MPa and the inlet temperature is 30 °C. The boiler is followed by a superheater and then by an adiabatic device that has no input or output of shaft work. The elevation of the outlet from the adiabatic device is 75 m relative to the boiler inlet and the exit velocity at this position is 394 m/s, while the exit specific enthalpy is 2883.9 kJ/kg. Calculate the rate of heat transfer to the water substance in the boiler and superheater. Comment on the significance of the changes in the kinetic energy per unit mass and the potential energy per unit mass in this case.

8-7 Using a spreadsheet application prepare a diagram, like Figure 6-3, showing only the saturated liquid line and the dry saturated vapour line as a graph of temperature versus specific entropy. Use data values from Table E-1, Appendix E. Plot only sufficient points to obtain a reasonably smooth outline. Use a temperature scale with a range from 0 °C to 400 °C.

8-8 Write a paragraph to synopsize potential environmental impact issues of a large coal-fired steam power plant that uses sea water for condenser cooling.

Chapter 9 The Refrigeration Plant

Block Diagram of a Refrigeration Plant

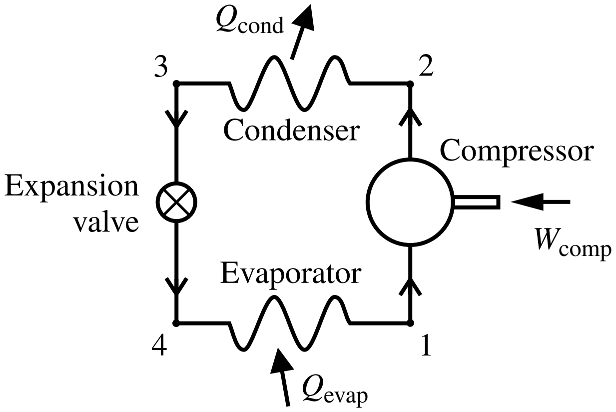


Figure 9-1 Block diagram of a refrigeration plant

Figure 9-1 shows the main components of a typical refrigeration plant. The working fluid, which is known as a refrigerant, is a substance that can exist as a liquid, as a vapour or as a mixture of the two: refrigerant 134a ($C_2H_2F_4$) and ammonia (NH_3) are two examples. The refrigerant undergoes evaporation in the evaporator and condensation in the condenser. Water substance is not suitable as a refrigerant for evaporating temperatures at or below ambient because its saturation pressure is too low at such temperatures. R134a has a saturation pressure of 1 bar absolute at about −25 °C, while ammonia has a saturation pressure of 1 bar absolute at about −34 °C.

The compressor maintains a sufficiently low pressure in the evaporator so that evaporation can take place at a desired temperature level below ambient temperature. The compressor also maintains a sufficiently high pressure in the condenser so that condensation can take place with heat rejection to the surroundings at a temperature above ambient temperature. For a given flow rate of the refrigerant, a corresponding rate of work input as mechanical power is required to drive the compressor. This power is commonly provided by an electric motor.

At state 1 in Figure 9-1 the refrigerant enters the compressor at the evaporating pressure. Usually, the refrigerant is superheated by perhaps 5 K to 10 K, e.g. its temperature might be 7 K higher than the evaporating or saturation temperature. The refrigerant leaves the compressor at the condensing pressure with an even greater amount of superheat, e.g. for R134a the temperature might be 25 K higher than the saturation temperature corresponding to the discharge pressure.

In the condenser, the refrigerant is first de-superheated and then condensed at essentially a constant pressure. Refrigeration condensers are usually cooled by ambient air, often blown by a fan, and are sometimes cooled by water. The refrigerant leaves the condenser as a saturated liquid, or there may be a small amount of subcooling.

The expansion valve allows the condensed refrigerant to pass from the condenser, where the pressure is relatively high, to the evaporator, where the pressure is relatively low. At the expansion valve there is no mechanical shaft work input or output and there is negligible heat transfer. As the refrigerant passes through the expansion valve, part of the liquid 'flashes' to vapour and so the refrigerant enters the evaporator as a two-phase mixture with a dryness fraction of perhaps 30%.

In the evaporator the refrigerant evaporates at low temperature and accepts heat transfer from the region that is being cooled or refrigerated, e.g. a cold store. The refrigerant leaves the evaporator in a slightly superheated state close to the dry saturated condition.

Flow Restrictions and Throttling

In general, when a fluid passes through a flow restriction (such as an orifice plate, a partially open valve or a porous plug), the fluid is said to undergo a 'throttling' process. In such a process there is a significant pressure drop, but no input or output of shaft work. In many cases there is no significant heat transfer at the throttling device and the flow process within it can be considered adiabatic, Figure 9-2. It follows from the steady flow energy equation, Equation (5-6), that the specific enthalpy of a fluid is unchanged when it passes through a flow restriction of this type. Other properties, e.g. pressure, specific volume and specific entropy, are changed. Downstream of an adiabatic throttling device the pressure is reduced, the specific volume is increased and the specific entropy is increased.

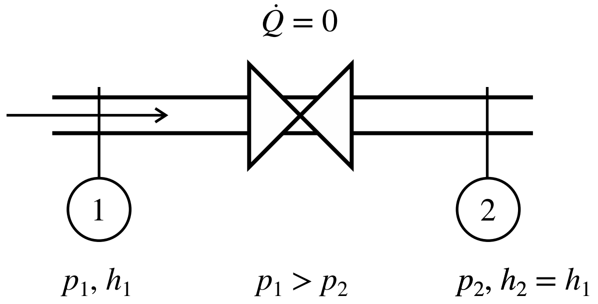


Figure 9-2 Flow through an adiabatic flow restriction

The Reversed Rankine Cycle

The vapour compression refrigeration cycle is like the Rankine steam cycle, but with the flow direction reversed. For this reason it is often called the reversed Rankine cycle. The ideal reversed Rankine cycle is represented on a *T*-*s* diagram in Figure 9-3. As shown, there is no superheat at point 1 and no subcooling at point 3.

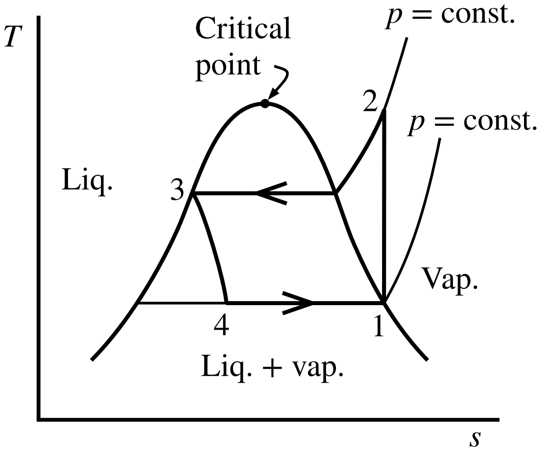


Figure 9-3 The ideal reversed Rankine cycle on a *T*-*s* diagram for the refrigerant

The processes undergone by the refrigerant are as follows:

1 → 2 Compression of the vapour with negligible heat transfer and, ideally, without any friction effects. The specific entropy, *s*, remains unchanged.

2 → 3 De-superheating followed by condensation at constant pressure. This involves heat output.

3 → 4 The refrigerant undergoes a throttling process. Friction effects are significant and there is no work input or output. Heat transfer is negligible. The specific enthalpy of the refrigerant is unchanged after this process. Fluid friction effects cause the specific entropy to increase even though there is no heat transfer.

4 → 1 The refrigerant is evaporated at constant pressure in the evaporator. This involves heat input.

The Pressure versus Specific Enthalpy Diagram

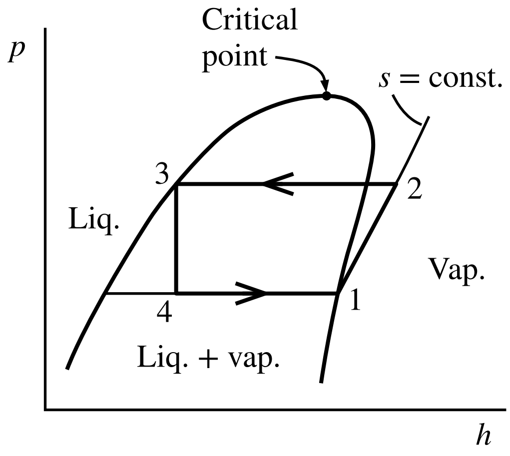


Figure 9-4 The ideal reversed Rankine cycle on a *p*-*h* diagram

Whereas Figure 9-3 allows the reversed Rankine refrigeration cycle to be compared to the Rankine steam cycle, it is much more usual to make use of a pressure versus specific enthalpy diagram for refrigeration calculations. This is shown in Figure 9-4 for a refrigeration cycle without vapour superheat at the evaporator exit or liquid subcooling at the condenser exit.

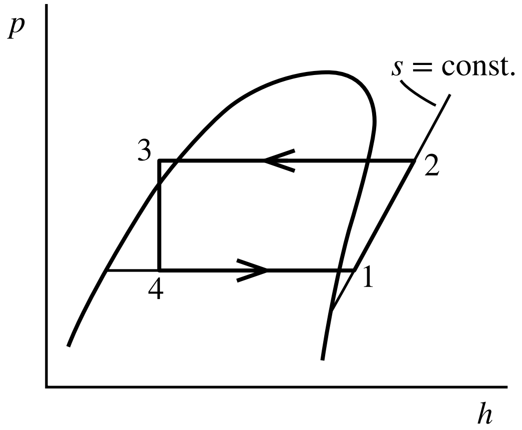


Figure 9-5 The reversed Rankine cycle on a *p*-*h* diagram with suction vapour superheat and liquid subcooling.

Figure 9-5 shows how the refrigeration cycle appears if there is some vapour superheating at the evaporator exit and some liquid subcooling at the condenser exit.

With assumed isentropic (s = const.) compression, isenthalpic (h = const.) expansion and constant pressure evaporation and condensation, the following information is required to define the cycle:

the refrigerant, e.g. R134a

the evaporating pressure or temperature

the condensing pressure or temperature

the amount of superheat at entry to the compressor

the amount of subcooling at entry to the expansion valve.

The Thermostatic Expansion Valve

One primary function of a thermostatic expansion valve (TEV), Figure 9-6, is to allow saturated liquid refrigerant at the condenser pressure to expand to the evaporating pressure and thereby undergo a drop in temperature so that it can provide a cooling effect by accepting latent heat transfer at the reduced temperature in the evaporator.

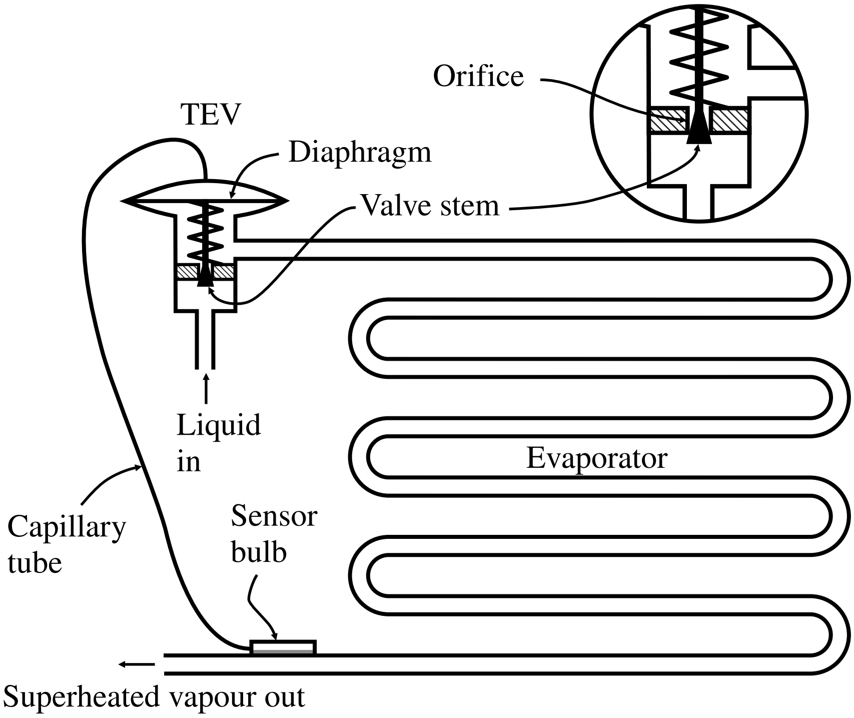


Figure 9-6 Schematic diagram of a thermostatic expansion valve and an evaporator

A second primary function of a thermostatic expansion valve is to control the flow of refrigerant into the evaporator so that the full heat transfer surface of the evaporator is used effectively. If too much liquid is supplied to the evaporator then the refrigerant leaving the evaporator is likely to be wet and unsuitable for compression in the compressor. If too little liquid is provided to the evaporator then much of the surface of the evaporator will not be exposed to wet refrigerant and so will not serve to cause evaporation: the refrigerant will leave the evaporator in a superheated state. The thermostatic expansion valve is designed to maintain a pre-determined small amount of superheat at the evaporator exit, e.g. 4 K or 7 K.

The sensor bulb shown in Figure 9-6 contains liquid and vapour refrigerant and is attached to the outside of the exit pipe from the evaporator so that it can sense the refrigerant temperature at that position on the pipe. When the temperature of the sensor bulb is higher than the saturation temperature in the evaporator by a pre-set amount, the pressure acting on the top of the diaphragm in the thermostatic expansion valve can overcome the pressure acting on the bottom of the diaphragm and the force of a pre-set spring to allow liquid refrigerant to pass through the valve. The refrigerant leaves the valve as a mixture of liquid and vapour at the pressure in the evaporator.

Response of a Thermostatic Expansion Valve to an Increase in Refrigeration Load

An increase in refrigeration load can occur, for example, if food products at ambient temperature are brought into a cold store. Being at a relatively high temperature, the products cause an increase in the rate of heat transfer to the evaporator and this will result in an increase in the amount of superheat at the position where the refrigerant leaves the evaporator. The increased exit temperature will cause an increase in the pressure within the sensor bulb of the thermostatic expansion valve. This higher pressure will act on the top of the diaphragm in the TEV, Figure 9-6, which will depress the valve stem to allow more liquid to enter the evaporator through the TEV.

The Capillary Tube

In some cases the expansion valve can be replaced by a capillary tube. This might typically have a length of about two metres and an inside diameter of less than a millimetre. The main advantages of a capillary tube as an expansion device are its simplicity and its low cost. For this reason capillary tubes are commonly used in mass-produced refrigeration systems such as domestic fridges or deep freezers. Where operating conditions vary widely, a thermostatic expansion valve is likely to be more satisfactory.

Environmental, Societal and Safety Aspects of Refrigeration

Modern refrigeration makes a very significant contribution to health and welfare. Refrigeration and freezing of food significantly extends its storage life and reduces the likelihood of food poisoning through eating food that has ‘gone-off’. In many parts of the world, air-conditioning involving refrigeration allows people to live and work in an environment that is more comfortable and in which they can work more effectively.

Some of the original chlorofluorocarbon (CFC) refrigerants, while most were excellent in terms of low toxicity and safe with regard to possible combustion or explosion, were found to damage the ozone layer in the Earth’s upper atmosphere, allowing harmful solar radiation to reach ground level. Considerable progress is being made in addressing this problem, through the development of replacement refrigerants that have a much lower effect on the ozone layer and also through ensuring that refrigerants are not released into the atmosphere.

Some refrigerants contribute to the greenhouse effect and therefore to global warming when released into the atmosphere. Here too progress is being made by reducing emissions and developing replacement refrigerants that have much less effect in this regard.

Refrigerants exist as liquid and vapour under pressure within refrigeration, air-conditioning or heat pump equipment. All the normal precautions for liquids and vapours under pressure apply. Some refrigerants such as ammonia (NH_3) are toxic and injurious if inhaled and are combustible or explosive if mixed with air or oxygen in certain concentrations. Appropriate precautions must be taken.

Problems

9-1 At what position in a refrigeration circuit would the highest refrigerant temperature be measured?

9-2 Is condensation the only process that takes place within the condenser of a refrigeration plant? Explain your answer.

9-3 Think about faults that could cause a thermostatic valve to malfunction and provide a brief explanation for two of them.

9-4 Using a spreadsheet application prepare a diagram, like Figure 9-4, showing only the saturated liquid line and the dry saturated vapour line as a graph of pressure versus specific enthalpy. Use data values from Table F-1, Appendix F. Plot only sufficient points to obtain a reasonably smooth outline. Use a logarithmic axis for pressure, with a range from 0.1 MPa to 10 MPa.

Chapter 10 Use of Refrigerant Tables

Just as tables are used to look up the properties of water substance, refrigerant tables are commonly used to find values of the properties of refrigerants for engineering calculations. A table of thermodynamic properties for refrigerant 134a is provided in Appendix F. This table is more compact than the water substance tables. It contains saturation properties and superheat properties.

One notable difference between the table for R134a and the water substance tables is that the refrigerant table does not show actual superheat temperatures, but rather tabulates properties for an 'amount of superheat'. The latter term describes the difference between the superheat temperature and the saturation temperature. For example, if the saturation temperature is 26 °C and the amount of superheat is 30 K then the superheat temperature is (26 + 30) °C = 56 °C.

Saturation Properties

The tabulated saturation properties are p_s, t_s, h_f, s_f, v_f, h_g, s_g and v_g.

Example 10-1 Saturation Properties of R134a

Find each of the following saturation properties in the table for R134a:

	Solution
Saturation pressure at 25 °C	0.665 MPa
Saturation temperature at 0.10 MPa	−26.4 °C
Specific volume of dry saturated vapour at −20 °C	0.1474 m^3/kg
Specific enthalpy of saturated liquid at 35 °C	100.9 kJ/kg

	Solution
(Values for specific internal energy are not listed as they are not usually required for refrigeration calculations—they could be found by using $u = h - pv$)	
Specific enthalpy of dry saturated vapour at −15 °C	241.5 kJ/kg
(Note that specific enthalpy differences h_{fg} are not included—they can be found using $h_{\mathrm{fg}} = h_{\mathrm{g}} - h_{\mathrm{f}}$.)	
Specific entropy of dry saturated vapour at 0.75 MPa	0.919 kJ/kgK

Properties of Saturated Mixtures or Wet Vapour

The procedures used are exactly the same as for steam, e.g.

$$h = h_{\mathrm{f}} + x\, h_{\mathrm{fg}}$$

(repeated) (7-1)

and also,

$$x = \frac{h - h_{\mathrm{f}}}{h_{\mathrm{fg}}}$$

(repeated) (7-2)

Properties of Subcooled Liquid or Superheated Vapour

Properties of Subcooled Liquid Refrigerant

For refrigeration calculations it is usually a reasonable approximation to use the properties of saturated liquid refrigerant at the same temperature.

Example 10-2 Specific Enthalpy of Subcooled Refrigerant

Find the specific enthalpy and the specific volume of liquid R134a at 62 °C and 1.45 MPa.

Solution

From the R134a table at 62 °C,

$$h \approx h_{\mathrm{f}} = 142.6 \text{ kJ/kg}$$

$$\upsilon \approx \upsilon_{\mathrm{f}} = 0.000960 \text{ m}^3\!/\text{kg}.$$

Properties of Superheated Refrigerant

The properties of superheated refrigerant are found in the superheat part of the table at a given pressure. The amount of superheat is calculated by subtracting the saturation temperature from the temperature of the vapour. If the required amount of superheat is not directly tabulated, linear interpolation can be used.

Example 10-3 Specific Enthalpy of Superheated Refrigerant

Find the specific enthalpy of R134a at 1.45 MPa and 62 °C.

Solution

From the R134a table at 1.45 MPa,

$$T_{\mathrm{s}} = 53.8 \text{ °C}$$

$$h_{\mathrm{g}} = 276.6 \text{ kJ/kg}$$

Therefore 62 °C corresponds to $(62 - 53.8)\text{ K} = 8.2\text{ K}$ of superheat, while 53.8 °C corresponds to 0 K of superheat.

With 10 K of superheat,

$$h_{10\text{ K}} = 288.9 \text{ kJ/kg}$$

Therefore with 8.2 K of superheat

$$h_{8.2\text{ K}} = h_{0\text{ K}} + \frac{8.2}{10}(h_{10\text{ K}} - h_{0\text{ K}})$$

$$= \left[276.6 + \frac{8.2}{10}(288.9 - 276.6)\right] \text{ kJ/kg}$$

$$= 286.7 \text{ kJ/kg}$$

The Steady Flow Energy Equation for the Refrigeration Plant

The steady flow energy equation, Equation (5-6), can be applied to each of the main components of the refrigeration plant (compressor, condenser, expansion valve, evaporator). Changes in kinetic energy and potential energy between positions 1, 2, 3 and 4 in Figure 9-1 are usually negligible and so do not feature.

Compressor

For the compressor, the steady flow energy equation can be written as

$$w_{\text{comp, in}} + q_{\text{comp, in}} = h_{\text{out}} - h_{\text{in}} \tag{10-1}$$

where

h	=	specific enthalpy	J/kg
$w_{\text{comp, in}}$	=	compressor net work input per unit mass	J/kg
$q_{\text{comp, in}}$	=	compressor net heat input per unit mass	J/kg

As any net heat transfer is normally from the refrigerant during compression, the equation can also be written as

$$w_{\text{comp, in}} = h_{\text{out}} - h_{\text{in}} + q_{\text{comp, out}} \tag{10-2}$$

where

$q_{\text{comp, out}}$	=	compressor net heat output per unit mass	J/kg

Thus Equation (10-2) can be used to calculate the net work input per unit mass if the specific enthalpy values at inlet and outlet and the net heat rejection per unit mass are known.

For an adiabatic compressor, or one where the net heat transfer is negligible, the steady flow energy equation can be written as

$$w_{\text{comp, in, adiab}} = h_{\text{out}} - h_{\text{in}} \tag{10-3}$$

For a given mass flow rate $\dot{m}$ of refrigerant around the circuit the net rate of energy transfer to the refrigerant as work in the compressor is given by

$$\dot{W}_{\text{comp, in}} = \dot{m}\,(h_{\text{out}} - h_{\text{in}}) + \dot{m}\,q_{\text{comp, out}} \tag{10-4}$$

or

$$\dot{W}_{\text{comp, in}} = \dot{m}\,(h_{\text{out}} - h_{\text{in}}) + \dot{Q}_{\text{comp, out}} \tag{10-5}$$

where

$\dot{W}_{\text{comp, in}}$	=	net rate of work input	W
$\dot{Q}_{\text{comp, out}}$	=	net rate of heat output	W

If the compressor is adiabatic, the rate of work input is given by

$$\dot{W}_{\text{comp, in, adiab}} = \dot{m}\,(h_{\text{out}} - h_{\text{in}}). \tag{10-6}$$

Condenser

The steady flow energy equation for the condenser can be written as

$$q_{\text{cond, out}} = h_{\text{in}} - h_{\text{out}} \tag{10-7}$$

where

$q_{\text{cond, out}}$	=	heat rejection at the condenser per unit mass	J/kg

For a given mass flow rate $\dot{m}$ of refrigerant through the condenser the rate of energy transfer from the refrigerant is given by:

$$\dot{Q}_{\text{cond, out}} = \dot{m}_{\text{refr}}(h_{\text{in}} - h_{\text{out}}) \tag{10-8}$$

where

$\dot{Q}_{\text{cond, out}}$	=	rate of heat transfer out of the condenser	W
$\dot{m}_{\text{refr}}$	=	mass flow rate of the refrigerant	kg/s

Expansion Valve

The rate of heat transfer to or from the refrigerant as it passes through the expansion valve can normally be neglected. It can also be noted that there is no work done on or by the refrigerant and that changes in kinetic energy or potential energy are normally negligible. Hence, the steady flow energy equation for the expansion valve can be written as

$$h_{\text{out}} = h_{\text{in}}. \tag{10-9}$$

Evaporator

The steady flow energy equation for the evaporator can be written as

$$q_{\text{evap, in}} = h_{\text{out}} - h_{\text{in}}. \tag{10-10}$$

With regard to the state points identified in Figure 9-1 it can be noted that the specific enthalpy entering the evaporator at state 4 is the same as the specific enthalpy entering the expansion valve at state 3. Therefore, for the evaporator $h_{\text{in}} = h_4 = h_3$.

For a given mass flow rate $\dot{m}$ of refrigerant through the evaporator the rate of energy transfer to the refrigerant is given by:

$$\dot{Q}_{\text{evap, in}} = \dot{m}_{\text{refr}}(h_{\text{out}} - h_{\text{in}}) \tag{10-11}$$

where

$\dot{Q}_{\text{evap, in}}$	=	rate of heat transfer into the evaporator	W

Refrigeration Effect

The refrigeration effect of a refrigeration plant is the amount of heat transfer to the refrigerant in the evaporator per unit mass of the refrigerant, i.e. $q_{\text{evap, in}}$ in Equation (10-10). The SI units for refrigeration effect are J/kg .

Example 10-4 Rate of Heat Transfer in a Refrigeration Condenser

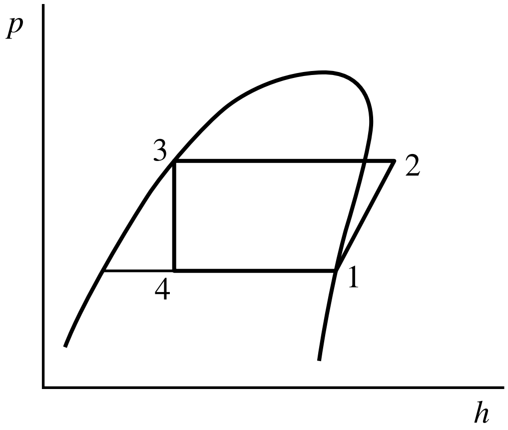
Refrigerant 134a enters the condenser of a refrigeration plant at a pressure of 0.95 MPa and with 20 K of superheat. It leaves the condenser as saturated liquid and its mass flow rate is 3.27×10^{-2} kg/s. Calculate the rate of heat rejection in the condenser.

Solution

$$\dot{Q}_{\text{cond, out}} = \dot{m}(h_2 - h_3)$$

From the table for R134a at a pressure of 0.95 MPa

$$h_3 = h_f = 104.5 \ \frac{\text{kJ}}{\text{kg}}.$$



At the same pressure, with 30 K of superheat

$$h = 302.0 \ \frac{\text{kJ}}{\text{kg}}$$

and with 10 K of superheat

$$h = 281.1 \ \frac{\text{kJ}}{\text{kg}}.$$

Therefore, with 20 K of superheat

$$h_2 = [281.1 + 0.5\,(302.0 - 281.1)] \ \frac{\text{kJ}}{\text{kg}}$$

$$= 291.6 \ \frac{\text{kJ}}{\text{kg}}.$$

Hence,

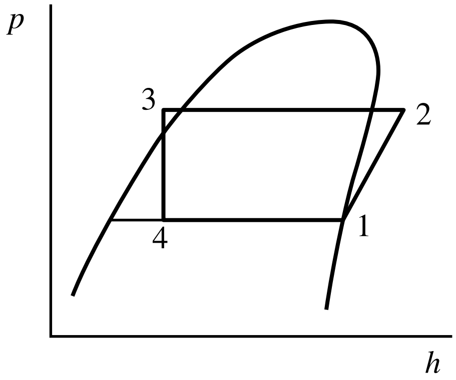
$$\dot{Q}_{\text{cond, out}} = 3.27 \times 10^{-2} \left[\frac{\text{kg}}{\text{s}}\right] (291.6 - 104.5\ ) \left[\frac{\text{kJ}}{\text{kg}}\right]$$

$$= 6.12 \text{ kW}.$$

Example 10-5 Rate of Heat Transfer in a Refrigeration Evaporator

Refrigerant R134a leaves the condenser of a refrigeration plant as subcooled liquid at a temperature of 28 °C and passes through an expansion valve into the evaporator, in which the saturation temperature is −20 °C. The refrigerant leaves the evaporator as dry saturated vapour. Calculate the rate of heat transfer to the refrigerant in the evaporator if the mass flow rate of the refrigerant is 1.893×10^{-2} kg/s.

Solution



The specific enthalpy of subcooled liquid refrigerant can be taken to be approximately the same as that of saturated liquid refrigerant at the same temperature. From the R134a table at a saturation temperature of 28 °C

$$h_\mathrm{f} = 90.7\ \frac{\mathrm{kJ}}{\mathrm{kg}}$$

and hence

$$h_4 = h_3 \approx 90.7\ \mathrm{kJ/kg}.$$

From the table for R134a at a saturation temperature of −20 °C

$$h_1 = h_\mathrm{g} = 238.4\ \frac{\mathrm{kJ}}{\mathrm{kg}}$$

Hence,

$$\dot{Q}_{\text{evap, in}} = \dot{m}\,(h_1 - h_4)$$

$$= 1.893 \times 10^{-2} \left[\frac{\mathrm{kg}}{\mathrm{s}}\right] (238.4 - 90.7) \left[\frac{\mathrm{kJ}}{\mathrm{kg}}\right]$$

$$= 2.80\ \mathrm{kW}.$$

Example 10-6 Refrigeration Cycle Properties and Flow Rates

In an ideal refrigeration cycle without evaporator superheat and without condenser subcooling, R134a evaporates at −25 °C and condenses at 30 °C.

a) Determine the pressures in the evaporator and the condenser.

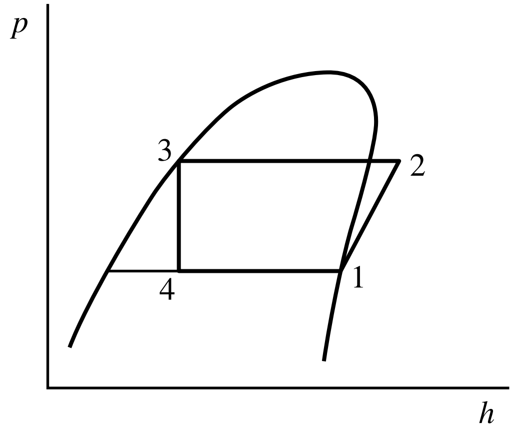
b) Find the specific enthalpy of the refrigerant as it leaves the evaporator and the specific enthalpy of the refrigerant as it leaves the condenser.

c) Calculate the mass flow rate of refrigerant if the rate of heat transfer in the evaporator is 17.29 kW.

d) Calculate the volume flow rate of the refrigerant as it leaves the evaporator.

e) Calculate the dryness fraction of the refrigerant mixture that enters the evaporator.

Solution



a) From the table for R134a at −25 °C

$$p_{\text{evap}} = p_{\text{s}} = 0.1064 \text{ MPa.}$$

At 30 °C

$$p_{\text{cond}} = p_{\text{s}} = 0.770 \text{ MPa.}$$

b) From the table at the evaporating pressure

$$h_1 = h_g = 235.3 \text{ kJ/kg}$$

From the table at the condensing pressure

$$h_3 = h_f = 93.6 \text{ kJ/kg.}$$

c) As the specific enthalpy leaving the expansion valve is the same as the value entering the valve

$$h_4 = h_3 = 93.6 \text{ kJ/kg}$$

$$\dot{Q}_{\text{evap, in}} = \dot{m}\,(h_1 - h_4).$$

Hence

$$\dot{m} = \frac{\dot{Q}_{\text{evap, in}}}{(h_1 - h_4)} = \frac{17.29 \text{ kW}}{(235.3 - 93.6) \text{ kJkg}^{-1}}$$

$$= 0.1220 \ \frac{\text{kg}}{\text{s}}.$$

d) The volume flow rate at position 1 is given by the product of the mass flow rate and the specific volume

$$\dot{\mathscr{V}}_1 = \dot{m}\,v_1$$

From the table at the evaporating pressure

$$v_1 = v_g = 0.1816 \ \frac{\text{m}^3}{\text{kg}}.$$

Hence

$$\dot{\mathscr{V}}_1 = 0.122 \left[\frac{\text{kg}}{\text{s}}\right] \times 0.1816 \left[\frac{\text{m}^3}{\text{kg}}\right]$$

$$= 0.0222 \ \frac{\text{m}^3}{\text{s}}$$

e) At the evaporating pressure

$$h_f = 19.0 \text{ kJ kg}^{-1}$$

$$h_g = 235.3\ \mathrm{kJ\,kg^{-1}}.$$

Hence

$$h_{fg} = h_g - h_f = (235.3 - 19.0)\ \mathrm{kJ\,kg^{-1}}$$

$$= 216.3\ \mathrm{kJ\,kg^{-1}}$$

Since $h_4 = h_f + x_4 h_{fg}$, the dryness fraction at position 4 is given by

$$x_4 = \frac{h_4 - h_f}{h_{fg}}$$

$$= \frac{93.6 - 19.0}{216.3} = 0.345$$

Problems

10-1 Find the specific volume and the specific entropy of dry saturated R134a at a saturation pressure of 1.5 MPa.

10-2 Find h_{fg} for refrigerant 134a at a saturation temperature of −26 °C.

10-3 Find the specific enthalpy of refrigerant 134a at a pressure of 14 bar and a temperature of 50 °C.

10-4 Find the specific enthalpy of refrigerant 134a if the saturation temperature is −15 °C and the dryness fraction is 0.313.

10-5 R134a enters the condenser of a refrigeration plant at a temperature of 65 °C and condenses at a temperature of 35 °C. The mass flow rate is 23.8×10^{-3} kg/s and the refrigerant leaves the condenser with 5 K of subcooling. Calculate the rate of heat rejection in the condenser.

10-6 R134a leaves the condenser of a refrigeration plant as saturated liquid at a temperature of 37 °C and passes through an expansion valve into the evaporator, in which the saturation temperature is

-15 °C. The refrigerant leaves the evaporator as dry saturated vapour. Calculate the rate of heat transfer to the refrigerant in the evaporator if the mass flow rate of the refrigerant is 278.3×10^{-3} kg/s.

Chapter 11 Refrigeration and Heat Pump Performance

Liquid Line Subcooling and Suction Superheat

With reference to Figure 9-5 (repeated below), some superheating is desirable at position 1, entry to the compressor, to ensure that no droplets or slugs of liquid are present. If a volume of liquid similar to or greater than the clearance volume enters the cylinder of a reciprocating compressor it is likely to cause damage, as the liquid is incompressible.

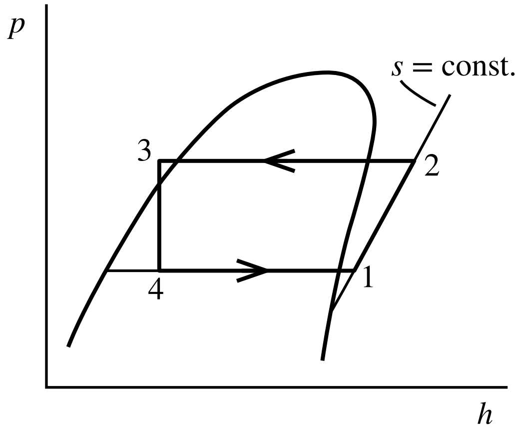


Figure 9-5 (repeated) The reversed Rankine cycle on a *p*-*h* diagram with suction vapour superheat and liquid subcooling.

The setting of the thermostatic expansion valve normally ensures a small amount of superheat at the position where the sensor bulb is attached to the suction line (or pipe) that leads to the compressor. Further superheating can result from heat pick-up from the surroundings or from within the shell of a hermetically sealed compressor (as used in domestic refrigerators). In some cases, a heat exchanger is provided between the liquid line coming from the condenser and the compressor suction line. This has the effect of increasing the amount of liquid line subcooling and increasing the suction superheat.

At position 3 in Figure 9-5 it is important that only liquid is present, as expansion devices are sized for liquid only. Any vapour that reached the expansion device would pass through only very slowly and the evaporator would be starved of refrigerant. A small amount of subcooling is therefore desirable to ensure that no vapour is present. This can be achieved by heat loss to the surroundings or by the use of a liquid-line to suction-line heat exchanger. It can also be seen from Figure 9-5 that, as $h_4 = h_3$, subcooling reduces the value of h_4 and therefore increases the refrigeration effect in the evaporator.

In practice, the compression process will not be perfectly isentropic. Friction and heat-gain can cause the specific enthalpy and temperature at state 2 to be higher than for the isentropic case. Also, heat loss can cause the specific enthalpy and temperature at exit from the compressor to be lower. Therefore, the exact exit state depends on friction and heat transfer effects within the particular compressor.

Compressor Volumetric Efficiency

For a refrigeration compressor, the volumetric efficiency, Equation (4-1), is the ratio of the actual volume of suction vapour at the suction state that is taken in per revolution to the swept volume (see Figure 4-2). As with air compressors, this varies as the ratio of the discharge pressure to the suction pressure changes. The volumetric efficiency is highest at low pressure ratios, Equation (4-2). For a given suction state and compressor speed, the mass flow rate will decrease as the discharge pressure is increased. Some of the reasons why the volumetric efficiency of a reciprocating compressor is usually considerably less than unity are:

1. The mass of refrigerant in the clearance volume is re-expanded before fresh vapour is taken in during the intake stroke.

2. As the refrigerant enters the cylinder of the compressor it undergoes a pressure drop and when the inlet valve of the compressor closes the pressure within the cylinder may be lower than the pressure in the suction line, thus causing the density of the refrigerant within the cylinder at the start of the compression process to be less than that in the suction line.
3. As the compressor is normally at a higher temperature than the suction vapour, some heat transfer can take place to the refrigerant as it flows into the cylinder, which reduces its density and hence the volumetric efficiency.

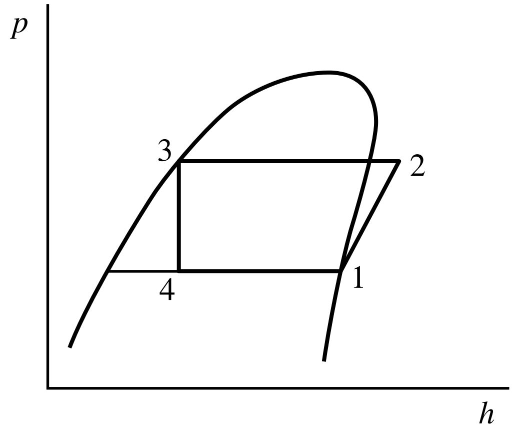
Example 11-1 Refrigeration Cycle

A refrigeration machine charged with R134a delivers 100 kW of cooling when operating under the following conditions:

evaporating temperature	5 °C
condensing temperature	39 °C
compressor volumetric efficiency	0.75

Determine the refrigerant mass flow rate and the compressor swept volume rate in litres per second (L/s) assuming a simple saturated cycle.

Solution:



From the table for R134a at 5 °C

$$h_1 = h_g = 253.3\ \text{kJ/kg}$$

$$h_f = 58.6\ \text{kJ/kg}.$$

From the table at the condensing temperature of 39 °C

$$h_3 = h_f = 106.8\ \text{kJ/kg}.$$

Also

$$h_4 = h_3 = 106.8\ \text{kJ/kg}.$$

Since $\dot{Q}_{\text{evap, in}} = \dot{m}\,(h_1 - h_4)$

$$\dot{m} = \frac{\dot{Q}_{\text{evap, in}}}{(h_1 - h_4)} = \frac{100\ \text{kW}}{(253.3 - 106.8)\ \text{kJ kg}^{-1}}$$

$$= 0.6826\ \frac{\text{kg}}{\text{s}}.$$

The volume flow rate at entry to the compressor is given by

$$\dot{\mathscr{V}}_1 = \dot{m}\, v_1.$$

From the table at the evaporating temperature

$$v_1 = v_g = 0.0584\ \frac{\text{m}^3}{\text{kg}}.$$

Hence the volume flow rate at inlet to the compressor is

$$\dot{\mathscr{V}}_1 = 0.6826 \left[\frac{\text{kg}}{\text{s}}\right] \times 0.0584 \left[\frac{\text{m}^3}{\text{kg}}\right]$$

$$= 0.03986\ \frac{\text{m}^3}{\text{s}}.$$

According to Equation (4-1) the volumetric efficiency is defined as

$$E_{\text{vol}} = \frac{\mathscr{V}_{\text{ind}}}{\mathscr{V}_{\text{sw}}} = \frac{\dot{\mathscr{V}}_1}{\dot{\mathscr{V}}_{\text{sw}}}.$$

Note that $\dot{\mathscr{V}}_1$ is the induced volume per unit time, while $\dot{\mathscr{V}}_{\text{sw}}$ is the swept volume per unit time. Hence, the compressor swept volume rate is given by

$$\dot{\mathscr{V}}_{\text{sw}} = \frac{\dot{\mathscr{V}}_1}{E_{\text{vol}}}$$

$$= \frac{0.03986\ [\text{m}^3/\text{s}]}{0.75}$$

$$= 0.05315\ \text{m}^3/\text{s} = 53.2\ \text{L/s}.$$

Coefficient of Performance

A refrigeration machine and a heat pump are both heat engines operating in reverse, i.e. each contains a working fluid that undergoes a cycle in the course of which heat transfer is accepted from a heat source at a low temperature and heat rejection occurs to a heat sink at high temperature while a net work input is required. The adjectives ‘low’ and ‘high’ here simply mean that the temperature of the heat source is lower than the temperature of the heat sink. Usually the low temperature is below ambient temperature and the high temperature is above ambient. Figure 11-1 can represent either a refrigeration machine or a heat pump.

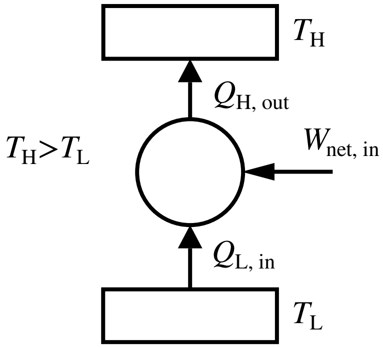


Figure 11-1 Schematic diagram of a heat engine operating in reverse

A refrigeration machine is intended to provide cooling at the low temperature, while a heat pump is intended to provide heating at the high temperature. The coefficients of performance (COP) are given by

$$\mathrm{COP}_{\text{heat pump}} = \frac{Q_{\text{H, out}}}{W_{\text{net, in}}}$$

(11-1)

$$\mathrm{COP}_{\text{refrig}} = \frac{Q_{\text{L, in}}}{W_{\text{net, in}}}$$

(11-2)

where

$\mathrm{COP}_{\text{heat pump}}$ = heat pump coefficient of performance

$\mathrm{COP}_{\text{refrig}}$ = refrigeration coefficient of performance

Example 11-2 Heat Pump Cycle

A reversed Rankine cycle heat pump operates with the following parameters:

Refrigerant:	R134a
Condensing temperature	30 °C
Amount of subcooling at condenser exit	negligible
Amount of superheat at compressor exit	15 K
Compressor work input (electrical) per unit mass of refrigerant	54.0 kJ/kg

Calculate the amount of heat rejection in the condenser per unit mass of refrigerant and determine the heat pump COP for the plant.

Solution

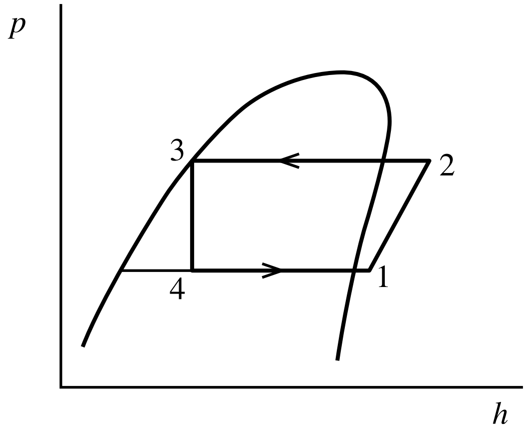
From the table for R134a at the condensing temperature, 30 °C,

$$p_s = 0.770 \text{ MPa.}$$

At this same pressure from the superheat columns in the table

$$h_{\text{10K s/h}} = 277.1 \text{ kJ/kg}$$

$$h_{\text{30K s/h}} = 297.3 \text{ kJ/kg}$$



Therefore, with 15 K of superheat

$$h_2 = h_{15\text{K s/h}} = \left[277.1 + \frac{(15-10)}{(30-10)}(297.3-277.1)\right]\ \text{kJ/kg}$$

$$= 282.2\ \text{kJ/kg}$$

Also, as there is negligible subcooling at state 3

$$h_3 = h_\text{f} = 93.6\ \text{kJ/kg}.$$

The amount of heat transfer out of the refrigerant per unit mass in the condenser is

$$q_\text{cond, out} = h_2 - h_3$$

$$= (282.2 - 93.6)\ \text{kJ/kg}$$

$$= 188.6\ \text{kJ/kg}$$

This is the amount of heat rejection in the condenser per unit mass. The amount of work in per unit mass is given as

$$w_\text{comp, in} = 54.0\ \frac{\text{kJ}}{\text{kg}}.$$

The heat pump COP is given by

$$\text{COP}_\text{heat pump} = \frac{Q_\text{H, out}}{W_\text{in}} = \frac{q_\text{cond, out}}{w_\text{comp, in}}$$

$$= \frac{188.6\ [\text{kJ/kg}]}{54.0\ [\text{kJ/kg}]}$$

$$= 3.49$$

The Air-to-Water Heat Pump

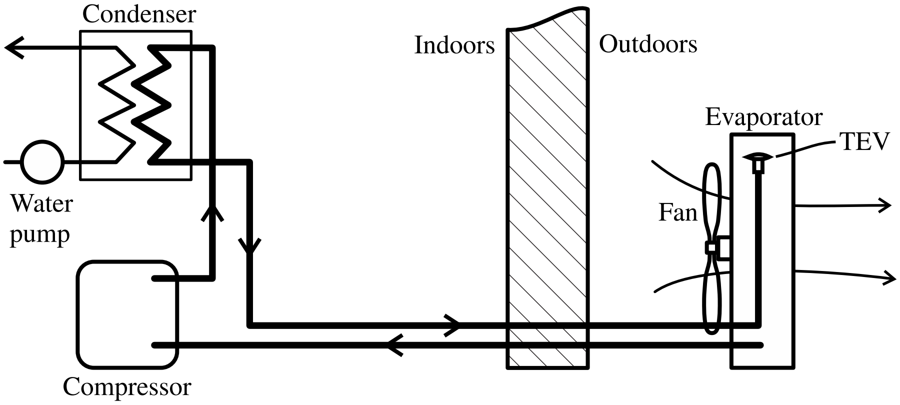


Figure 11-2 Diagram of an air-to-water heat pump

Figure 11-2 illustrates an air-to-water heat pump, as might be used for domestic space heating. The air-source evaporator is located outside the building. Heat transfer is provided to water that flows through the condenser. When used for domestic space heating, the water flow temperature might be about 50 °C, which is considerably cooler than water from a central heating boiler (65 °C to 85 °C). Therefore larger radiators are required. Alternatively, the heated water can be circulated through pipes embedded in the floor with a layer of insulation underneath.

Whereas an electrically powered flow boiler can heat water with an efficiency of almost 100%, an air source heat pump can provide a seasonal COP of up to about three. The seasonal COP is the total heat supplied to the water divided by the total electricity consumed over a heating season (both quantities expressed in energy units, e.g. MJ).

The rate of heat transfer in the condenser is given, as usual, by Equation (10-8), which is repeated below.

$$\dot{Q}_{\text{cond, out}} = \dot{m}_{\text{refr}}(h_2 - h_3)$$

(repeated) (10-8)

where

$\dot{Q}_{\text{cond, out}}$ = rate of heat transfer out of the condenser W

$\dot{m}_{\text{refr}}$ = mass flow rate of the refrigerant kg/s

h_2 = specific enthalpy of refrigerant entering the condenser J/kg

h_3 = specific enthalpy of refrigerant leaving the condenser J/kg

On the water side of the condenser this same rate of heat transfer can be expressed as

$$\dot{Q}_{\text{cond, out}} = \dot{m}_{\text{w}}\left(h_{\text{w, out}} - h_{\text{w, in}}\right). \tag{11-3}$$

where

$\dot{Q}_{\text{cond, out}}$ = rate of heat transfer out of the condenser W

$\dot{m}_{\text{w}}$ = mass flow rate of water kg/s

$h_{\text{w, in}}$ = specific enthalpy of water entering the condenser J/kg

$h_{\text{w, out}}$ = specific enthalpy of water leaving the condenser J/kg

Rather than looking up the specific enthalpy values for the water, it is often convenient to make use of the specific heat (as water is very nearly incompressible $c_p \approx c_v \approx c$).

$$\dot{Q}_{\text{cond, out}} = \dot{m}_{\text{w}} c_{\text{w}}\, \Delta T_{\text{w}} \tag{11-4}$$

where

c_w = specific heat capacity of water J/kgK

ΔT_w = temperature increase of water from inlet to outlet K

Note: $c_w = 4.18$ kJ/kgK

Example 11-3 Water-heating Heat Pump

In a water-heating heat pump the volume flow rate of water through the condenser is 14.5 litres per minute. The water enters at 36.1 °C and leaves at 51.3 °C. If the total instantaneous electric power input to operate the heat pump is 4.31 kW, calculate the rate of heat output and the COP.

Solution:

As the density of water is 1000 kg/m^3, each litre of volume corresponds to 1 kg of mass. Hence

$$\dot{m}_{\mathrm{w}} = \frac{14.5}{60}\ \mathrm{kg/s} = 0.2417\ \mathrm{kg/s}$$

$$\dot{Q}_{\mathrm{cond,\,out}} = \dot{m}_{\mathrm{w}}\, c_{\mathrm{w}}\, \Delta T_{\mathrm{w}}$$

$$= 0.2417 \left[\frac{\mathrm{kg}}{\mathrm{s}}\right] \times 4.18 \left[\frac{\mathrm{kJ}}{\mathrm{kgK}}\right] \times (51.3 - 36.1)[\mathrm{K}]$$

$$= 15.36\ \mathrm{kW}$$

$$\mathrm{COP} = \frac{\dot{Q}_{\mathrm{cond,\,out}}}{\dot{W}_{\mathrm{in}}} = \frac{15.36}{4.31} = 3.56$$

Problems

11-1 A commercial heat pump plant operates with the following parameters:

Refrigerant: R134a

Condensing temperature	65 °C
Amount of subcooling at condenser exit	0 K
Amount of superheat at entry to the condenser (compressor exit)	26 K
Compressor work input (electrical) per unit mass of refrigerant	59.1 kJ/kg

(a) Calculate the amount of heat rejection in the condenser per unit mass of refrigerant.

(b) Determine the heat pump C.O.P. for the plant.

(c) What is the rate of heat output if the mass flow rate of refrigerant is 0.306 kg/s?

11-2 R134a enters the condenser of a heat pump plant at a pressure of 1.6 MPa and with 30 K of superheat. It leaves the condenser as liquid that is subcooled by 10 K. Determine the saturation temperature in the condenser and calculate the mass flow rate of the refrigerant if the rate of heat rejection in the condenser is 11.6 kW.

11-3 A heat pump plant operates with the following parameters:

Refrigerant:	R134a
Evaporating temperature	7 °C
Amount of superheat at evaporator exit	6 K
Condensing temperature	58 °C
Amount of superheat at condenser entry	22 K
Amount of subcooling at condenser exit	4 K
Refrigerant mass flow rate	0.106 kg/s

Compressor power input (electrical)	6.01 kW

Calculate the rate of heat rejection in the condenser, the rate of heat acceptance in the evaporator and the heat pump C.O.P. for the plant.

11-4 While running at 1000 r.p.m. an automotive air conditioner provides 3.3 kW of cooling at the operating conditions listed below. Calculate the volume flow rate at the compressor suction condition and calculate the swept volume per revolution of the compressor. Assume that the volumetric efficiency is equal to 90% of the ideal volumetric efficiency given by Equation (4-2), repeated below. The clearance ratio for the compressor is 0.03 and the effective polytropic index for compression is 1.055.

$$E_{\text{vol, ideal}} = 1 - r_{\text{cl}} \left[\left(\frac{p_2}{p_1} \right)^{1/n} - 1 \right]$$

$$r_{\text{cl}} = \frac{\mathscr{V}_{\text{cl}}}{\mathscr{V}_{\text{sw}}}$$

Refrigerant:	R134a
Evaporating temperature	5 °C
Amount of superheat at evaporator exit	5 K
Condensing temperature	60 °C
Amount of subcooling at condenser exit	5 K

Appendix A Formulae

Adiabatic Process for an Ideal Gas

$$p\mathscr{V}^{\gamma} = \text{ const.} = p_1\mathscr{V}_1^{\gamma} = p_2\mathscr{V}_2^{\gamma}$$

where

p = absolute pressure Pa

$\mathscr{V}$ = volume m^3

γ = adiabatic index

Amount of substance

$$n = \frac{\text{mass}}{\text{molar mass}} = \frac{m}{\bar{m}}$$

where

n = amount of substance mol

m = mass kg

$\bar{m}$ = molar mass kg/mol

Area of a Circle

$$A = \frac{\pi d^2}{4}$$

where

A = area m^2

d = diameter m

Boiler Heat Transfer Rate

$$\dot{Q}_{\text{ boiler}} = \dot{Q}_{\text{ in}} = \dot{m}\ (h_{\text{out}} - h_{\text{in}}).$$

where

$\dot{Q}_{\text{boiler}}$ = rate of heat transfer that occurs into the system in a boiler W

$\dot{Q}_{\text{in}}$ = rate of heat transfer into the system W

$\dot{m}$ = mass flow rate of the water substance kg/s

h_{out} = specific enthalpy of the water substance coming out of the system J/kg

h_{in} = specific enthalpy of the water substance going into the system J/kg

Closed System Heat Transfer at Constant Pressure

$$Q_{\text{in},1\rightarrow 2}\Big|_{p\,=\,\text{const}} = H_2 - H_1 = m(h_2 - h_1)$$

where

$Q_{\text{in},1\rightarrow 2}\Big|_{p\,=\,\text{const}}$ = heat transfer in for process $1 \rightarrow 2$ at constant pressure J

H = enthalpy J

m = mass kg

h = specific enthalpy J/kg

Closed System Heat Transfer at Constant Volume

$$Q_{\text{in},1\rightarrow 2}\Big|_{\mathscr{V}\,=\,\text{const}} = U_2 - U_1 = m\,(u_2 - u_1)$$

where

$Q_{\text{in},1\rightarrow 2}\Big|_{\mathscr{V}\,=\,\text{const}}$ = heat transfer in for process $1 \rightarrow 2$ at constant volume J

U = internal energy J

m = mass kg

u = specific internal energy J/kg

Coefficient of Performance

$$\text{COP}_{\text{heat pump}} = \frac{Q_{\text{H, out}}}{W_{\text{in}}}$$

$$\text{COP}_{\text{refrig}} = \frac{Q_{\text{L, in}}}{W_{\text{in}}}$$

where

$\text{COP}_{\text{heat pump}}$ = heat pump coefficient of performance

$\text{COP}_{\text{refrig}}$ = refrigeration coefficient of performance

$Q_{\text{H, out}}$ = heat transfer out to heat sink J

$Q_{\text{L, in}}$ = heat transfer in from heat source J

W_{in} = work input J

Compressor Volumetric Efficiency

$$E_{\text{vol}} = \frac{\mathscr{V}_{\text{ind}}}{\mathscr{V}_{\text{sw}}}$$

where

E_{vol} = volumetric efficiency

$\mathscr{V}_{\text{ind}}$ = induced volume m^3

$\mathscr{V}_{\text{sw}}$ = swept volume m^3

For an ideal reciprocating compressor:

$$E_{\text{vol}} = 1 - r_{\text{cl}} \left[\left(\frac{p_2}{p_1} \right)^{1/n} - 1 \right]$$

$$r_{\text{cl}} = \frac{\mathscr{V}_{\text{cl}}}{\mathscr{V}_{\text{sw}}}$$

where

r_{cl} = clearance ratio

$\mathscr{V}_{\text{cl}}$ = clearance volume m^3

p_1 = suction pressure Pa

p_2 = discharge pressure Pa

n = polytropic index

Condenser Heat Transfer Rate

$$\dot{Q}_{\text{cond}} = \dot{Q}_{\text{out}} = \dot{m}\,(h_{\text{in}} - h_{\text{out}}).$$

where

$\dot{Q}_{\text{cond}}$ = rate of heat transfer that occurs out of the system in a condenser W

$\dot{Q}_{\text{out}}$ = rate of heat transfer out of the system W

$\dot{m}$ = mass flow rate of the condensing fluid kg/s

h_{out} = specific enthalpy of the condensate coming out of the system J/kg

h_{in} = specific enthalpy of the vapour that is to be condensed going into the system J/kg

Condenser Heat Transfer Rate to Cooling Water

$$\dot{Q}_{\text{cond, out}} = \dot{m}_{\text{w}}\, c_{p,\text{w}}\, \Delta T_{\text{w}}$$

where

$\dot{Q}_{\text{cond, out}}$ = rate of heat transfer out of the condenser W

$\dot{m}_{\text{w}}$ = mass flow rate of cooling water kg/s

$c_{p,\text{w}}$ = specific heat capacity of water at constant pressure J/kgK

ΔT_w = temperature change of cooling water from inlet to outlet K

Dryness Fraction or Vapour Fraction or Quality

For a two phase mixture of liquid and vapour the dryness fraction (or vapour fraction or quality) x is defined as:

$$x = \frac{\text{mass of vapour}}{\text{total mass of liquid and vapour}} = \frac{m_\mathrm{g}}{m}$$

where

m_g = mass of vapour kg

m = total mass of liquid and vapour kg

The specific enthalpy of a wet mixture of known dryness fraction is given by

$$h = h_\mathrm{f} + x\, h_\mathrm{fg}$$

The dryness fraction of a wet mixture of known specific enthalpy is given by

$$x = \frac{h - h_\mathrm{f}}{h_\mathrm{fg}}$$

where

x = dryness fraction or vapour fraction

h = specific enthalpy J/kg

h_f = specific enthalpy of saturated liquid J/kg

h_fg = specific enthalpy difference, $h_\mathrm{g} - h_\mathrm{f}$ J/kg

h_g = specific enthalpy of dry saturated vapour J/kg

Enthalpy

$$H = U + p\mathscr{V}$$

$$h = u + pv$$

where

H = enthalpy J

h = specific enthalpy J/kg

U = internal energy J

u = specific internal energy J/kg

p = pressure Pa

$\mathscr{V}$ = volume m^3

v = specific volume m^3/kg

Enthalpy Change at constant pressure

$$\Delta h \Big|_{p\,=\,\mathrm{const}} = h_2 - h_1 = c_{p,\,\mathrm{avg}}\,\Delta T$$

where

Δh = increase in specific enthalpy J/kg

c_p = specific heat at constant pressure J/kgK

ΔT = increase in temperature K

subscripts

const	constant
avg	average

Enthalpy Change for an Incompressible Substance

$$\Delta h_{\mathrm{incomp}} = h_2 - h_1 = c_{\mathrm{avg}}(T_2 - T_1) + (p_2 - p_1)v$$

where

Δh = increase in specific enthalpy J/kg

c = specific heat J/kgK

v = specific volume m^3/kg

T = temperature K

subscripts

incomp	incompressible

avg	average

Enthalpy Change for an Ideal Gas

$$\Delta h = h_2 - h_1 = c_{p,\,\mathrm{avg}}\,\Delta T$$

where

c_p = specific heat at constant pressure J/kgK

ΔT = increase in temperature K

Evaporator Heat Transfer Rate

$$\dot{Q}_{\mathrm{evap,\,in}} = \dot{Q}_{\mathrm{in}} = \dot{m}\,(h_{\mathrm{out}} - h_{\mathrm{in}})$$

where

$\dot{Q}_{\mathrm{evap,\,in}}$ = rate of heat transfer that occurs into a system in an evaporator W

$\dot{Q}_{\mathrm{in}}$ = rate of heat transfer into the system W

$\dot{m}$ = mass flow rate of the fluid that evaporates kg/s

h_{out} = specific enthalpy of fluid leaving the evaporator J/kg

h_{in} = specific enthalpy of fluid entering the evaporator J/kg

Feed Pump Work or Power

$$w_{\mathrm{pump,\,in}} = h_{\mathrm{out}} - h_{\mathrm{in}} + q_{\mathrm{pump,\,out}}$$

$$\dot{W}_{\mathrm{pump,\,in}} = \dot{m}\,(h_{\mathrm{out}} - h_{\mathrm{in}}) + \dot{m}\,q_{\mathrm{pump,\,out}}$$

$$\dot{W}_{\mathrm{pump,\,in}} = \dot{m}\,(h_{\mathrm{out}} - h_{\mathrm{in}}) + \dot{Q}_{\mathrm{pump,\,out}}$$

$$\dot{W}_{\mathrm{pump,\,in,\,ideal}} = \dot{m}\,v\,(p_{\mathrm{out}} - p_{\mathrm{in}})$$

where

h = specific enthalpy J/kg

$w_{\text{pump, in}}$ = pump net work input per unit mass J/kg

$\dot{W}_{\text{pump, in}}$ = net rate of work input W

$\dot{W}_{\text{pump, in, ideal}}$ = net rate of work input of an ideal frictionless pump W

$q_{\text{pump, out}}$ = pump net heat output per unit mass J/kg

$\dot{Q}_{\text{pump, out}}$ = net rate of heat output W

$\dot{m}$ = mass flow rate kg/s

v = specific volume of incompressible fluid m^3/kg

p = pressure Pa

Refrigeration Compressor Steady Flow Energy Equation

$$\dot{W}_{\text{comp, in}} = \dot{m}\,(h_{\text{out}} - h_{\text{in}}) + \dot{Q}_{\text{comp, out}}$$

where

$\dot{W}_{\text{comp, in}}$ = net rate of work input W

$\dot{Q}_{\text{comp, out}}$ = net rate of heat output W

h = specific enthalpy in or out J/kg

$\dot{m}$ = mass flow rate of the refrigerant kg/s

Flow Restriction (Throttling) Energy Balance Equation

$$h_{\text{out}} = h_{\text{in}}$$

where

h_{in} = specific enthalpy upstream of the flow restriction J/kg

h_{out} = specific enthalpy downstream of the flow restriction J/kg

Flow Work per Unit Mass (Specific Flow Work)

$$w_{\text{flow}} = pv$$

where

w_{flow} = specific flow work J/kg

p = pressure Pa

v = specific volume m^3/kg

Ideal Gas Equation

$$p\mathscr{V} = mRT$$

$$pv = RT$$

$$p\mathscr{V} = n\bar{R}\,T$$

where

p = absolute pressure Pa

$\mathscr{V}$ = volume m^3

v = specific volume m^3kg^{-1}

m = mass kg

R = specific gas constant J/kgK

T = absolute temperature K

n = amount of substance mol

$\bar{R}$ = molar or universal gas constant J/molK

Internal Energy

Internal Energy Change at Constant Volume

$$\Delta u \Big|_{v\,=\,\mathrm{const}} = u_2 - u_1 = c_{v,\,\mathrm{avg}}\,(T_2 - T_1)$$

where

Δu = increase in specific internal energy J/kg

c_v = specific heat at constant volume J/kgK

T = temperature K

subscripts

incomp	incompressible
avg	average

Internal Energy Change for an Incompressible Substance

$$\Delta u_{\mathrm{incomp}} = u_2 - u_1 = c_{\mathrm{avg}}(T_2 - T_1)$$

where

Δu = increase in specific internal energy J/kg

c = specific heat J/kgK

T = temperature K

subscripts

incomp	incompressible
avg	average

Internal Energy Change for an Ideal Gas

$$\Delta u = u_2 - u_1 = c_{v,\,\mathrm{avg}}\,\Delta T$$

where

c_v = specific heat at constant volume J/kgK

ΔT = increase in temperature K

Isothermal Process for an Ideal Gas

$$pv = \text{const.} = p_1 v_1 = p_2 v_2$$

$$p\mathscr{V} = \text{const.} = p_1 \mathscr{V}_1 = p_2 \mathscr{V}_2$$

where

p	=	pressure	Pa
v	=	specific volume	m^3kg^{-1}
$\mathscr{V}$	=	volume	m^3

Kinetic Energy

$$E_\text{k} = \frac{m\,V^2}{2}$$

where

E_k	=	kinetic energy	J
m	=	mass	kg
V	=	velocity	ms^{-1}

Newton’s Second Law Applied to SI Units

$$F = ma$$

where

F	=	force	N
m	=	mass	kg
a	=	acceleration	ms^{-2}

Hence,

$$1\ \text{N} = 1\ \text{kg m s}^{-2}$$

Non-Flow Energy Equation

$$Q_\text{in} + W_\text{in} = \Delta U$$

where

Q_in	=	net heat transfer into system	J

W_{in} = net work into system J

U = internal energy J

ΔU = increase in internal energy J

On a per-unit-mass basis,

$$q_{\text{in}} + w_{\text{in}} = \Delta u$$

where

q_{in} = net heat transfer into system per unit mass J/kg

w_{in} = net work into system per unit mass J/kg

Δu = increase in specific internal energy J/kg

Polytropic Relationships for Compression or Expansion

$$p\mathscr{V}^{n} = \text{const.} = p_1\mathscr{V}_1^{n} = p_2\mathscr{V}_2^{n}$$

$$p_1 v_1^n = p_2 v_2^n$$

For ideal gases

$$\frac{T_2}{T_1} = \left(\frac{\mathscr{V}_1}{\mathscr{V}_2}\right)^{n-1}$$

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$$

where

p = absolute pressure Pa

$\mathscr{V}$ = volume m^3

v = specific volume m^3/kg

n = polytropic exponent

T = absolute temperature K

Potential Energy

$$E_{\mathrm{p}} = mgz$$

where

E_{p} = potential energy J

m = mass kg

z = elevation m

g = acceleration due to gravity $\mathrm{m\,s^{-2}}$

Pressure

$$p = \frac{F}{\mathrm{A}}$$

where

p = pressure $\mathrm{N\,m^{-2}}$ or Pa

F = Force N

A = area $\mathrm{m^2}$

Pumping Power (ideal)

$$\begin{aligned} \dot{W}_{\text{in, ideal}} &= \dot{m}\,(h_2 - h_1) \\ &= \dot{m}\,v\,(p_2 - p_1) \\ &= \dot{\mathscr{V}}\ (p_2 - p_1). \end{aligned}$$

where

$\dot{W}_{\text{in, ideal}}$ = ideal pumping power W

$\dot{m}$ = mass flow rate $\mathrm{kg\,s^{-1}}$

h = specific enthalpy J/kg

v = specific volume $\mathrm{m^3kg^{-1}}$

$\dot{\mathscr{V}}$ = volume flow rate $\mathrm{m^3/s}$

p = pressure Pa

The overall efficiency of a pump is defined as

$$E_{\text{pump}} = \frac{\dot{W}_{\text{in, ideal}}}{\dot{W}_{\text{in}}}$$

where

$\dot{W}_{\text{in}}$ = actual power input W

Specific Enthalpy

$$h = u + pv$$

where

h = specific enthalpy J/kg

u = specific internal energy J/kg

p = pressure Pa

v = specific volume m^3kg^{-1}

Specific Enthalpy of Subcooled Liquid

$$h = u + pv$$

(If the liquid can be assumed incompressible then u and v depend only on the temperature, so can be found for saturated liquid from the saturation table at the given temperature.)

$$h_{\text{subcooled liquid}} = u_{\text{f @ }T} + p\,v_{\text{f @ }T}$$

or

$$h_{\text{subcooled liquid}} = h_{\text{f @ }T} + (p - p_{\text{s @ }T})\,v_{\text{f @ }T}$$

where

h = specific enthalpy J/kg

$h_{\text{subcooled liquid}}$ = specific enthalpy of subcooled liquid J/kg

$h_{\text{f @ }T}$ = specific enthalpy of saturated liquid at the given temperature J/kg

$v_{\mathrm{f} \,@\, T}$ = specific volume of saturated liquid at the given temperature $\mathrm{m^3/kg}$

$p_{\mathrm{s} \,@\, T}$ = saturation pressure at the given temperature Pa

u = specific internal energy J/kg

$u_{\mathrm{f} \,@\, T}$ = specific internal energy of saturated liquid at the given temperature J/kg

p = absolute pressure Pa

v = specific volume $\mathrm{m^3\,kg^{-1}}$

T = temperature K

Specific Heat Capacity

Specific Heat of Incompressible Substances

$$c = \left.\frac{\Delta u}{\Delta T}\right|_{\Delta T \to 0}$$

$$\Delta u_{\mathrm{incomp}} = u_2 - u_1 = c_{\mathrm{avg}}(T_2 - T_1)$$

c_{avg} = average specific heat J/kg K

u = specific internal energy J/kg

Δu = increase in specific internal energy J/kg

ΔT = increase in temperature K

Subscripts

incomp	incompressible
avg	average

Specific Heat at Constant Pressure

$$c_p = \left.\frac{\Delta h}{\Delta T}\right|_{\Delta T \to 0,\ p = \text{const}}$$

$$\Delta h \Big|_{p = \text{const}} = h_2 - h_1 = c_{p,\ \text{avg}}\,(T_2 - T_1)$$

For an ideal gas:

$$\Delta h = h_2 - h_1 = c_{p,\ \text{avg}}\,(T_2 - T_1)$$

where

c_p	=	specific heat at constant pressure	J/kgK
h	=	specific enthalpy	J/kg
Δh	=	increase in specific enthalpy	J/kg

Specific Heat at Constant Volume

$$c_v = \left.\frac{\Delta u}{\Delta T}\right|_{\Delta T \to 0,\ v = \text{const}}$$

$$\Delta u \Big|_{v = \text{const}} = u_2 - u_1 = c_{v,\ \text{avg}}\,(T_2 - T_1)$$

For an ideal gas:

$$\Delta u = u_2 - u_1 = c_{v,\ \text{avg}}\,(T_2 - T_1)$$

where

c_v	=	specific heat at constant volume	J/kgK
u	=	specific internal energy	J/kg
Δu	=	increase in specific internal energy	J/kg

Steady Flow Energy Equation

$$\dot{m}\left(h_1+\frac{V_1^2}{2}+gz_1\right)+\dot{Q}_{\text{in}}+\dot{W}_{\text{in}}=\dot{m}\left(h_2+\frac{V_2^2}{2}+gz_2\right)$$

or, on a per unit mass basis,

$$h_1+\frac{V_1^2}{2}+gz_1+q_{\text{in}}+w_{\text{in}}=h_2+\frac{V_2^2}{2}+gz_2$$

where

$\dot{Q}_{\text{in}}$	=	net heat transfer rate into system	W
g	=	acceleration due to gravity	$\mathrm{m\,s^{-2}}$
$\dot{W}_{\text{in}}$	=	net shaft work rate into system	W
h	=	specific enthalpy	J/kg
V	=	velocity	$\mathrm{m\,s^{-1}}$
$\dot{m}$	=	mass flow rate	$\mathrm{kg\,s^{-1}}$
q_{in}	=	net heat transfer into system per unit mass	J/kg
w_{in}	=	net shaft work into system per unit mass	J/kg

Turbine Steady Flow Energy Equation

$$w_{\text{turb, out}}=h_{\text{in}}-h_{\text{out}}$$

$$\dot{W}_{\text{turb, out}}=\dot{m}\,(h_{\text{in}}-h_{\text{out}})$$

where

$w_{\text{turb, out}}$	=	turbine net work output per unit mass	J/kg
$\dot{W}_{\text{turb, out}}$	=	turbine net rate of work output	W
h	=	specific enthalpy in or out	kJ/kg
$\dot{m}$	=	mass flow rate	kg/s

Thermal Efficiency

$$E_{\text{th}} = \frac{W_{\text{net, out}}}{Q_{\text{H, in}}} = \frac{\dot{W}_{\text{net, out}}}{\dot{Q}_{\text{H, in}}}$$

where

E_{th} = thermal efficiency

$Q_{\text{H, in}}$ = heat input at T_{H} J

$W_{\text{net, out}}$ = net work output J

$\dot{Q}_{\text{H, in}}$ = heat input rate at T_{H} W

$\dot{W}_{\text{net, out}}$ = net work output rate (net power output) W

Volume Flow Rate

$$\dot{\mathcal{V}} = \dot{m}\, v$$

where

$\dot{\mathcal{V}}$ = volume flow rate $\text{m}^3\text{/s}$

v = specific volume $\text{m}^3\text{/kg}$

$\dot{m}$ = mass flow rate kg/s

also

$$\dot{\mathcal{V}} = VA$$

where

V = velocity $\text{m}\,\text{s}^{-1}$

A = area m^2

Work

$$W = F s \cos\theta$$

where

W = work J

F = force N

s = displacement m

θ = angle rad

Appendix B Glossary of Terms

Absolute Pressure

Absolute pressure is the true pressure. This term is used when it is necessary to emphasize that the pressure being referred to is not a relative pressure, such as gauge pressure, or a differential pressure, such as the pressure drop across a valve. The lowest possible value of absolute pressure is zero (in any pressure units).

Absolute Temperature

Absolute temperature is temperature as measured on the absolute scale, which has a zero at the level through which no substance can be cooled.

Adiabatic

Adiabatic means ‘without heat transfer’. For instance, an adiabatic system is one that is insulated from its surroundings such that no heat transfer can occur between them. In an adiabatic process being undergone by a closed system or taking place within an open system there is no heat transfer to or from the system.

Amount of Substance

‘Amount of substance’ is a measure and a property of a collection of specified entities of a substance (or mixture of substances). The entities would typically be atoms, molecules or ions. The SI unit for amount of substance is the mole, which can be abbreviated to mol.

Amount of Superheat

This describes the difference between the temperature of superheated vapour and the saturation temperature at the same pressure, i.e. $t - t_s$.

Atmospheric Pressure

This is the pressure of the atmosphere, which can be measured by a barometer.

$$1 \text{ standard atmosphere} = 1.01325 \times 10^5 \text{ Pa}$$

Boiling

This is evaporation accompanied by considerable vapour bubble formation within the evaporating liquid.

Capillary Tube

A capillary tube is a tube having a very small diameter, e.g. 1 mm. If the end of such a tube were placed in a liquid such as water or oil the liquid would rise in the tube due to capillary action. In refrigeration a capillary tube, having a length of perhaps a metre or so, is sometimes used as an expansion device.

Clearance Volume

The clearance volume of a cylinder within a reciprocating compressor is the volume within the cylinder when the piston is at the top-dead-centre (minimum volume) position.

Coefficient of Performance of a Heat Pump

The coefficient of performance (COP) of a heat pump is the ratio of the heat output (to a high temperature reservoir or region) to the net work input of the plant.

Coefficient of Performance of a Refrigeration Plant

The coefficient of performance (COP) of a refrigeration plant is the ratio of the heat input (from a low temperature reservoir or region) to the net work input of the plant.

Conduction Heat Transfer

Conduction heat transfer is heat transfer that occurs by direct contact within or between objects or systems, or regions of substance.

Convection Heat Transfer

Convection heat transfer is heat transfer that occurs between a solid and a fluid, or within a fluid, and is accompanied by relative movement between the solid and fluid, or between regions within the fluid. The relative movement can be due to buoyancy effects or the presence of an agitator, pump or fan that induces flow.

Cycle

A cycle is a series of processes as a result of which a system or amount of substance that starts off at a given state is brought through other states and back to the initial state. A closed non-flow system can undergo a cycle over a period of time. A cycle can also exist within a closed steady flow system, wherein a fluid undergoes changes in its state as it moves around a closed circuit of the system.

Displacement Work

Displacement work is work at the boundary of a system involving either a displacement of the boundary or flow through the boundary.

Dryness Fraction

The dryness fraction (or vapour fraction or quality) of a saturated mixture of liquid and vapour of a pure substance is the mass of vapour divided by the total mass of the substance present.

Energy

Energy is a property that characterizes the capacity of a system or an amount of matter to do work (irrespective of whether this is at the macroscopic level or the molecular level).

Enthalpy

Enthalpy, with the symbol H (upper-case letter) and units of J, is a thermodynamic property of a system or an amount of substance that is defined in terms of three other properties (internal energy, pressure and volume) as $H = U + p\mathscr{V}$. Specific enthalpy (enthalpy per unit mass) has the symbol h (lower-case letter) and units of J/kg.

Entropy

Entropy, with the symbol S (upper-case letter) and units of J/K, is a thermodynamic property of a system or an amount of substance that quantifies the thermodynamic disorder of the system or substance at the atomic and molecular level. In a pure crystalline solid at absolute zero temperature (0 K) there is no disorder: atoms retain their arrangement and have no chaotic motion or vibrations. Specific entropy (entropy per unit mass) has the symbol s (lower-case letter) and units of $\mathrm{J/kg\,K}$.

Equilibrium

A system is said to be in equilibrium (or in an equilibrium state) if none of its thermodynamic properties would change if the system were instantly enclosed by a boundary that prevented all energy interactions with the surroundings.

Equilibrium Process

An equilibrium process is a change of state that takes place in such a manner that equilibrium is maintained throughout. There must be no mechanical or fluid friction, finite temperature differences causing heat transfer, or un-resisted expansion within the system. For a system comprising a substance it is an ideal that can be approximated.

First Law of Thermodynamics

The first law of thermodynamics states that if a system has undergone no net change after heat transfer and work interactions have taken place then the sum of the net heat transfer into the system plus the net work done on the system must be zero. It is a statement that recognizes that work and heat transfer are both forms of energy transfer and that energy is conserved.

Fluid

A fluid is a substance that cannot sustain a shear stress without undergoing relative movement. Liquids, vapours and gases are fluids.

Gas

A gas is matter in a state wherein molecules have sufficient molecular level kinetic energy that they are not held together by attractive forces and move with random chaotic motion due to collisions.

Gauge Pressure

Gauge pressure is a relative pressure: it is the amount by which the pressure exceeds the pressure of the atmosphere.

Heat (Heat Transfer)

Heat (or heat transfer) is energy transfer due to temperature difference.

Heat Engine

A heat engine is a system that undergoes a cycle in the course of which heat transfer is accepted from a heat source and heat rejection occurs to a heat sink at lower temperature while a net work output is produced.

Heat Engine Operating in Reverse

A heat engine operating in reverse is a system that undergoes a cycle in the course of which heat transfer is accepted from a heat source and heat rejection occurs to a heat sink at higher temperature while a net work input is required.

Ideal Adiabatic Process

This is a process (a change of state) during which there are no friction effects and no heat transfer. The gas is assumed to be in equilibrium throughout the process.

Ideal Adiabatic Process for an Ideal Gas

An ideal adiabatic process for an ideal gas is a change of state of the ideal gas in which the pressure, volume and temperature of the gas change without any friction effects being present and without any heat transfer occurring to or from the gas. The gas is assumed to be in equilibrium throughout the process.

Ideal Gas

An ideal gas is a gas that is assumed to follow the ideal gas equation. All gases can be represented by this equation as the pressure approaches zero.

Incompressible

Matter is said to be incompressible if its volume does not change with changes in pressure if the temperature is held constant. Gases are compressible (i.e. they are not incompressible), as a moderate change in pressure can cause a significant change in volume. However, liquids and solids have very low compressibility and, as a simplification, can be considered incompressible.

Internal Energy

Internal energy is the energy possessed by matter, or a substance, that is associated with the translation, rotation or vibration of the molecules or sub-molecular constituents that comprise the matter and with the attractive and repulsive forces that bind the matter together or determine its atomic and molecular level arrangement and configuration.

Isenthalpic Process

An isenthalpic process is a change during which enthalpy or specific enthalpy remains constant. When a fluid passes through an adiabatic flow restriction and undergoes a pressure drop, the process can be regarded as isenthalpic for calculation purposes. Such processes (known as throttling processes) are non-equilibrium processes wherein the fluid has the same specific enthalpy downstream of the flow restriction as it has upstream.

Isentropic Process

An isentropic process is a change during which the entropy or specific entropy remains constant. Ideal adiabatic compression or expansion processes that do not involve any fluid friction are examples of isentropic processes.

Isothermal Process

An isothermal process is a change during which the temperature remains constant.

Kinetic Energy

Kinetic energy is the energy possessed by matter due to its velocity.

Liquid

A liquid is matter in a state wherein molecules are in close proximity and are held together by attractive forces, but bulk relative sliding movement will occur in any plane where there is a shear stress, no matter how small the stress is.

Liquid Flashes to Vapour

A phenomenon whereby saturated or slightly subcooled liquid suddenly evaporates in part, due to a sudden reduction in pressure, yielding saturated vapour.

Mole

A mole (abbreviation: mol) is an amount of substance with the same number of entities as there are atoms of carbon 12 in 0.012 kg (i.e. 12 g) of carbon 12. This is the SI unit for amount of substance.

Newton’s Second Law

Force equals mass times acceleration.

Polytropic Process

A polytropic process is a change in the state of a system or substance that can be described by an equation of the form

$$p\mathscr{V}^{n} = \text{const.}$$

Potential Energy (Gravitational)

Potential energy is the energy possessed by matter due to its elevation within a gravitational field (usually the Earth’s).

Power

Power is the rate of doing work. It has the SI units J/s or watt, W.

Pressure

Pressure is force exerted per unit area in a direction that is normal to and towards the area. It is expressed as

$$p = \frac{F}{A}$$

Principle of Conservation of Energy

The principle of conservation of energy states that energy is conserved. Energy can be transformed from one form to another, but cannot be created or destroyed. This is subject to the assumption that mass-to-energy or energy-to-mass conversions do not occur.

Process

In thermodynamics a process is a change that occurs in the properties of a system or substance.

Quality of Steam

The quality of wet steam (a saturated mixture of vapour and suspended liquid droplets) is its dryness fraction, which is the mass of water vapour divided by the total mass of liquid water and water vapour.

Quasi-equilibrium

Recognizing that considering a system to be in equilibrium during a process or while heat transfer occurs to the system is usually an idealization, the term quasi-equilibrium encompasses states that are close to equilibrium states. If a system is in a quasi-equilibrium state, its thermodynamic properties would change only slightly if the system were instantly enclosed by a boundary that prevented all energy interactions with the surroundings.

Radiation Heat Transfer

Radiation heat transfer is heat transfer that occurs between objects that share a line of sight. It is a form of electromagnetic radiation (that includes infra-red radiation, ultraviolet radiation and visible light) and requires a vacuum or a medium that is at least partially transparent to electromagnetic radiation.

Refrigeration Effect

The refrigeration effect of a refrigeration plant is the amount of heat transfer to the refrigerant in the evaporator per unit mass of the refrigerant. The SI units for refrigeration effect are J/kg.

Saturated State

A saturated state of a pure substance is a state where two or more phases co-exist in equilibrium.

Saturated Mixture

A saturated mixture is a mixture of two or more phases of the same substance (most commonly liquid and vapour phases) that co-exist in equilibrium.

Second Law of Thermodynamics

The second law of thermodynamics states that heat transfer cannot be converted completely to work at the macroscopic level. A system or machine that accepts heat transfer and produces a net work output without undergoing any net change in its own state must also reject heat.

Shaft Work

Shaft work is work of the type that can be done by the rotation of a shaft. In thermodynamics this term is often used to emphasize that the work in question is not displacement work. The term ‘shaft work’ can also include electrical work, which is equivalent in the thermodynamic sense.

Solid

A solid is matter in a state wherein molecules are held tightly together by attractive forces and can only be made to slide over one another by the imposition of shear stresses that are high enough to overcome the attractive forces.

Specific Heat Capacity (Specific Heat)

Specific heat capacity is defined as the amount of heat transfer (or, more generally, energy input) required to raise the temperature of a unit mass of a substance through one temperature unit. The SI units for specific heat capacity are J/kgK.

State of a System or Substance

The state of a system or substance is a condition or configuration of the system or substance that can be described, for energy-related purposes, by assigning values to a sufficient number of its properties.

Steady Flow

Flow is said to be steady if the velocities and other parameters, e.g. density and pressure, to not vary with time. The velocity and other parameters may vary from point to point within the flow.

Subcooled

A pure substance is subcooled if it is at a temperature below the saturation temperature corresponding to its pressure.

Subcooled Liquid

A pure substance in the liquid state is subcooled if it is at a temperature below the saturation temperature corresponding to its pressure.

Substance

Substance is matter of a particular chemical composition.

Superheated

A pure substance is superheated if it is at a temperature above the saturation temperature corresponding to its pressure.

Superheated Vapour

A pure substance in the vapour state is superheated if it is at a temperature above the saturation temperature corresponding to its pressure.

Swept Volume

The swept volume of a cylinder within a reciprocating compressor is the volume through which the piston sweeps for each stroke from bottom-dead-centre to top-dead-centre. It equals the length of the stroke multiplied by the cross-sectional area of the cylinder.

System

A system is a region in space, or the content of a real or virtual container. It is defined by a boundary that encloses volume.

Temperature

Temperature is the formal measure of the property that humans sense as ‘hotness’ or ‘coldness’. Objects that are at higher temperatures will lose energy to objects that are at lower temperatures if they are allowed to interact by being brought into contact or by the removal of anything that could block energy exchange by radiation between them.

Thermal Efficiency of a Heat Engine

The thermal efficiency of a heat engine is the ratio of the net work output to the heat input.

Thermodynamic Properties

Thermodynamic properties of a substance or system are quantifiable characteristics that relate to energy or energy interactions. Pressure, temperature, mass and internal energy are examples.

Throttling

Throttling is said to occur wherever a flow restriction causes a pressure drop.

Vacuum and Vacuum Pressure

Vacuum pressure is the amount by which a pressure is less than atmospheric pressure. In a perfect vacuum the absolute pressure would be zero.

Vector

A vector is a quantity that has both a magnitude and a direction. Examples of physical quantities that are vectors include force, displacement (units: m) and velocity.

Vapour

A vapour is a gas at a temperature low enough that the substance could also be a solid-gas mixture or a liquid-gas mixture at the same temperature if the pressure were high enough. A vapour can be liquefied by increasing the pressure while keeping the temperature constant. Another definition is that a vapour is a gas where the temperature is below the critical temperature. The tendency is to favour the term ‘vapour’ when the temperature is at, or above but fairly close to, the saturation temperature.

Volumetric Efficiency of a Reciprocating Compressor

The volumetric efficiency of a reciprocating compressor is the ratio of the induced volume (the volume of gas taken in at the suction pressure and temperature) to the swept volume.

Wet Steam or Wet Vapour

Sometimes vapour can leave a boiler or evaporator and can flow in a pipe in a state where tiny droplets of liquid are entrained and suspended within it. Such steam or refrigerant vapour is called ‘wet steam’ or ‘wet vapour’. Wet vapour is thus a mixture of vapour and a small proportion of liquid, with the liquid suspended as tiny particles. The dryness fraction quantifies the proportion by mass of vapour in the mixture.

Work

Work is the product of the magnitude of a force vector acting on an object, the magnitude of the displacement vector of the point of action of the force and the cosine of the angle between the force vector and the displacement vector. The SI unit for work is the newton metre, or the joule.

Appendix C Constants and Multipliers

Table C-1 Constants and standard properties

Standard atmospheric pressure (1 atm)	101.325 kPa
Triple point temperature of water	273.16 K, 0.01 °C
Avogadro's number[9]	6.022×10^{23} mol^{-1}
Standard acceleration due to gravity[9], g	9.81 ms^{-2}
Universal gas constant[9], $\bar{R}$	8.3145 kJ/kmolK

Table C-2 Common SI prefixes

μ	micro	10^{-6}
m	milli	0.001
c	centi	0.01
h	hecto	100
k	kilo	1000
M	mega	10^{6}
G	giga	10^{9}

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[9] These constants are not shown to full precision.

Appendix D Ideal Gas Data

Table D-1 Data for some ideal gases[10]

Gas		$\bar{m}$ [kg/kmol]	R [kJ/kgK]	c_p [kJ/kgK]	c_v [kJ/kgK]	γ
Dry air	-	28.97	0.2871	1.0042	0.7171	1.400
Argon	Ar	39.95	0.2081	0.5203	0.3122	1.667
Carbon dioxide	CO_2	44.01	0.1889	0.8334	0.6445	1.293
Helium	He	4.003	2.077	5.193	3.116	1.667
Hydrogen	H_2	2.016	4.124	14.265	10.141	1.407
Nitrogen	N	28.01	0.2968	1.0395	0.7427	1.400
Oxygen	O_2	32.00	0.2598	0.9166	0.6568	1.396

These values are for use in calculations where ideal gas behaviour with constant specific heats can be assumed. The values of c_p are at 15 °C and zero pressure. The values of R, c_v and γ are calculated from $\bar{m}$, $\bar{R}$ and c_p.

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[10] Principal data source: Lemmon, E.W., Huber, M.L., McLinden, M.O., NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 9.1, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg, 2013.

Appendix E Properties of Water Substance

As an approximation, if liquid water is regarded as incompressible at temperatures and pressures close to 15 °C and 1 atm (0.101325 MPa) it is convenient to assume

specific volume, $v = 0.00100\,\mathrm{m^3/kg}$

specific heat, $c = 4.18$ kJ/kgK.

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The thermodynamic properties in these tables were calculated using the Excel add-in of the software FLUIDCAL, version 'Water (IAPWS-95)' dated 11/3/2013 for the IAPWS-95 Formulation of the International Association for the Properties of Water and Steam[11].

While care has been taken in preparing the tables, no warranty of accuracy or fitness for purpose is made for the data.

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[11] Wagner, W., Pruß, A.: The IAPWS formulation 1995 for the thermodynamic properties of ordinary water substance for general and scientific use. J. Phys. Chem. Ref. Data 31 (2002), 387 – 535.

Table E-1 Saturation properties of water substance

p_s [MPa]	t_s [°C]	u_f [kJ/kg]	u_{fg} [kJ/kg]	u_g [kJ/kg]	h_f [kJ/kg]	h_{fg} [kJ/kg]	h_g [kJ/kg]	s_f [kJ/kgK]	s_{fg} [kJ/kgK]	s_g [kJ/kgK]	v_f [m^3/kg]	v_{fg} [m^3/kg]	v_g [m^3/kg]
0.000612	**0.01**	0.0	2374.9	2374.9	0.0	2500.9	2500.9	0.000	9.155	9.155	0.001000	205.990	205.991
0.000657	**1**	4.2	2372.1	2376.3	4.2	2498.5	2502.7	0.015	9.114	9.129	0.001000	192.438	192.439
0.000706	**2**	8.4	2369.3	2377.7	8.4	2496.2	2504.6	0.031	9.072	9.103	0.001000	179.757	179.758
0.000814	**4**	16.8	2363.6	2380.4	16.8	2491.4	2508.2	0.061	8.990	9.051	0.001000	157.115	157.116
0.000935	**6**	25.2	2358.0	2383.2	25.2	2486.7	2511.9	0.091	8.908	8.999	0.001000	137.632	137.633
0.001	7.0	29.3	2355.2	2384.5	29.3	2484.4	2513.7	0.106	8.869	8.975	0.001000	129.177	129.178
0.00107	**8**	33.6	2352.3	2385.9	33.6	2482.0	2515.6	0.121	8.828	8.949	0.001000	120.828	120.829
0.00123	**10**	42.0	2346.6	2388.6	42.0	2477.2	2519.2	0.151	8.749	8.900	0.001000	106.302	106.303
0.00140	**12**	50.4	2341.0	2391.4	50.4	2472.5	2522.9	0.181	8.670	8.851	0.001001	93.718	93.719
0.00160	**14**	58.8	2335.3	2394.1	58.8	2467.7	2526.5	0.210	8.594	8.804	0.001001	82.792	82.793
0.00182	**16**	67.2	2329.7	2396.9	67.2	2463.0	2530.2	0.239	8.518	8.757	0.001001	73.285	73.286
0.002	17.5	73.4	2325.5	2398.9	73.4	2459.5	2532.9	0.261	8.462	8.723	0.001001	66.986	66.987
0.00206	**18**	75.5	2324.1	2399.6	75.5	2458.3	2533.8	0.268	8.443	8.711	0.001001	64.997	64.998
0.00234	**20**	83.9	2318.4	2402.3	83.9	2453.5	2537.4	0.296	8.370	8.666	0.001002	57.756	57.757
0.00265	**22**	92.3	2312.7	2405.0	92.3	2448.8	2541.1	0.325	8.297	8.622	0.001002	51.417	51.418
0.00299	**24**	100.6	2307.2	2407.8	100.6	2444.1	2544.7	0.353	8.225	8.578	0.001003	45.857	45.858
0.003	24.1	101.0	2306.9	2407.9	101.0	2443.8	2544.8	0.354	8.222	8.576	0.001003	45.652	45.653
0.00336	**26**	109.0	2301.5	2410.5	109.0	2439.3	2548.3	0.381	8.154	8.535	0.001003	40.972	40.973
0.00378	**28**	117.4	2295.8	2413.2	117.4	2434.5	2551.9	0.409	8.084	8.493	0.001004	36.671	36.672
0.004	29.0	121.4	2293.1	2414.5	121.4	2432.3	2553.7	0.422	8.051	8.473	0.001004	34.790	34.791
0.00425	**30**	125.7	2290.2	2415.9	125.7	2429.8	2555.5	0.437	8.015	8.452	0.001004	32.877	32.878
0.00476	**32**	134.1	2284.5	2418.6	134.1	2425.1	2559.2	0.464	7.947	8.411	0.001005	29.525	29.526
0.005	32.9	137.7	2282.1	2419.8	137.7	2423.0	2560.7	0.476	7.918	8.394	0.001005	28.184	28.185

Table E-1 Saturation properties of water substance

p_s [MPa]	t_s [°C]	u_f [kJ/kg]	u_{fg} [kJ/kg]	u_g [kJ/kg]	h_f [kJ/kg]	h_{fg} [kJ/kg]	h_g [kJ/kg]	s_f [kJ/kgK]	s_{fg} [kJ/kgK]	s_g [kJ/kgK]	v_f [m^3/kg]	v_{fg} [m^3/kg]	v_g [m^3/kg]
0.00533	**34**	142.4	2278.9	2421.3	142.5	2420.3	2562.8	0.492	7.879	8.371	0.001006	26.559	26.560
0.00595	**36**	150.8	2273.2	2424.0	150.8	2415.5	2566.3	0.519	7.813	8.332	0.001006	23.928	23.929
0.006	36.2	151.5	2272.7	2424.2	151.5	2415.1	2566.6	0.521	7.808	8.329	0.001006	23.732	23.733
0.00663	**38**	159.2	2267.5	2426.7	159.2	2410.7	2569.9	0.546	7.748	8.294	0.001007	21.592	21.593
0.007	39.0	163.3	2264.7	2428.0	163.4	2408.3	2571.7	0.559	7.715	8.274	0.001008	20.523	20.524
0.00738	**40**	167.5	2261.9	2429.4	167.5	2406.0	2573.5	0.572	7.684	8.256	0.001008	19.514	19.515
0.008	41.5	173.8	2257.6	2431.4	173.8	2402.4	2576.2	0.592	7.635	8.227	0.001008	18.098	18.099
0.00821	**42**	175.9	2256.2	2432.1	175.9	2401.2	2577.1	0.599	7.619	8.218	0.001009	17.663	17.664
0.009	43.8	183.2	2251.2	2434.4	183.3	2396.9	2580.2	0.622	7.564	8.186	0.001009	16.198	16.199
0.00911	**44**	184.2	2250.5	2434.7	184.3	2396.3	2580.6	0.625	7.556	8.181	0.001010	16.010	16.011
0.010	45.8	191.8	2245.4	2437.2	191.8	2392.1	2583.9	0.649	7.500	8.149	0.001010	14.669	14.670
0.01010	**46**	192.6	2244.8	2437.4	192.6	2391.6	2584.2	0.652	7.493	8.145	0.001010	14.533	14.534
0.011	47.7	199.6	2240.1	2439.7	199.7	2387.5	2587.2	0.674	7.441	8.115	0.001011	13.411	13.412
0.01118	**48**	201.0	2239.1	2440.1	201.0	2386.8	2587.8	0.678	7.432	8.110	0.001011	13.211	13.212
0.012	49.4	206.9	2235.1	2442.0	206.9	2383.4	2590.3	0.696	7.389	8.085	0.001012	12.357	12.358
0.0124	**50**	209.3	2233.4	2442.7	209.3	2382.0	2591.3	0.704	7.371	8.075	0.001012	12.026	12.027
0.015	54.0	225.9	2222.1	2448.0	225.9	2372.4	2598.3	0.755	7.252	8.007	0.001014	10.019	10.020
0.0158	**55**	230.2	2219.1	2449.3	230.3	2369.8	2600.1	0.768	7.222	7.990	0.001015	9.563	9.564
0.0199	**60**	251.2	2204.7	2455.9	251.2	2357.6	2608.8	0.831	7.077	7.908	0.001017	7.666	7.667
0.02	60.1	251.4	2204.6	2456.0	251.4	2357.5	2608.9	0.832	7.075	7.907	0.001017	7.647	7.648
0.0250	**65**	272.1	2190.3	2462.4	272.1	2345.4	2617.5	0.894	6.936	7.830	0.001020	6.193	6.194
0.03	69.1	289.2	2178.5	2467.7	289.3	2335.2	2624.5	0.944	6.823	7.767	0.001022	5.227	5.228
0.0312	**70**	293.0	2175.9	2468.9	293.1	2333.0	2626.1	0.955	6.799	7.754	0.001023	5.039	5.040

Table E-1 Saturation properties of water substance

p_s [MPa]	t_s [°C]	u_f [kJ/kg]	u_{fg} [kJ/kg]	u_g [kJ/kg]	h_f [kJ/kg]	h_{fg} [kJ/kg]	h_g [kJ/kg]	s_f [kJ/kgK]	s_{fg} [kJ/kgK]	s_g [kJ/kgK]	v_f [m^3/kg]	v_{fg} [m^3/kg]	v_g [m^3/kg]
0.0386	**75**	314.0	2161.2	2475.2	314.0	2320.6	2634.6	1.016	6.665	7.681	0.001026	4.128	4.129
0.04	75.9	317.6	2158.7	2476.3	317.6	2318.5	2636.1	1.026	6.643	7.669	0.001026	3.992	3.993
0.0474	**80**	335.0	2146.6	2481.6	335.0	2308.0	2643.0	1.076	6.535	7.611	0.001029	3.404	3.405
0.05	81.3	340.5	2142.7	2483.2	340.5	2304.7	2645.2	1.091	6.502	7.593	0.001030	3.239	3.240
0.0579	**85**	356.0	2131.8	2487.8	356.0	2295.3	2651.3	1.135	6.408	7.543	0.001032	2.825	2.826
0.06	85.9	359.8	2129.2	2489.0	359.9	2293.0	2652.9	1.145	6.386	7.531	0.001033	2.731	2.732
0.07	89.9	376.7	2117.2	2493.9	376.8	2282.6	2659.4	1.192	6.287	7.479	0.001036	2.364	2.365
0.0702	**90**	377.0	2117.0	2494.0	377.0	2282.5	2659.5	1.193	6.285	7.478	0.001036	2.358	2.359
0.08	93.5	391.6	2106.6	2498.2	391.7	2273.5	2665.2	1.233	6.201	7.434	0.001039	2.086	2.087
0.0846	**95**	398.0	2102.0	2500.0	398.1	2269.5	2667.6	1.250	6.165	7.415	0.001040	1.980	1.981
0.09	96.7	405.1	2097.0	2502.1	405.2	2265.1	2670.3	1.270	6.124	7.394	0.001041	1.868	1.869
0.1	99.6	417.4	2088.2	2505.6	417.5	2257.4	2674.9	1.303	6.056	7.359	0.001043	1.693	1.694
0.101325	99.97	419.0	2087.0	2506.0	419.1	2256.4	2675.5	1.307	6.047	7.354	0.001043	1.672	1.673
0.1014	**100**	419.1	2086.9	2506.0	419.2	2256.4	2675.6	1.307	6.047	7.354	0.001043	1.671	1.672
0.11	102.3	428.7	2080.0	2508.7	428.8	2250.4	2679.2	1.333	5.994	7.327	0.001045	1.548	1.549
0.12	104.8	439.2	2072.5	2511.7	439.4	2243.7	2683.1	1.361	5.937	7.298	0.001047	1.427	1.428
0.13	107.1	449.1	2065.3	2514.4	449.2	2237.4	2686.6	1.387	5.884	7.271	0.001049	1.324	1.325
0.1434	**110**	461.3	2056.4	2517.7	461.4	2229.7	2691.1	1.419	5.819	7.238	0.001052	1.208	1.209
0.15	111.3	467.0	2052.2	2519.2	467.1	2226.0	2693.1	1.434	5.789	7.223	0.001053	1.158	1.159
0.1987	**120**	503.6	2025.3	2528.9	503.8	2202.1	2705.9	1.528	5.601	7.129	0.001060	0.8901	0.8912
0.20	120.2	504.5	2024.6	2529.1	504.7	2201.5	2706.2	1.530	5.597	7.127	0.001061	0.8846	0.8857
0.25	127.4	535.1	2001.7	2536.8	535.3	2181.2	2716.5	1.607	5.445	7.052	0.001067	0.7176	0.7187
0.2703	**130**	546.1	1993.4	2539.5	546.4	2173.7	2720.1	1.635	5.391	7.026	0.001070	0.6669	0.6680

Table E-1 Saturation properties of water substance

p_s [MPa]	t_s [°C]	u_f [kJ/kg]	u_{fg} [kJ/kg]	u_g [kJ/kg]	h_f [kJ/kg]	h_{fg} [kJ/kg]	h_g [kJ/kg]	s_f [kJ/kgK]	s_{fg} [kJ/kgK]	s_g [kJ/kgK]	v_f [m^3/kg]	v_{fg} [m^3/kg]	v_g [m^3/kg]
0.30	133.5	561.1	1982.1	2543.2	561.4	2163.5	2724.9	1.672	5.320	6.992	0.001073	0.6047	0.6058
0.35	138.9	583.9	1964.6	2548.5	584.3	2147.7	2732.0	1.727	5.213	6.940	0.001079	0.5231	0.5242
0.3615	**140**	588.8	1960.8	2549.6	589.2	2144.2	2733.4	1.739	5.190	6.929	0.001080	0.5074	0.5085
0.40	143.6	604.2	1948.9	2553.1	604.7	2133.4	2738.1	1.776	5.119	6.895	0.001084	0.4613	0.4624
0.45	147.9	622.6	1934.5	2557.1	623.1	2120.3	2743.4	1.820	5.036	6.856	0.001088	0.4128	0.4139
0.4762	**150**	631.7	1927.4	2559.1	632.2	2113.7	2745.9	1.842	4.995	6.837	0.001091	0.3914	0.3925
0.5	151.8	639.5	1921.2	2560.7	640.1	2108.0	2748.1	1.860	4.961	6.821	0.001093	0.3737	0.3748
0.6	158.8	669.7	1897.1	2566.8	670.4	2085.7	2756.1	1.931	4.828	6.759	0.001101	0.3145	0.3156
0.6182	**160**	674.8	1893.0	2567.8	675.5	2081.9	2757.4	1.943	4.806	6.749	0.001102	0.3057	0.3068
0.7	164.9	696.2	1875.6	2571.8	697.0	2065.8	2762.8	1.992	4.715	6.707	0.001108	0.2717	0.2728
0.7922	**170**	718.2	1857.5	2575.7	719.1	2048.8	2767.9	2.042	4.623	6.665	0.001114	0.2415	0.2426
0.8	170.4	720.0	1856.0	2576.0	720.9	2047.4	2768.3	2.046	4.616	6.662	0.001115	0.2392	0.2403
0.9	175.4	741.6	1838.0	2579.6	742.6	2030.4	2773.0	2.094	4.527	6.621	0.001121	0.2138	0.2149
1.0	179.9	761.4	1821.3	2582.7	762.5	2014.6	2777.1	2.138	4.447	6.585	0.001127	0.1933	0.1944
1.003	**180**	761.9	1820.9	2582.8	763.1	2014.1	2777.2	2.139	4.445	6.584	0.001127	0.1927	0.1938
1.2	188.0	797.0	1790.8	2587.8	798.3	1985.4	2783.7	2.216	4.306	6.522	0.001139	0.1622	0.1633
1.255	**190**	806.0	1783.0	2589.0	807.4	1977.9	2785.3	2.235	4.271	6.506	0.001141	0.1553	0.1564
1.4	195.0	828.4	1763.4	2591.8	830.0	1958.8	2788.8	2.284	4.183	6.467	0.001149	0.1397	0.1408
1.555	**200**	850.5	1743.7	2594.2	852.3	1939.7	2792.0	2.331	4.099	6.430	0.001157	0.1260	0.1272
1.6	201.4	856.6	1738.2	2594.8	858.5	1934.3	2792.8	2.343	4.077	6.420	0.001159	0.1225	0.1237
1.8	207.1	882.4	1714.8	2597.2	884.5	1911.4	2795.9	2.397	3.980	6.377	0.001168	0.1092	0.1104
1.908	**210**	895.4	1702.9	2598.3	897.6	1899.7	2797.3	2.425	3.931	6.356	0.001173	0.1031	0.1043
2.0	212.4	906.1	1693.0	2599.1	908.5	1889.8	2798.3	2.447	3.892	6.339	0.001177	0.09841	0.09959

Table E-1 Saturation properties of water substance

p_s [MPa]	t_s [°C]	u_f [kJ/kg]	u_{fg} [kJ/kg]	u_g [kJ/kg]	h_f [kJ/kg]	h_{fg} [kJ/kg]	h_g [kJ/kg]	s_f [kJ/kgK]	s_{fg} [kJ/kgK]	s_g [kJ/kgK]	v_f [m^3/kg]	v_{fg} [m^3/kg]	v_g [m^3/kg]
2.320	**220**	940.8	1660.4	2601.2	943.6	1857.3	2800.9	2.518	3.766	6.284	0.001190	0.08490	0.08609
2.5	224.0	958.9	1643.2	2602.1	961.9	1840.0	2801.9	2.554	3.702	6.256	0.001197	0.07875	0.07995
2.797	**230**	986.8	1616.1	2602.9	990.2	1812.7	2802.9	2.610	3.603	6.213	0.001209	0.07029	0.07150
3.0	233.9	1004.7	1598.5	2603.2	1008.3	1794.9	2803.2	2.646	3.540	6.186	0.001217	0.06544	0.06666
3.347	**240**	1033.4	1569.7	2603.1	1037.6	1765.4	2803.0	2.702	3.440	6.142	0.001229	0.05847	0.05970
3.5	242.6	1045.5	1557.4	2602.9	1049.8	1752.8	2802.6	2.725	3.399	6.124	0.001235	0.05583	0.05706
3.976	**250**	1080.8	1521.0	2601.8	1085.8	1715.1	2800.9	2.794	3.278	6.072	0.001252	0.04883	0.05008
4.0	250.4	1082.5	1519.2	2601.7	1087.5	1713.3	2800.8	2.797	3.273	6.070	0.001253	0.04853	0.04978
4.5	257.4	1116.5	1483.2	2599.7	1122.2	1675.7	2797.9	2.862	3.158	6.020	0.001270	0.04279	0.04406
4.692	**260**	1129.0	1469.7	2598.7	1135.0	1661.6	2796.6	2.885	3.117	6.002	0.001276	0.04089	0.04217
5	263.9	1148.2	1448.8	2597.0	1154.6	1639.6	2794.2	2.921	3.053	5.974	0.001286	0.03816	0.03945
5.503	**270**	1178.1	1415.6	2593.7	1185.3	1604.4	2789.7	2.976	2.954	5.930	0.001303	0.03432	0.03562
6	275.6	1206.0	1383.9	2589.9	1213.9	1570.7	2784.6	3.028	2.862	5.890	0.001319	0.03113	0.03245
6.417	**280**	1228.3	1358.1	2586.4	1236.9	1543.0	2779.9	3.068	2.790	5.858	0.001333	0.02882	0.03015
7	285.8	1258.2	1322.8	2581.0	1267.7	1504.9	2772.6	3.122	2.693	5.815	0.001352	0.02603	0.02738
7.442	**290**	1279.9	1296.6	2576.5	1290.0	1476.7	2766.7	3.161	2.622	5.783	0.001366	0.02418	0.02555
8	295.0	1306.2	1264.3	2570.5	1317.3	1441.4	2758.7	3.208	2.537	5.745	0.001385	0.02215	0.02353
8.588	**300**	1332.9	1230.7	2563.6	1345.0	1404.6	2749.6	3.255	2.451	5.706	0.001404	0.02026	0.02166
9	303.3	1351.1	1207.4	2558.5	1363.9	1379.0	2742.9	3.287	2.392	5.679	0.001418	0.01907	0.02049
9.865	**310**	1387.9	1159.2	2547.1	1402.2	1325.7	2727.9	3.351	2.273	5.624	0.001448	0.01688	0.01833
10	311.0	1393.5	1151.7	2545.2	1408.1	1317.4	2725.5	3.361	2.255	5.616	0.001453	0.01658	0.01803
11	318.1	1434.1	1096.4	2530.5	1450.4	1255.9	2706.3	3.430	2.124	5.554	0.001489	0.01450	0.01599
11.284	**320**	1445.3	1080.7	2526.0	1462.2	1238.4	2700.6	3.449	2.088	5.537	0.001499	0.01397	0.01547

Table E-1 Saturation properties of water substance

p_s [MPa]	t_s [°C]	u_f [kJ/kg]	u_{fg} [kJ/kg]	u_g [kJ/kg]	h_f [kJ/kg]	h_{fg} [kJ/kg]	h_g [kJ/kg]	s_f [kJ/kgK]	s_{fg} [kJ/kgK]	s_g [kJ/kgK]	v_f [m^3/kg]	v_{fg} [m^3/kg]	v_g [m^3/kg]
12	324.7	1473.1	1041.2	2514.3	1491.5	1193.9	2685.4	3.497	1.997	5.494	0.001526	0.01273	0.01426
12.858	**330**	1505.8	993.4	2499.2	1525.9	1140.1	2666.0	3.552	1.890	5.442	0.001561	0.01142	0.01298
13	330.9	1511.1	985.4	2496.5	1531.5	1131.2	2662.7	3.561	1.873	5.434	0.001566	0.01121	0.01278
14	336.7	1548.4	928.7	2477.1	1571.0	1066.9	2637.9	3.623	1.750	5.373	0.001610	0.009875	0.011485
14.601	**340**	1570.6	893.8	2464.4	1594.5	1027.3	2621.8	3.660	1.676	5.336	0.001638	0.009143	0.010781
15	342.2	1585.3	870.3	2455.6	1610.2	1000.5	2610.7	3.685	1.626	5.311	0.001657	0.008681	0.010338
16	347.4	1622.3	809.5	2431.8	1649.7	931.1	2580.8	3.746	1.500	5.246	0.001709	0.007600	0.009309
16.529	**350**	1642.1	776.0	2418.1	1670.9	892.7	2563.6	3.778	1.433	5.211	0.001740	0.007062	0.008802
17	352.3	1659.9	745.3	2405.2	1690.0	857.5	2547.5	3.808	1.371	5.179	0.001769	0.006602	0.008371
18	357.0	1699.0	675.8	2374.8	1732.1	777.7	2509.8	3.872	1.234	5.106	0.001840	0.005662	0.007502
18.666	**360**	1726.3	625.5	2351.8	1761.7	719.8	2481.5	3.917	1.137	5.054	0.001895	0.005054	0.006949
19	361.5	1740.5	598.6	2339.1	1777.2	688.8	2466.0	3.940	1.086	5.026	0.001927	0.004750	0.006677
20	365.7	1786.4	508.6	2295.0	1827.2	585.1	2412.3	4.016	0.915	4.931	0.002040	0.003825	0.005865
20.5	367.8	1812.0	455.6	2267.6	1855.3	523.9	2379.2	4.058	0.817	4.875	0.002113	0.003333	0.005446
21	369.8	1841.2	392.5	2233.7	1887.6	451.0	2338.6	4.106	0.702	4.808	0.002206	0.002790	0.004996
21.044	**370**	1844.1	386.2	2230.3	1890.7	443.8	2334.5	4.111	0.690	4.801	0.002215	0.002739	0.004954
21.5	371.8	1879.1	307.8	2186.9	1929.5	353.6	2283.1	4.170	0.548	4.718	0.002347	0.002126	0.004473
21.8	372.9	1912.9	231.3	2144.2	1967.4	265.5	2232.9	4.227	0.411	4.638	0.002498	0.001570	0.004068
22	373.7	1951.8	141.0	2092.8	2011.3	161.8	2173.1	4.295	0.250	4.545	0.002704	0.000943	0.003647
22.064	373.946	2015.7	0.0	2015.7	2084.3	0.0	2084.3	4.407	0.000	4.407	0.003106	0.000000	0.003106

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	0.000612	Triple point pressure				0.000612					
t /[°C]	**0.01**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2374.9	2445.4	2516.4	2588.4	2661.7	2736.3	2812.5	2890.1	2969.4	3050.4	3133.0
h /[kJ/kg]	2500.9	2594.5	2688.61	2783.7	2880.0	2977.8	3077.0	3177.7	3280.1	3384.1	3489.8
s /[kJ/kgK]	9.155	9.470	10	9.980	10.2	10.391	10.573	10.741	10.899	11.048	11.189
v /[m^3/kg]	205.991	243.783	281.532	319.268	357.000	394.729	432.458	470.187	507.915	545.642	583.370
p /[MPa]	0.000657					0.000657					
t /[°C]	**1**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2376.3	2445.4	2516.4	2588.4	2661.7	2736.3	2812.4	2890.1	2969.4	3050.4	3133.0
h /[kJ/kg]	2502.7	2594.5	2688.6	2783.7	2880.0	2977.8	3077.0	3177.7	3280.1	3384.1	3489.8
s /[kJ/kgK]	9.129	9.437	9.708	9.947	10.162	10.358	10.539	10.708	10.866	11.015	11.156
v /[m^3/kg]	192.439	226.925	262.065	297.192	332.316	367.437	402.558	437.678	472.797	507.916	543.036
p /[MPa]	0.000706					0.000706					
t /[°C]	**2**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2377.7	2445.4	2516.4	2588.4	2661.7	2736.3	2812.4	2890.1	2969.4	3050.4	3133.0
h /[kJ/kg]	2504.6	2594.5	2688.6	2783.7	2880.0	2977.7	3077.0	3177.7	3280.1	3384.1	3489.8
s /[kJ/kgK]	9.103	9.404	9.675	9.914	10.129	10.325	10.506	10.675	10.833	10.982	11.123
v /[m^3/kg]	179.758	211.204	243.911	276.606	309.297	341.986	374.674	407.362	440.049	472.736	505.422
p /[MPa]	0.000814					0.000814					
t /[°C]	**4**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2380.4	2445.4	2516.4	2588.4	2661.7	2736.3	2812.4	2890.1	2969.4	3050.4	3133.0
h /[kJ/kg]	2508.2	2594.5	2688.6	2783.7	2880.0	2977.7	3077.0	3177.7	3280.1	3384.1	3489.8
s /[kJ/kgK]	9.051	9.338	9.609	9.848	10.063	10.260	10.441	10.609	10.767	10.916	11.058
v /[m^3/kg]	157.116	183.274	211.659	240.033	268.402	296.770	325.136	353.502	381.867	410.233	438.598

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	0.000935	0.000935									
t /[°C]	**6**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2383.2	2445.3	2516.4	2588.4	2661.7	2736.3	2812.4	2890.1	2969.4	3050.4	3133.0
h /[kJ/kg]	2511.9	2594.4	2688.6	2783.7	2880.0	2977.7	3077.0	3177.7	3280.1	3384.1	3489.8
s /[kJ/kgK]	8.999	9.274	9.545	9.784	9.999	10.195	10.377	10.545	10.703	10.852	10.993
υ /[m^3/kg]	137.633	159.401	184.093	208.773	233.448	258.122	282.794	307.466	332.138	356.810	381.481
p /[MPa]	**0.001**	**0.001**									
t /[°C]	7.0	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2384.5	2445.3	2516.4	2588.4	2661.7	2736.3	2812.4	2890.1	2969.4	3050.4	3133.0
h /[kJ/kg]	2513.7	2594.4	2688.6	2783.7	2880.0	2977.7	3077.0	3177.7	3280.1	3384.1	3489.8
s /[kJ/kgK]	8.975	9.243	9.514	9.753	9.968	10.165	10.346	10.514	10.672	10.821	10.963
υ /[m^3/kg]	129.178	149.093	172.190	195.275	218.356	241.435	264.513	287.590	310.667	333.744	356.820
p /[MPa]	0.00107	0.00107									
t /[°C]	**8**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2385.9	2445.3	2516.4	2588.4	2661.7	2736.3	2812.4	2890.1	2969.4	3050.4	3133.0
h /[kJ/kg]	2515.6	2594.4	2688.5	2783.7	2880.0	2977.7	3077.0	3177.7	3280.1	3384.1	3489.8
s /[kJ/kgK]	8.949	9.210	9.481	9.721	9.936	10.132	10.313	10.482	10.640	10.789	10.930
υ /[m^3/kg]	120.829	138.947	160.475	181.990	203.501	225.010	246.518	268.025	289.532	311.039	332.546
p /[MPa]	0.00123	0.00123									
t /[°C]	**10**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2388.6	2445.3	2516.3	2588.4	2661.6	2736.3	2812.4	2890.1	2969.4	3050.4	3133.0
h /[kJ/kg]	2519.2	2594.4	2688.5	2783.7	2880.0	2977.7	3077.0	3177.7	3280.1	3384.1	3489.8
s /[kJ/kgK]	8.900	9.148	9.419	9.658	9.873	10.070	10.251	10.419	10.577	10.726	10.868
υ /[m^3/kg]	106.303	121.383	140.193	158.990	177.784	196.575	215.365	234.155	252.944	271.733	290.522

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	0.00140	0.00140									
t /[°C]	**12**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2391.4	2445.2	2516.3	2588.4	2661.6	2736.3	2812.4	2890.1	2969.4	3050.3	3133.0
h /[kJ/kg]	2522.9	2594.3	2688.5	2783.6	2880.0	2977.7	3076.9	3177.7	3280.1	3384.1	3489.8
s /[kJ/kgK]	8.851	9.087	9.358	9.597	9.812	10.008	10.189	10.358	10.516	10.665	10.806
υ /[m^3/kg]	93.719	106.266	122.736	139.195	155.649	172.101	188.552	205.003	221.453	237.903	254.353
p /[MPa]	0.00160	0.00160									
t /[°C]	**14**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2394.1	2445.2	2516.3	2588.4	2661.6	2736.3	2812.4	2890.1	2969.4	3050.3	3133.0
h /[kJ/kg]	2526.5	2594.3	2688.5	2783.6	2880.0	2977.7	3076.9	3177.7	3280.1	3384.1	3489.8
s /[kJ/kgK]	8.804	9.026	9.297	9.536	9.752	9.948	10.129	10.298	10.456	10.605	10.746
υ /[m^3/kg]	82.793	93.225	107.678	122.119	136.555	150.990	165.423	179.856	194.289	208.721	223.153
p /[MPa]	0.00182	0.00182									
t /[°C]	**16**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2396.9	2445.1	2516.3	2588.3	2661.6	2736.3	2812.4	2890.1	2969.4	3050.3	3133.0
h /[kJ/kg]	2530.2	2594.2	2688.5	2783.6	2880.0	2977.7	3076.9	3177.7	3280.1	3384.1	3489.8
s /[kJ/kgK]	8.757	8.966	9.238	9.477	9.692	9.888	10.070	10.238	10.396	10.545	10.686
υ /[m^3/kg]	73.286	81.952	94.660	107.357	120.049	132.739	145.428	158.117	170.805	183.493	196.181
p /[MPa]	**0.002**	**0.002**									
t /[°C]	17.5	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2398.9	2445.1	2516.3	2588.3	2661.6	2736.3	2812.4	2890.1	2969.4	3050.3	3133.0
h /[kJ/kg]	2532.9	2594.1	2688.4	2783.6	2880.0	2977.7	3076.9	3177.7	3280.1	3384.1	3489.8
s /[kJ/kgK]	8.723	8.922	9.194	9.433	9.648	9.845	10.026	10.194	10.352	10.501	10.643
υ /[m^3/kg]	66.987	74.524	86.083	97.630	109.172	120.713	132.253	143.792	155.331	166.870	178.409

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	0.00206	0.00206									
t /[°C]	**18**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2399.6	2445.1	2516.3	2588.3	2661.6	2736.3	2812.4	2890.1	2969.4	3050.3	3133.0
h /[kJ/kg]	2533.8	2594.1	2688.4	2783.6	2880.0	2977.7	3076.9	3177.7	3280.1	3384.1	3489.8
s /[kJ/kgK]	8.711	8.908	9.179	9.418	9.634	9.830	10.011	10.180	10.338	10.487	10.628
v /[m^3/kg]	64.998	72.186	83.383	94.568	105.749	116.928	128.107	139.284	150.461	161.638	172.815
p /[MPa]	0.00234	0.00234									
t /[°C]	**20**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2402.3	2445.0	2516.2	2588.3	2661.6	2736.3	2812.4	2890.1	2969.4	3050.3	3133.0
h /[kJ/kg]	2537.4	2594.1	2688.4	2783.6	2879.9	2977.7	3076.9	3177.7	3280.1	3384.1	3489.8
s /[kJ/kgK]	8.666	8.850	9.121	9.361	9.576	9.772	9.953	10.122	10.280	10.429	10.570
v /[m^3/kg]	57.757	63.707	73.593	83.466	93.335	103.203	113.069	122.935	132.800	142.665	152.530
p /[MPa]	0.00265	0.00265									
t /[°C]	**22**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2405.0	2445.0	2516.2	2588.3	2661.6	2736.3	2812.4	2890.1	2969.4	3050.3	3133.0
h /[kJ/kg]	2541.1	2594.0	2688.4	2783.6	2879.9	2977.7	3076.9	3177.7	3280.1	3384.1	3489.8
s /[kJ/kgK]	8.622	8.793	9.064	9.304	9.519	9.716	9.897	10.065	10.223	10.372	10.514
v /[m^3/kg]	51.418	56.332	65.076	73.809	82.537	91.263	99.988	108.712	117.437	126.161	134.884
p /[MPa]	0.00299	0.00299									
t /[°C]	**24**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2407.8	2444.9	2516.2	2588.3	2661.6	2736.3	2812.4	2890.1	2969.4	3050.3	3133.0
h /[kJ/kg]	2544.7	2593.9	2688.3	2783.5	2879.9	2977.7	3076.9	3177.7	3280.1	3384.1	3489.8
s /[kJ/kgK]	8.578	8.737	9.009	9.248	9.463	9.660	9.841	10.009	10.167	10.316	10.458
v /[m^3/kg]	45.858	49.903	57.653	65.391	73.124	80.856	88.586	96.316	104.046	111.775	119.504

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	**0.003**	**0.003**									
t /[°C]	24.1	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2407.9	2444.9	2516.2	2588.3	2661.6	2736.3	2812.4	2890.1	2969.4	3050.3	3133.0
h /[kJ/kg]	2544.8	2593.9	2688.3	2783.5	2879.9	2977.7	3076.9	3177.7	3280.1	3384.1	3489.8
s /[kJ/kgK]	8.576	8.735	9.006	9.246	9.461	9.657	9.839	10.007	10.165	10.314	10.455
v /[m^3/kg]	45.653	49.667	57.380	65.081	72.778	80.473	88.167	95.860	103.553	111.246	118.938
p /[MPa]	0.00336	0.00336									
t /[°C]	**26**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2410.5	2444.8	2516.1	2588.3	2661.6	2736.2	2812.4	2890.1	2969.4	3050.3	3132.9
h /[kJ/kg]	2548.3	2593.8	2688.3	2783.5	2879.9	2977.7	3076.9	3177.7	3280.1	3384.1	3489.8
s /[kJ/kgK]	8.535	8.682	8.953	9.193	9.408	9.605	9.786	9.954	10.112	10.261	10.403
v /[m^3/kg]	40.973	44.289	51.170	58.039	64.904	71.767	78.629	85.490	92.351	99.211	106.072
p /[MPa]	0.00378	0.00378									
t /[°C]	**28**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2413.2	2444.7	2516.1	2588.2	2661.6	2736.2	2812.4	2890.1	2969.4	3050.3	3132.9
h /[kJ/kg]	2551.9	2593.7	2688.2	2783.5	2879.9	2977.6	3076.9	3177.7	3280.0	3384.1	3489.8
s /[kJ/kgK]	8.493	8.627	8.899	9.139	9.354	9.550	9.732	9.900	10.058	10.207	10.348
v /[m^3/kg]	36.672	39.377	45.498	51.607	57.711	63.814	69.916	76.017	82.118	88.218	94.319
p /[MPa]	**0.004**	**0.004**									
t /[°C]	29.0	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2414.5	2444.7	2516.1	2588.2	2661.5	2736.2	2812.4	2890.1	2969.4	3050.3	3132.9
h /[kJ/kg]	2553.7	2593.6	2688.2	2783.5	2879.9	2977.6	3076.9	3177.7	3280.0	3384.1	3489.8
s /[kJ/kgK]	8.473	8.601	8.873	9.113	9.328	9.525	9.706	9.874	10.032	10.181	10.323
v /[m^3/kg]	34.791	37.238	43.029	48.807	54.581	60.353	66.123	71.894	77.664	83.433	89.203

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	0.00425	0.00425									
t /[°C]	**30**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2415.9	2444.6	2516.1	2588.2	2661.5	2736.2	2812.4	2890.1	2969.4	3050.3	3132.9
h /[kJ/kg]	2555.5	2593.5	2688.2	2783.4	2879.9	2977.6	3076.9	3177.7	3280.0	3384.1	3489.8
s /[kJ/kgK]	8.452	8.573	8.846	9.085	9.301	9.497	9.678	9.847	10.005	10.154	10.295
v /[m^3/kg]	32.878	35.070	40.525	45.968	51.406	56.842	62.278	67.713	73.147	78.581	84.015
p /[MPa]	0.00476	0.00476									
t /[°C]	**32**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2418.6	2444.5	2516.0	2588.2	2661.5	2736.2	2812.4	2890.1	2969.4	3050.3	3132.9
h /[kJ/kg]	2559.2	2593.4	2688.1	2783.4	2879.8	2977.6	3076.9	3177.6	3280.0	3384.0	3489.7
s /[kJ/kgK]	8.411	8.520	8.793	9.033	9.248	9.444	9.625	9.794	9.952	10.101	10.242
v /[m^3/kg]	29.526	31.288	36.158	41.015	45.868	50.720	55.570	60.420	65.269	70.118	74.967
p /[MPa]	**0.005**	**0.005**									
t /[°C]	32.9	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2419.8	2444.4	2516.0	2588.2	2661.5	2736.2	2812.4	2890.1	2969.4	3050.3	3132.9
h /[kJ/kg]	2560.7	2593.3	2688.1	2783.4	2879.8	2977.6	3076.9	3177.6	3280.0	3384.0	3489.7
s /[kJ/kgK]	8.394	8.498	8.770	9.010	9.225	9.422	9.603	9.771	9.929	10.078	10.220
v /[m^3/kg]	28.185	29.781	34.418	39.042	43.662	48.280	52.897	57.514	62.130	66.746	71.362
p /[MPa]	0.00533	0.00533									
t /[°C]	**34**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2421.3	2444.4	2515.9	2588.2	2661.5	2736.2	2812.4	2890.1	2969.4	3050.3	3132.9
h /[kJ/kg]	2562.8	2593.3	2688.0	2783.4	2879.8	2977.6	3076.9	3177.6	3280.0	3384.0	3489.7
s /[kJ/kgK]	8.371	8.468	8.741	8.981	9.196	9.392	9.574	9.742	9.900	10.049	10.191
v /[m^3/kg]	26.560	27.961	32.315	36.658	40.996	45.333	49.668	54.003	58.337	62.671	67.006

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	0.00595	0.00595									
t /[°C]	**36**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2424.0	2444.2	2515.9	2588.1	2661.5	2736.2	2812.4	2890.1	2969.4	3050.3	3132.9
h /[kJ/kg]	2566.3	2593.1	2688.0	2783.3	2879.8	2977.6	3076.8	3177.6	3280.0	3384.0	3489.7
s /[kJ/kgK]	8.332	8.417	8.690	8.930	9.145	9.341	9.523	9.691	9.849	9.998	10.140
v /[m^3/kg]	23.929	25.028	28.929	32.818	36.702	40.585	44.466	48.347	52.228	56.108	59.989
p /[MPa]	**0.006**	**0.006**									
t /[°C]	36.2	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2424.2	2444.2	2515.9	2588.1	2661.5	2736.2	2812.4	2890.1	2969.4	3050.3	3132.9
h /[kJ/kg]	2566.6	2593.1	2687.9	2783.3	2879.8	2977.6	3076.8	3177.6	3280.0	3384.0	3489.7
s /[kJ/kgK]	8.329	8.413	8.686	8.925	9.141	9.337	9.519	9.687	9.845	9.994	10.136
v /[m^3/kg]	23.733	24.810	28.677	32.533	36.383	40.232	44.080	47.928	51.774	55.621	59.468
p /[MPa]	0.00663	0.00663									
t /[°C]	**38**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2426.7	2444.1	2515.8	2588.1	2661.5	2736.2	2812.3	2890.1	2969.4	3050.3	3132.9
h /[kJ/kg]	2569.9	2592.9	2687.9	2783.3	2879.8	2977.6	3076.8	3177.6	3280.0	3384.0	3489.7
s /[kJ/kgK]	8.294	8.366	8.639	8.879	9.095	9.291	9.472	9.641	9.799	9.948	10.089
v /[m^3/kg]	21.593	22.438	25.939	29.427	32.911	36.393	39.874	43.354	46.834	50.314	53.794
p /[MPa]	**0.007**	**0.007**									
t /[°C]	39.0	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2428.0	2444.0	2515.8	2588.1	2661.4	2736.2	2812.3	2890.0	2969.4	3050.3	3132.9
h /[kJ/kg]	2571.7	2592.8	2687.8	2783.2	2879.7	2977.5	3076.8	3177.6	3280.0	3384.0	3489.7
s /[kJ/kgK]	8.274	8.341	8.614	8.854	9.070	9.266	9.447	9.616	9.774	9.923	10.064
v /[m^3/kg]	20.524	21.259	24.577	27.883	31.184	34.484	37.782	41.080	44.378	47.675	50.972

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	0.00738	0.00738									
t /[°C]	**40**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2429.4	2443.9	2515.7	2588.0	2661.4	2736.2	2812.3	2890.0	2969.3	3050.3	3132.9
h /[kJ/kg]	2573.5	2592.7	2687.8	2783.2	2879.7	2977.5	3076.8	3177.6	3280.0	3384.0	3489.7
s /[kJ/kgK]	8.256	8.316	8.589	8.829	9.045	9.241	9.423	9.591	9.749	9.898	10.040
v /[m^3/kg]	19.515	20.148	23.295	26.429	29.558	32.686	35.812	38.938	42.064	45.190	48.315
p /[MPa]	**0.008**	**0.008**									
t /[°C]	41.5	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2431.4	2443.8	2515.7	2588.0	2661.4	2736.1	2812.3	2890.0	2969.3	3050.3	3132.9
h /[kJ/kg]	2576.2	2592.5	2687.7	2783.2	2879.7	2977.5	3076.8	3177.6	3280.0	3384.0	3489.7
s /[kJ/kgK]	8.227	8.279	8.552	8.792	9.008	9.205	9.386	9.554	9.712	9.861	10.003
v /[m^3/kg]	18.099	18.596	21.502	24.395	27.285	30.172	33.059	35.944	38.830	41.715	44.600
p /[MPa]	0.00821	0.00821									
t /[°C]	**42**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2432.1	2443.7	2515.7	2588.0	2661.4	2736.1	2812.3	2890.0	2969.3	3050.3	3132.9
h /[kJ/kg]	2577.1	2592.5	2687.7	2783.2	2879.7	2977.5	3076.8	3177.6	3280.0	3384.0	3489.7
s /[kJ/kgK]	8.218	8.266	8.540	8.781	8.996	9.193	9.374	9.542	9.700	9.849	9.991
v /[m^3/kg]	17.664	18.120	20.952	23.772	26.588	29.402	32.215	35.027	37.839	40.650	43.462
p /[MPa]	**0.009**	**0.009**									
t /[°C]	43.8	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2434.4	2443.5	2515.6	2588.0	2661.4	2736.1	2812.3	2890.0	2969.3	3050.3	3132.9
h /[kJ/kg]	2580.2	2592.2	2687.6	2783.1	2879.6	2977.5	3076.8	3177.6	3280.0	3384.0	3489.7
s /[kJ/kgK]	8.186	8.223	8.498	8.738	8.954	9.150	9.331	9.500	9.658	9.807	9.948
v /[m^3/kg]	16.199	16.524	19.110	21.683	24.252	26.819	29.385	31.950	34.515	37.080	39.644

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	0.00911	0.00911									
t /[°C]	**44**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2434.7	2443.5	2515.6	2588.0	2661.4	2736.1	2812.3	2890.0	2969.3	3050.3	3132.9
h /[kJ/kg]	2580.6	2592.2	2687.6	2783.1	2879.6	2977.5	3076.8	3177.6	3280.0	3384.0	3489.7
s /[kJ/kgK]	8.181	8.218	8.492	8.732	8.948	9.144	9.326	9.494	9.652	9.801	9.943
v /[m^3/kg]	16.011	16.320	18.874	21.415	23.953	26.488	29.022	31.556	34.089	36.622	39.155
p /[MPa]	**0.010**	**0.010**									
t /[°C]	45.8	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2437.2	2443.3	2515.5	2587.9	2661.3	2736.1	2812.3	2890.0	2969.3	3050.3	3132.9
h /[kJ/kg]	2583.9	2592.0	2687.5	2783.0	2879.6	2977.4	3076.7	3177.5	3279.9	3384.0	3489.7
s /[kJ/kgK]	8.149	8.174	8.449	8.689	8.905	9.101	9.283	9.451	9.609	9.758	9.900
v /[m^3/kg]	14.670	14.867	17.196	19.513	21.826	24.136	26.446	28.755	31.063	33.371	35.680
p /[MPa]	0.01010	0.01010									
t /[°C]	**46**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2437.4	2443.3	2515.5	2587.9	2661.3	2736.1	2812.3	2890.0	2969.3	3050.3	3132.9
h /[kJ/kg]	2584.2	2591.9	2687.4	2783.0	2879.6	2977.4	3076.7	3177.5	3279.9	3384.0	3489.7
s /[kJ/kgK]	8.145	8.169	8.444	8.685	8.900	9.097	9.278	9.447	9.605	9.754	9.895
v /[m^3/kg]	14.534	14.720	17.027	19.321	21.611	23.898	26.185	28.471	30.757	33.043	35.328
p /[MPa]	**0.011**	**0.011**									
t /[°C]	47.7	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2439.7	2443.1	2515.4	2587.9	2661.3	2736.1	2812.3	2890.0	2969.3	3050.3	3132.9
h /[kJ/kg]	2587.2	2591.7	2687.3	2783.0	2879.6	2977.4	3076.7	3177.5	3279.9	3384.0	3489.7
s /[kJ/kgK]	8.115	8.129	8.405	8.645	8.861	9.057	9.239	9.407	9.565	9.714	9.856
v /[m^3/kg]	13.412	13.511	15.631	17.738	19.840	21.941	24.041	26.140	28.239	30.337	32.436

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	0.01118	0.01118									
t /[°C]	**48**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2440.1	2443.0	2515.4	2587.8	2661.3	2736.1	2812.3	2890.0	2969.3	3050.3	3132.9
h /[kJ/kg]	2587.8	2591.6	2687.3	2783.0	2879.5	2977.4	3076.7	3177.5	3279.9	3384.0	3489.7
s /[kJ/kgK]	8.110	8.122	8.397	8.638	8.853	9.050	9.231	9.400	9.558	9.707	9.848
v /[m^3/kg]	13.212	13.296	15.383	17.457	19.526	21.593	23.660	25.726	27.791	29.857	31.922
p /[MPa]	**0.012**	**0.012**									
t /[°C]	49.4	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
u /[kJ/kg]	2442.0	2442.8	2515.3	2587.8	2661.3	2736.0	2812.2	2890.0	2969.3	3050.2	3132.9
h /[kJ/kg]	2590.3	2591.4	2687.2	2782.9	2879.5	2977.4	3076.7	3177.5	3279.9	3384.0	3489.7
s /[kJ/kgK]	8.085	8.088	8.364	8.605	8.821	9.017	9.198	9.367	9.525	9.674	9.816
v /[m^3/kg]	12.358	12.381	14.326	16.258	18.186	20.112	22.037	23.961	25.885	27.809	29.733
p /[MPa]	0.0124	0.0124									
t /[°C]	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2442.7	2515.3	2587.8	2661.3	2736.0	2812.2	2890.0	2969.3	3050.2	3132.9	3217.2
h /[kJ/kg]	2591.3	2687.2	2782.9	2879.5	2977.4	3076.7	3177.5	3279.9	3384.0	3489.7	3597.1
s /[kJ/kgK]	8.075	8.351	8.591	8.807	9.004	9.185	9.354	9.512	9.661	9.802	9.937
v /[m^3/kg]	12.027	13.917	15.795	17.668	19.539	21.409	23.278	25.148	27.017	28.885	30.754
p /[MPa]	**0.015**	**0.015**									
t /[°C]	54.0	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2448.0	2515.0	2587.6	2661.2	2736.0	2812.2	2889.9	2969.3	3050.2	3132.9	3217.2
h /[kJ/kg]	2598.3	2686.8	2782.7	2879.4	2977.3	3076.6	3177.5	3279.9	3383.9	3489.6	3597.1
s /[kJ/kgK]	8.007	8.260	8.501	8.717	8.914	9.095	9.264	9.422	9.571	9.713	9.847
v /[m^3/kg]	10.020	11.456	13.003	14.547	16.088	17.628	19.168	20.707	22.247	23.785	25.324

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	0.0158	0.0158									
t /[°C]	**55**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2449.3	2514.9	2587.6	2661.1	2735.9	2812.2	2889.9	2969.3	3050.2	3132.8	3217.2
h /[kJ/kg]	2600.1	2686.7	2782.6	2879.3	2977.3	3076.6	3177.4	3279.9	3383.9	3489.6	3597.1
s /[kJ/kgK]	7.990	8.237	8.478	8.694	8.891	9.073	9.241	9.399	9.548	9.690	9.824
v /[m^3/kg]	9.564	10.901	12.374	13.843	15.310	16.776	18.241	19.706	21.171	22.635	24.100
p /[MPa]	0.0199	0.0199									
t /[°C]	**60**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2455.9	2514.5	2587.4	2661.0	2735.8	2812.1	2889.9	2969.2	3050.2	3132.8	3217.2
h /[kJ/kg]	2608.8	2686.2	2782.3	2879.1	2977.1	3076.5	3177.4	3279.8	3383.9	3489.6	3597.0
s /[kJ/kgK]	7.908	8.128	8.369	8.585	8.782	8.964	9.132	9.291	9.440	9.581	9.716
v /[m^3/kg]	7.667	8.609	9.775	10.937	12.096	13.255	14.413	15.571	16.729	17.886	19.044
p /[MPa]	**0.02**	**0.02**									
t /[°C]	60.1	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2456.0	2514.5	2587.4	2661.0	2735.8	2812.1	2889.9	2969.2	3050.2	3132.8	3217.2
h /[kJ/kg]	2608.9	2686.2	2782.3	2879.1	2977.1	3076.5	3177.4	3279.8	3383.9	3489.6	3597.0
s /[kJ/kgK]	7.907	8.126	8.368	8.584	8.781	8.962	9.131	9.289	9.438	9.580	9.714
v /[m^3/kg]	7.648	8.585	9.749	10.907	12.064	13.220	14.375	15.530	16.684	17.838	18.993
p /[MPa]	0.0250	0.0250									
t /[°C]	**65**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2462.4	2514.0	2587.1	2660.8	2735.7	2812.0	2889.8	2969.1	3050.1	3132.8	3217.1
h /[kJ/kg]	2617.5	2685.6	2782.0	2878.9	2977.0	3076.4	3177.3	3279.7	3383.8	3489.5	3597.0
s /[kJ/kgK]	7.830	8.021	8.264	8.480	8.677	8.859	9.027	9.185	9.335	9.476	9.611
v /[m^3/kg]	6.194	6.852	7.783	8.709	9.633	10.557	11.480	12.402	13.324	14.247	15.168

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	**0.03**	**0.03**									
t /[°C]	69.1	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2467.7	2513.5	2586.8	2660.7	2735.6	2811.9	2889.7	2969.1	3050.1	3132.7	3217.1
h /[kJ/kg]	2624.5	2685.0	2781.6	2878.7	2976.8	3076.2	3177.2	3279.6	3383.7	3489.5	3596.9
s /[kJ/kgK]	7.767	7.937	8.180	8.396	8.593	8.775	8.944	9.102	9.251	9.393	9.527
v /[m^3/kg]	5.228	5.715	6.494	7.268	8.040	8.811	9.582	10.352	11.122	11.891	12.661
p /[MPa]	0.0312	0.0312									
t /[°C]	**70**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2468.9	2513.4	2586.8	2660.6	2735.6	2811.9	2889.7	2969.1	3050.1	3132.7	3217.1
h /[kJ/kg]	2626.1	2684.8	2781.5	2878.6	2976.8	3076.2	3177.1	3279.6	3383.7	3489.5	3596.9
s /[kJ/kgK]	7.754	7.918	8.161	8.378	8.575	8.757	8.926	9.084	9.233	9.374	9.509
v /[m^3/kg]	5.040	5.494	6.243	6.988	7.730	8.472	9.213	9.953	10.693	11.434	12.174
p /[MPa]	0.0386	0.0386									
t /[°C]	**75**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2475.2	2512.7	2586.4	2660.4	2735.4	2811.8	2889.6	2969.0	3050.0	3132.7	3217.0
h /[kJ/kg]	2634.6	2683.9	2781.0	2878.3	2976.5	3076.0	3177.0	3279.5	3383.6	3489.4	3596.9
s /[kJ/kgK]	7.681	7.818	8.062	8.279	8.477	8.658	8.827	8.986	9.135	9.276	9.411
v /[m^3/kg]	4.129	4.437	5.044	5.647	6.248	6.847	7.447	8.045	8.644	9.243	9.841
p /[MPa]	**0.04**	**0.04**									
t /[°C]	75.9	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2476.3	2512.5	2586.3	2660.3	2735.4	2811.7	2889.6	2969.0	3050.0	3132.7	3217.0
h /[kJ/kg]	2636.1	2683.7	2780.9	2878.2	2976.5	3076.0	3177.0	3279.5	3383.6	3489.4	3596.8
s /[kJ/kgK]	7.669	7.801	8.046	8.263	8.460	8.642	8.811	8.969	9.118	9.260	9.394
v /[m^3/kg]	3.993	4.280	4.866	5.448	6.028	6.607	7.185	7.763	8.340	8.918	9.495

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	0.0474	0.0474									
t /[°C]	**80**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2481.6	2511.8	2585.9	2660.0	2735.2	2811.6	2889.5	2968.9	3049.9	3132.6	3217.0
h /[kJ/kg]	2643.0	2682.8	2780.4	2877.9	2976.2	3075.8	3176.8	3279.4	3383.5	3489.3	3596.8
s /[kJ/kgK]	7.611	7.721	7.966	8.184	8.381	8.563	8.732	8.890	9.040	9.181	9.316
v /[m^3/kg]	3.405	3.607	4.103	4.594	5.084	5.573	6.061	6.548	7.036	7.523	8.010
p /[MPa]	**0.05**	**0.05**									
t /[°C]	81.3	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2483.2	2511.5	2585.7	2660.0	2735.1	2811.6	2889.4	2968.9	3049.9	3132.6	3217.0
h /[kJ/kg]	2645.2	2682.4	2780.2	2877.8	2976.1	3075.8	3176.8	3279.3	3383.5	3489.3	3596.8
s /[kJ/kgK]	7.593	7.695	7.941	8.159	8.357	8.539	8.708	8.866	9.015	9.157	9.291
v /[m^3/kg]	3.240	3.419	3.890	4.356	4.821	5.284	5.747	6.209	6.672	7.134	7.596
p /[MPa]	0.0579	0.0579									
t /[°C]	**85**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2487.8	2510.7	2585.3	2659.7	2734.9	2811.4	2889.3	2968.8	3049.8	3132.5	3216.9
h /[kJ/kg]	2651.3	2681.4	2779.7	2877.4	2975.9	3075.6	3176.6	3279.2	3383.4	3489.2	3596.7
s /[kJ/kgK]	7.543	7.626	7.873	8.091	8.289	8.471	8.640	8.798	8.948	9.089	9.224
v /[m^3/kg]	2.826	2.950	3.359	3.762	4.164	4.565	4.965	5.365	5.764	6.164	6.563
p /[MPa]	**0.06**	**0.06**									
t /[°C]	85.9	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2489.0	2510.5	2585.2	2659.6	2734.9	2811.4	2889.3	2968.7	3049.8	3132.5	3216.9
h /[kJ/kg]	2652.9	2681.1	2779.5	2877.3	2975.8	3075.5	3176.6	3279.2	3383.3	3489.2	3596.7
s /[kJ/kgK]	7.531	7.608	7.856	8.074	8.272	8.454	8.623	8.782	8.931	9.072	9.207
v /[m^3/kg]	2.732	2.844	3.239	3.628	4.016	4.402	4.788	5.174	5.559	5.944	6.329

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	**0.07**	**0.07**									
t /[°C]	89.9	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2493.9	2509.4	2584.6	2659.3	2734.6	2811.2	2889.2	2968.6	3049.7	3132.4	3216.8
h /[kJ/kg]	2659.4	2679.8	2778.8	2876.8	2975.5	3075.3	3176.4	3279.0	3383.2	3489.1	3596.6
s /[kJ/kgK]	7.479	7.534	7.783	8.002	8.201	8.383	8.552	8.710	8.860	9.001	9.136
v /[m^3/kg]	2.365	2.434	2.774	3.108	3.441	3.773	4.104	4.434	4.765	5.095	5.425
p /[MPa]	0.0702	0.0702									
t /[°C]	**90**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2494.0	2509.4	2584.6	2659.3	2734.6	2811.2	2889.2	2968.6	3049.7	3132.4	3216.8
h /[kJ/kg]	2659.5	2679.8	2778.8	2876.8	2975.5	3075.3	3176.4	3279.0	3383.2	3489.1	3596.6
s /[kJ/kgK]	7.478	7.533	7.782	8.001	8.199	8.382	8.551	8.709	8.858	9.000	9.135
v /[m^3/kg]	2.359	2.428	2.766	3.100	3.432	3.763	4.093	4.423	4.752	5.082	5.411
p /[MPa]	**0.08**	**0.08**									
t /[°C]	93.5	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2498.2	2508.4	2584.1	2658.9	2734.4	2811.0	2889.0	2968.5	3049.6	3132.3	3216.8
h /[kJ/kg]	2665.2	2678.5	2778.1	2876.4	2975.2	3075.0	3176.2	3278.9	3383.1	3488.9	3596.5
s /[kJ/kgK]	7.434	7.470	7.720	7.940	8.138	8.321	8.490	8.648	8.798	8.939	9.074
v /[m^3/kg]	2.087	2.127	2.425	2.718	3.010	3.300	3.590	3.879	4.169	4.458	4.746
p /[MPa]	0.0846	0.0846									
t /[°C]	**95**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2500.0	2507.9	2583.8	2658.7	2734.3	2810.9	2889.0	2968.5	3049.6	3132.3	3216.7
h /[kJ/kg]	2667.6	2677.9	2777.7	2876.2	2975.0	3074.9	3176.1	3278.8	3383.0	3488.9	3596.4
s /[kJ/kgK]	7.415	7.443	7.694	7.914	8.112	8.295	8.464	8.623	8.772	8.913	9.048
v /[m^3/kg]	1.981	2.009	2.292	2.570	2.845	3.120	3.394	3.668	3.941	4.215	4.488

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	**0.09**					**0.09**					
t /[°C]	96.7	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2502.1	2507.3	2583.5	2658.6	2734.1	2810.8	2888.9	2968.4	3049.5	3132.3	3216.7
h /[kJ/kg]	2670.3	2677.1	2777.3	2875.9	2974.8	3074.8	3176.0	3278.7	3383.0	3488.8	3596.4
s /[kJ/kgK]	7.394	7.413	7.665	7.885	8.084	8.266	8.435	8.594	8.743	8.885	9.020
v /[m^3/kg]	1.869	1.887	2.154	2.415	2.674	2.933	3.191	3.448	3.705	3.962	4.219
p /[MPa]	**0.1**					**0.1**					
t /[°C]	99.6	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2505.6	2506.2	2582.9	2658.2	2733.9	2810.6	2888.7	2968.3	3049.4	3132.2	3216.6
h /[kJ/kg]	2674.9	2675.8	2776.6	2875.5	2974.5	3074.5	3175.8	3278.6	3382.8	3488.7	3596.3
s /[kJ/kgK]	7.359	7.361	7.615	7.836	8.035	8.217	8.387	8.545	8.695	8.836	8.971
v /[m^3/kg]	1.694	1.696	1.937	2.172	2.406	2.639	2.871	3.103	3.334	3.566	3.797
p /[MPa]	**0.101325**	Standard atmospheric pressure				**0.101325**					
t /[°C]	99.97	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**
u /[kJ/kg]	2506.0	2506.0	2582.9	2658.2	2733.9	2810.6	2888.7	2968.3	3049.4	3132.2	3216.6
h /[kJ/kg]	2675.5	2675.6	2776.5	2875.4	2974.5	3074.5	3175.8	3278.5	3382.8	3488.7	3596.3
s /[kJ/kgK]	7.354	7.355	7.608	7.829	8.028	8.211	8.380	8.539	8.688	8.830	8.965
v /[m^3/kg]	1.673	1.673	1.911	2.144	2.375	2.604	2.833	3.062	3.291	3.519	3.747
p /[MPa]	0.1014					0.1014					
t /[°C]	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
u /[kJ/kg]	2506.0	2582.9	2658.2	2733.9	2810.6	2888.7	2968.3	3049.4	3132.2	3216.6	3302.8
h /[kJ/kg]	2675.6	2776.5	2875.4	2974.5	3074.5	3175.8	3278.5	3382.8	3488.7	3596.3	3705.6
s /[kJ/kgK]	7.354	7.608	7.829	8.028	8.211	8.380	8.539	8.688	8.830	8.964	9.093
v /[m^3/kg]	1.672	1.909	2.142	2.372	2.602	2.831	3.059	3.288	3.516	3.744	3.972

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	**0.11**	**0.11**									
t /[°C]	102.3	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
u /[kJ/kg]	2508.7	2582.4	2657.9	2733.7	2810.5	2888.6	2968.2	3049.3	3132.1	3216.6	3302.7
h /[kJ/kg]	2679.2	2775.9	2875.0	2974.2	3074.3	3175.6	3278.4	3382.7	3488.6	3596.2	3705.5
s /[kJ/kgK]	7.327	7.569	7.791	7.990	8.173	8.342	8.501	8.650	8.792	8.927	9.056
v /[m^3/kg]	1.549	1.759	1.974	2.187	2.398	2.609	2.820	3.031	3.241	3.451	3.662
p /[MPa]	**0.12**	**0.12**									
t /[°C]	104.8	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
u /[kJ/kg]	2511.7	2581.8	2657.5	2733.4	2810.3	2888.4	2968.1	3049.2	3132.0	3216.5	3302.7
h /[kJ/kg]	2683.1	2775.1	2874.5	2973.9	3074.0	3175.4	3278.3	3382.6	3488.5	3596.1	3705.4
s /[kJ/kgK]	7.298	7.528	7.750	7.949	8.132	8.302	8.461	8.610	8.752	8.887	9.016
v /[m^3/kg]	1.428	1.611	1.808	2.004	2.198	2.392	2.585	2.778	2.971	3.164	3.356
p /[MPa]	**0.13**	**0.13**									
t /[°C]	107.1	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
u /[kJ/kg]	2514.4	2581.2	2657.1	2733.2	2810.1	2888.3	2967.9	3049.1	3131.9	3216.4	3302.6
h /[kJ/kg]	2686.6	2774.4	2874.0	2973.5	3073.8	3175.3	3278.1	3382.5	3488.4	3596.0	3705.3
s /[kJ/kgK]	7.271	7.490	7.712	7.912	8.095	8.265	8.424	8.573	8.715	8.850	8.979
v /[m^3/kg]	1.3250	1.4859	1.6685	1.8490	2.0284	2.2073	2.3858	2.5640	2.7421	2.9201	3.0979
p /[MPa]	0.1434	0.1434									
t /[°C]	**110**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
u /[kJ/kg]	2517.7	2580.5	2656.7	2732.8	2809.9	2888.1	2967.8	3049.0	3131.8	3216.3	3302.5
h /[kJ/kg]	2691.1	2773.4	2873.4	2973.1	3073.5	3175.0	3277.9	3382.3	3488.3	3595.9	3705.2
s /[kJ/kgK]	7.238	7.443	7.666	7.866	8.049	8.219	8.378	8.528	8.669	8.804	8.933
v /[m^3/kg]	1.2090	1.3457	1.5117	1.6757	1.8385	2.0008	2.1628	2.3245	2.4860	2.6474	2.8087

Table E-2 Superheat properties of water substance

	Dry sat.	Superheated									
p /[MPa]	**0.15**	**0.15**									
t /[°C]	111.3	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
u /[kJ/kg]	2519.2	2580.1	2656.4	2732.7	2809.7	2888.0	2967.7	3048.9	3131.8	3216.3	3302.5
h /[kJ/kg]	2693.1	2772.9	2873.1	2972.9	3073.3	3174.9	3277.8	3382.2	3488.2	3595.8	3705.2
s /[kJ/kgK]	7.223	7.421	7.645	7.845	8.028	8.198	8.357	8.507	8.649	8.783	8.912
v /[m^3/kg]	1.1590	1.2855	1.4445	1.6013	1.7571	1.9123	2.0671	2.2217	2.3761	2.5304	2.6846
p /[MPa]	0.1987	0.1987									
t /[°C]	**120**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
u /[kJ/kg]	2528.9	2577.2	2654.7	2731.5	2808.8	2887.3	2967.2	3048.5	3131.4	3216.0	3302.2
h /[kJ/kg]	2705.9	2769.2	2870.8	2971.3	3072.1	3173.9	3277.0	3381.6	3487.7	3595.4	3704.8
s /[kJ/kgK]	7.129	7.284	7.511	7.713	7.897	8.068	8.227	8.376	8.518	8.653	8.782
v /[m^3/kg]	0.891	0.966	1.088	1.207	1.325	1.443	1.560	1.677	1.793	1.910	2.026
p /[MPa]	**0.20**	**0.20**									
t /[°C]	120.2	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
u /[kJ/kg]	2529.1	2577.1	2654.6	2731.4	2808.8	2887.3	2967.1	3048.5	3131.4	3215.9	3302.2
h /[kJ/kg]	2706.2	2769.1	2870.7	2971.2	3072.1	3173.9	3277.0	3381.6	3487.7	3595.4	3704.8
s /[kJ/kgK]	7.127	7.281	7.508	7.710	7.894	8.064	8.224	8.373	8.515	8.650	8.779
v /[m^3/kg]	0.8857	0.9599	1.0805	1.1989	1.3162	1.4330	1.5493	1.6655	1.7814	1.8973	2.0130
p /[MPa]	**0.25**	**0.25**									
t /[°C]	127.4	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
u /[kJ/kg]	2536.8	2574.1	2652.8	2730.2	2807.9	2886.6	2966.6	3048.0	3131.0	3215.6	3301.9
h /[kJ/kg]	2716.5	2765.2	2868.3	2969.5	3070.8	3172.9	3276.2	3380.9	3487.1	3594.9	3704.4
s /[kJ/kgK]	7.052	7.171	7.401	7.605	7.789	7.960	8.120	8.270	8.412	8.547	8.676
v /[m^3/kg]	0.7187	0.7644	0.8621	0.9574	1.0517	1.1454	1.2387	1.3317	1.4246	1.5174	1.6100

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	0.2703	0.2703									
t /[°C]	**130**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
u /[kJ/kg]	2539.5	2572.8	2652.1	2729.7	2807.5	2886.3	2966.3	3047.8	3130.8	3215.5	3301.8
h /[kJ/kg]	2720.1	2763.6	2867.3	2968.9	3070.3	3172.5	3275.9	3380.7	3486.9	3594.8	3704.3
s /[kJ/kgK]	7.026	7.132	7.364	7.568	7.753	7.924	8.083	8.233	8.376	8.511	8.640
v /[m^3/kg]	0.6680	0.7057	0.7965	0.8850	0.9723	1.0590	1.1454	1.2315	1.3175	1.4033	1.4891
p /[MPa]	**0.30**	**0.30**									
t /[°C]	133.5	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
u /[kJ/kg]	2543.2	2571.0	2651.0	2728.9	2807.0	2885.9	2966.0	3047.5	3130.6	3215.3	3301.6
h /[kJ/kg]	2724.9	2761.2	2865.9	2967.9	3069.6	3172.0	3275.5	3380.3	3486.6	3594.5	3704.0
s /[kJ/kgK]	6.992	7.079	7.313	7.518	7.704	7.875	8.035	8.185	8.327	8.462	8.591
v /[m^3/kg]	0.6058	0.6340	0.7164	0.7964	0.8753	0.9536	1.0315	1.1092	1.1867	1.2641	1.3414
p /[MPa]	**0.35**	**0.35**									
t /[°C]	138.9	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
u /[kJ/kg]	2548.5	2567.8	2649.1	2727.7	2806.1	2885.2	2965.4	3047.1	3130.2	3214.9	3301.3
h /[kJ/kg]	2732.0	2757.1	2863.4	2966.2	3068.3	3171.0	3274.7	3379.7	3486.1	3594.0	3703.6
s /[kJ/kgK]	6.940	7.000	7.238	7.444	7.631	7.803	7.963	8.113	8.255	8.391	8.520
v /[m^3/kg]	0.5242	0.5408	0.6124	0.6814	0.7494	0.8167	0.8836	0.9503	1.0168	1.0832	1.1495
p /[MPa]	0.3615	0.3615									
t /[°C]	**140**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
u /[kJ/kg]	2549.6	2567.0	2648.7	2727.4	2805.8	2885.0	2965.3	3046.9	3130.1	3214.8	3301.2
h /[kJ/kg]	2733.4	2756.1	2862.9	2965.8	3068.0	3170.8	3274.5	3379.5	3485.9	3593.9	3703.5
s /[kJ/kgK]	6.929	6.983	7.222	7.429	7.616	7.787	7.948	8.098	8.240	8.376	8.505
v /[m^3/kg]	0.5085	0.5230	0.5925	0.6594	0.7252	0.7904	0.8553	0.9198	0.9843	1.0485	1.1127

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	**0.40**	**0.40**									
t /[°C]	143.6	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
u /[kJ/kg]	2553.1	2564.4	2647.2	2726.4	2805.1	2884.4	2964.9	3046.6	3129.8	3214.6	3301.0
h /[kJ/kg]	2738.1	2752.8	2860.9	2964.5	3067.1	3170.0	3273.9	3379.0	3485.5	3593.6	3703.2
s /[kJ/kgK]	6.895	6.931	7.172	7.380	7.568	7.740	7.900	8.051	8.193	8.329	8.458
v /[m^3/kg]	0.4624	0.4709	0.5343	0.5952	0.6549	0.7140	0.7726	0.8311	0.8894	0.9475	1.0056
p /[MPa]	**0.45**	**0.45**									
t /[°C]	147.9	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
u /[kJ/kg]	2557.1	2560.9	2645.3	2725.1	2804.2	2883.7	2964.3	3046.1	3129.4	3214.2	3300.7
h /[kJ/kg]	2743.4	2748.3	2858.4	2962.8	3065.8	3169.1	3273.1	3378.4	3485.0	3593.1	3702.9
s /[kJ/kgK]	6.856	6.868	7.114	7.324	7.512	7.684	7.845	7.996	8.138	8.274	8.403
v /[m^3/kg]	0.4139	0.4164	0.4736	0.5281	0.5814	0.6341	0.6863	0.7384	0.7902	0.8420	0.8936
p /[MPa]	0.4762	0.4762									
t /[°C]	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**
u /[kJ/kg]	2559.1	2644.3	2724.4	2803.7	2883.3	2964.0	3045.9	3129.2	3214.1	3300.6	3388.8
h /[kJ/kg]	2745.9	2857.1	2961.9	3065.2	3168.5	3272.7	3378.0	3484.7	3592.9	3702.7	3814.1
s /[kJ/kgK]	6.837	7.086	7.296	7.485	7.658	7.818	7.969	8.112	8.248	8.377	8.501
v /[m^3/kg]	0.3925	0.4469	0.4986	0.5491	0.5989	0.6484	0.6976	0.7467	0.7956	0.8444	0.8932
p /[MPa]	**0.5**	**0.5**									
t /[°C]	151.8	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**
u /[kJ/kg]	2560.7	2643.3	2723.8	2803.2	2883.0	2963.7	3045.6	3129.0	3213.9	3300.4	3388.6
h /[kJ/kg]	2748.1	2855.8	2961.0	3064.6	3168.1	3272.3	3377.7	3484.5	3592.7	3702.5	3813.9
s /[kJ/kgK]	6.821	7.061	7.272	7.461	7.635	7.796	7.947	8.089	8.225	8.354	8.478
v /[m^3/kg]	0.3748	0.4250	0.4744	0.5226	0.5702	0.6173	0.6642	0.7109	0.7576	0.8041	0.8505

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	**0.6**	**0.6**									
t /[°C]	158.8	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**
u /[kJ/kg]	2566.8	2639.3	2721.2	2801.4	2881.6	2962.5	3044.7	3128.2	3213.2	3299.8	3388.1
h /[kJ/kg]	2756.1	2850.6	2957.6	3062.0	3166.1	3270.8	3376.5	3483.4	3591.8	3701.7	3813.2
s /[kJ/kgK]	6.759	6.968	7.183	7.374	7.548	7.710	7.861	8.004	8.140	8.270	8.394
v /[m^3/kg]	0.3156	0.3521	0.3939	0.4344	0.4743	0.5137	0.5530	0.5920	0.6309	0.6698	0.7085
p /[MPa]	0.6182	0.6182									
t /[°C]	**160**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**
u /[kJ/kg]	2567.8	2638.6	2720.7	2801.0	2881.3	2962.3	3044.5	3128.1	3213.1	3299.7	3388.0
h /[kJ/kg]	2757.4	2849.6	2956.9	3061.5	3165.8	3270.5	3376.2	3483.2	3591.6	3701.6	3813.1
s /[kJ/kgK]	6.749	6.953	7.168	7.360	7.534	7.696	7.847	7.990	8.126	8.256	8.380
v /[m^3/kg]	0.3068	0.3414	0.3820	0.4214	0.4601	0.4985	0.5365	0.5745	0.6123	0.6500	0.6876
p /[MPa]	**0.7**	**0.7**									
t /[°C]	164.9	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**
u /[kJ/kg]	2571.8	2635.3	2718.6	2799.5	2880.1	2961.4	3043.7	3127.4	3212.5	3299.2	3387.6
h /[kJ/kg]	2762.8	2845.3	2954.0	3059.4	3164.2	3269.2	3375.2	3482.3	3590.9	3700.9	3812.6
s /[kJ/kgK]	6.707	6.888	7.107	7.299	7.475	7.637	7.789	7.932	8.068	8.198	8.322
v /[m^3/kg]	0.2728	0.3000	0.3364	0.3714	0.4058	0.4398	0.4735	0.5070	0.5405	0.5738	0.6071
p /[MPa]	0.7922	0.7922									
t /[°C]	**170**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**
u /[kJ/kg]	2575.7	2631.4	2716.1	2797.7	2878.7	2960.3	3042.8	3126.7	3211.9	3298.7	3387.1
h /[kJ/kg]	2767.9	2840.2	2950.7	3057.1	3162.3	3267.8	3374.0	3481.3	3590.0	3700.2	3811.9
s /[kJ/kgK]	6.665	6.823	7.045	7.239	7.415	7.578	7.730	7.874	8.010	8.140	8.264
v /[m^3/kg]	0.2426	0.2636	0.2962	0.3274	0.3580	0.3881	0.4180	0.4477	0.4773	0.5068	0.5363

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	**0.8**	**0.8**									
t /[°C]	170.4	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**
u /[kJ/kg]	2576.0	2631.0	2715.9	2797.5	2878.6	2960.2	3042.8	3126.6	3211.9	3298.7	3387.1
h /[kJ/kg]	2768.3	2839.7	2950.4	3056.9	3162.2	3267.6	3373.9	3481.3	3590.0	3700.1	3811.9
s /[kJ/kgK]	6.662	6.818	7.040	7.234	7.411	7.573	7.726	7.869	8.005	8.135	8.260
v /[m^3/kg]	0.2403	0.2609	0.2932	0.3242	0.3544	0.3843	0.4139	0.4433	0.4726	0.5019	0.5310
p /[MPa]	**0.9**	**0.9**									
t /[°C]	175.4	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**
u /[kJ/kg]	2579.6	2626.7	2713.1	2795.6	2877.2	2959.0	3041.8	3125.8	3211.2	3298.1	3386.6
h /[kJ/kg]	2773.0	2834.1	2946.8	3054.3	3160.2	3266.1	3372.6	3480.2	3589.0	3699.4	3811.2
s /[kJ/kgK]	6.621	6.754	6.980	7.177	7.354	7.517	7.670	7.814	7.950	8.080	8.205
v /[m^3/kg]	0.2149	0.2304	0.2596	0.2874	0.3145	0.3411	0.3675	0.3938	0.4199	0.4459	0.4718
p /[MPa]	**1.0**	**1.0**									
t /[°C]	179.9	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**
u /[kJ/kg]	2582.7	2622.2	2710.4	2793.6	2875.7	2957.9	3040.9	3125.0	3210.5	3297.5	3386.0
h /[kJ/kg]	2777.1	2828.3	2943.1	3051.6	3158.2	3264.5	3371.3	3479.1	3588.1	3698.6	3810.5
s /[kJ/kgK]	6.585	6.696	6.926	7.125	7.303	7.467	7.620	7.764	7.901	8.031	8.156
v /[m^3/kg]	0.1944	0.2060	0.2327	0.2580	0.2825	0.3066	0.3304	0.3541	0.3777	0.4011	0.4245
p /[MPa]	1.003	1.003									
t /[°C]	**180**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**
u /[kJ/kg]	2582.8	2622.1	2710.3	2793.6	2875.6	2957.8	3040.8	3125.0	3210.5	3297.5	3386.0
h /[kJ/kg]	2777.2	2828.1	2943.0	3051.6	3158.1	3264.4	3371.3	3479.1	3588.1	3698.6	3810.5
s /[kJ/kgK]	6.584	6.694	6.925	7.123	7.302	7.466	7.619	7.763	7.899	8.030	8.154
v /[m^3/kg]	0.1938	0.2054	0.2321	0.2572	0.2817	0.3057	0.3295	0.3531	0.3766	0.4000	0.4233

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	**1.2**					**1.2**					
t /[°C]	188.0	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**
u /[kJ/kg]	2587.8	2612.9	2704.7	2789.7	2872.7	2955.5	3038.9	3123.4	3209.1	3296.3	3385.0
h /[kJ/kg]	2783.7	2816.1	2935.6	3046.3	3154.2	3261.3	3368.7	3476.9	3586.3	3697.0	3809.2
s /[kJ/kgK]	6.522	6.591	6.831	7.033	7.214	7.379	7.533	7.678	7.815	7.946	8.070
v /[m^3/kg]	0.1633	0.1693	0.1924	0.2139	0.2346	0.2548	0.2748	0.2946	0.3143	0.3339	0.3535
p /[MPa]	1.255					1.255					
t /[°C]	**190**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**
u /[kJ/kg]	2589.0	2610.1	2703.1	2788.6	2871.9	2954.9	3038.4	3122.9	3208.7	3296.0	3384.7
h /[kJ/kg]	2785.3	2812.5	2933.5	3044.8	3153.0	3260.4	3368.0	3476.3	3585.8	3696.6	3808.8
s /[kJ/kgK]	6.506	6.564	6.807	7.011	7.192	7.358	7.512	7.657	7.794	7.924	8.049
v /[m^3/kg]	0.1564	0.1612	0.1835	0.2041	0.2240	0.2434	0.2626	0.2816	0.3004	0.3192	0.3379
p /[MPa]	**1.4**					**1.4**					
t /[°C]	195.0	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**
u /[kJ/kg]	2591.8	2602.7	2698.9	2785.7	2869.7	2953.1	3037.0	3121.8	3207.7	3295.1	3384.0
h /[kJ/kg]	2788.8	2803.0	2927.9	3040.9	3150.1	3258.1	3366.1	3474.8	3584.5	3695.4	3807.8
s /[kJ/kgK]	6.467	6.497	6.749	6.955	7.138	7.305	7.459	7.605	7.742	7.873	7.998
v /[m^3/kg]	0.1408	0.1430	0.1636	0.1823	0.2003	0.2178	0.2351	0.2522	0.2691	0.2860	0.3028
p /[MPa]	1.555					1.555					
t /[°C]	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**
u /[kJ/kg]	2594.2	2694.2	2782.5	2867.3	2951.3	3035.5	3120.5	3206.7	3294.2	3383.1	3473.7
h /[kJ/kg]	2792.0	2921.7	3036.7	3146.9	3255.6	3364.1	3473.1	3583.1	3694.2	3806.8	3920.8
s /[kJ/kgK]	6.430	6.691	6.901	7.086	7.253	7.409	7.555	7.692	7.824	7.949	8.069
v /[m^3/kg]	0.1272	0.1463	0.1635	0.1798	0.1957	0.2113	0.2268	0.2421	0.2573	0.2724	0.2875

Table E-2 Superheat properties of water substance

	Dry sat.	Superheated									
p /[MPa]	**1.6**					**1.6**					
t /[°C]	201.4	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**
u /[kJ/kg]	2594.8	2692.9	2781.6	2866.6	2950.7	3035.0	3120.1	3206.3	3293.9	3382.9	3473.5
h /[kJ/kg]	2792.8	2919.9	3035.4	3146.0	3254.9	3363.5	3472.6	3582.6	3693.9	3806.5	3920.5
s /[kJ/kgK]	6.420	6.675	6.886	7.071	7.239	7.395	7.541	7.679	7.810	7.935	8.056
v /[m^3/kg]	0.1237	0.1419	0.1587	0.1746	0.1901	0.2053	0.2203	0.2352	0.2500	0.2647	0.2794
p /[MPa]	**1.8**					**1.8**					
t /[°C]	207.1	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**
u /[kJ/kg]	2597.2	2686.7	2777.4	2863.6	2948.3	3033.1	3118.5	3205.0	3292.7	3381.9	3472.6
h /[kJ/kg]	2795.9	2911.7	3029.9	3141.8	3251.6	3360.9	3470.4	3580.8	3692.3	3805.1	3919.4
s /[kJ/kgK]	6.377	6.609	6.825	7.012	7.181	7.338	7.484	7.623	7.754	7.880	8.000
v /[m^3/kg]	0.11040	0.12502	0.14025	0.15460	0.16849	0.18209	0.19551	0.20880	0.22200	0.23514	0.24821
p /[MPa]	1.908					1.908					
t /[°C]	**210**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**
u /[kJ/kg]	2598.3	2683.2	2775.1	2861.9	2947.0	3032.0	3117.6	3204.2	3292.1	3381.3	3472.1
h /[kJ/kg]	2797.3	2907.2	3026.8	3139.6	3249.9	3359.4	3469.3	3579.8	3691.5	3804.4	3918.7
s /[kJ/kgK]	6.356	6.575	6.794	6.982	7.153	7.310	7.457	7.595	7.727	7.852	7.973
v /[m^3/kg]	0.10430	0.11739	0.13193	0.14557	0.15874	0.17162	0.18432	0.19689	0.20937	0.22177	0.23413
p /[MPa]	**2.0**					**2.0**					
t /[°C]	212.4	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**
u /[kJ/kg]	212.4	2680.2	2773.2	2860.5	2945.9	3031.1	3116.9	3203.6	3291.5	3380.8	3471.6
h /[kJ/kg]	2798.3	2903.2	3024.2	3137.7	3248.3	3358.2	3468.2	3579.0	3690.7	3803.8	3918.2
s /[kJ/kgK]	6.339	6.547	6.768	6.958	7.129	7.287	7.434	7.572	7.704	7.830	7.951
v /[m^3/kg]	0.09959	0.11150	0.12551	0.13860	0.15121	0.16354	0.17568	0.18770	0.19961	0.21146	0.22326

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	2.320	2.320									
t /[°C]	**220**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**
u /[kJ/kg]	2601.2	2669.6	2766.2	2855.4	2942.0	3028.0	3114.3	3201.4	3289.6	3379.2	3470.2
h /[kJ/kg]	2800.9	2889.2	3014.9	3130.9	3243.1	3354.0	3464.7	3576.0	3688.2	3801.6	3916.3
s /[kJ/kgK]	6.284	6.458	6.688	6.882	7.055	7.214	7.362	7.501	7.634	7.760	7.881
v /[m^3/kg]	0.08609	0.09468	0.10721	0.11875	0.12979	0.14054	0.15110	0.16152	0.17185	0.18211	0.19232
p /[MPa]	**2.5**	**2.5**									
t /[°C]	224.0	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**
u /[kJ/kg]	2602.1	2663.3	2762.2	2852.5	2939.8	3026.2	3112.8	3200.1	3288.5	3378.2	3469.3
h /[kJ/kg]	2801.9	2880.9	3009.6	3127.0	3240.1	3351.6	3462.7	3574.3	3686.8	3800.4	3915.2
s /[kJ/kgK]	6.256	6.411	6.646	6.842	7.017	7.177	7.325	7.465	7.598	7.724	7.845
v /[m^3/kg]	0.07995	0.08705	0.09894	0.10979	0.12012	0.13015	0.13999	0.14970	0.15931	0.16886	0.17835
p /[MPa]	2.797	2.797									
t /[°C]	**230**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**
u /[kJ/kg]	2602.9	2652.4	2755.5	2847.7	2936.1	3023.2	3110.3	3198.0	3286.7	3376.6	3468.0
h /[kJ/kg]	2802.9	2866.7	3000.6	3120.5	3235.1	3347.6	3459.5	3571.6	3684.4	3798.3	3913.4
s /[kJ/kgK]	6.213	6.337	6.582	6.783	6.960	7.121	7.270	7.411	7.544	7.671	7.792
v /[m^3/kg]	0.07150	0.07660	0.08763	0.09753	0.10690	0.11596	0.12483	0.13356	0.14219	0.15076	0.15927
p /[MPa]	**3.0**	**3.0**									
t /[°C]	233.9	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**
u /[kJ/kg]	2603.2	2644.7	2750.8	2844.4	2933.5	3021.2	3108.6	3196.6	3285.5	3375.6	3467.0
h /[kJ/kg]	2803.2	2856.5	2994.3	3116.1	3231.7	3344.8	3457.2	3569.7	3682.8	3796.9	3912.2
s /[kJ/kgK]	6.186	6.289	6.541	6.745	6.923	7.086	7.236	7.377	7.510	7.637	7.759
v /[m^3/kg]	0.06666	0.07063	0.08118	0.09056	0.09938	0.10789	0.11620	0.12437	0.13245	0.14045	0.14841

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	3.347	3.347									
t /[°C]	**240**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**
u /[kJ/kg]	2603.1	2630.6	2742.5	2838.6	2929.2	3017.7	3105.7	3194.2	3283.4	3373.8	3465.4
h /[kJ/kg]	2803.0	2838.2	2983.4	3108.3	3225.8	3340.1	3453.4	3566.5	3680.1	3794.6	3910.2
s /[kJ/kgK]	6.142	6.210	6.476	6.685	6.866	7.030	7.182	7.323	7.457	7.585	7.707
v /[m^3/kg]	0.05970	0.06203	0.07195	0.08058	0.08862	0.09634	0.10386	0.11124	0.11852	0.12573	0.13289
p /[MPa]	**3.5**	**3.5**									
t /[°C]	242.6	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**
u /[kJ/kg]	2602.9	2624.0	2738.8	2836.0	2927.2	3016.1	3104.5	3193.1	3282.5	3372.9	3464.7
h /[kJ/kg]	2802.6	2829.7	2978.4	3104.8	3223.2	3338.0	3451.6	3565.0	3678.9	3793.5	3909.3
s /[kJ/kgK]	6.124	6.176	6.448	6.660	6.843	7.007	7.159	7.301	7.436	7.563	7.685
v /[m^3/kg]	0.05706	0.05876	0.06845	0.07680	0.08456	0.09198	0.09919	0.10627	0.11325	0.12016	0.12702
p /[MPa]	3.976	3.976									
t /[°C]	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**
u /[kJ/kg]	2601.8	2726.8	2827.8	2921.1	3011.2	3100.5	3189.7	3279.6	3370.4	3462.5	3555.9
h /[kJ/kg]	2800.9	2962.5	3093.9	3214.9	3331.5	3446.3	3560.6	3675.1	3790.2	3906.4	4023.8
s /[kJ/kgK]	6.072	6.368	6.588	6.775	6.942	7.095	7.238	7.373	7.502	7.624	7.742
v /[m^3/kg]	0.05008	0.05927	0.06691	0.07390	0.08054	0.08698	0.09327	0.09946	0.10558	0.11165	0.11767
p /[MPa]	**4.0**	**4.0**									
t /[°C]	250.4	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**
u /[kJ/kg]	2601.7	2726.2	2827.4	2920.7	3011.0	3100.3	3189.5	3279.4	3370.3	3462.4	3555.8
h /[kJ/kg]	2800.8	2961.7	3093.3	3214.5	3331.2	3446.0	3560.3	3674.9	3790.1	3906.3	4023.6
s /[kJ/kgK]	6.070	6.364	6.584	6.771	6.939	7.092	7.235	7.371	7.499	7.621	7.739
v /[m^3/kg]	0.04978	0.05887	0.06647	0.07343	0.08004	0.08644	0.09270	0.09886	0.10494	0.11098	0.11697

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	**4.5**	**4.5**									
t /[°C]	257.4	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**
u /[kJ/kg]	2599.7	2713.0	2818.6	2914.2	3005.8	3096.0	3186.0	3276.4	3367.7	3460.0	3553.7
h /[kJ/kg]	2797.9	2944.2	3081.5	3205.6	3324.2	3440.4	3555.6	3670.9	3786.6	3903.3	4021.0
s /[kJ/kgK]	6.020	6.285	6.515	6.707	6.877	7.032	7.177	7.313	7.442	7.565	7.683
v /[m^3/kg]	0.04406	0.05138	0.05842	0.06477	0.07076	0.07652	0.08214	0.08766	0.09311	0.09850	0.10385
p /[MPa]	4.692	4.692									
t /[°C]	**260**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**
u /[kJ/kg]	2598.7	2707.7	2815.1	2911.6	3003.8	3094.4	3184.6	3275.2	3366.6	3459.1	3552.9
h /[kJ/kg]	2796.6	2937.2	3076.8	3202.2	3321.5	3438.2	3553.8	3669.3	3785.3	3902.1	4020.0
s /[kJ/kgK]	6.002	6.256	6.490	6.684	6.855	7.011	7.156	7.292	7.421	7.544	7.663
v /[m^3/kg]	0.04217	0.04891	0.05578	0.06193	0.06771	0.07327	0.07868	0.08399	0.08923	0.09441	0.09955
p /[MPa]	**5**	**5**									
t /[°C]	263.9	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**
u /[kJ/kg]	2597.0	2699.0	2809.5	2907.5	3000.6	3091.7	3182.4	3273.3	3365.0	3457.7	3551.6
h /[kJ/kg]	2794.2	2925.7	3069.3	3196.7	3317.2	3434.7	3550.9	3666.8	3783.2	3900.3	4018.4
s /[kJ/kgK]	5.974	6.211	6.452	6.648	6.821	6.978	7.124	7.261	7.390	7.514	7.632
v /[m^3/kg]	0.03945	0.04535	0.05197	0.05784	0.06332	0.06858	0.07369	0.07870	0.08364	0.08852	0.09335
p /[MPa]	5.503	5.503									
t /[°C]	**270**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**
u /[kJ/kg]	2593.7	2684.1	2800.0	2900.6	2995.2	3087.4	3178.8	3270.2	3362.3	3455.3	3549.5
h /[kJ/kg]	2789.7	2906.1	3056.7	3187.5	3310.1	3428.9	3546.1	3662.8	3779.7	3897.3	4015.8
s /[kJ/kgK]	5.930	6.139	6.392	6.594	6.769	6.928	7.075	7.213	7.343	7.467	7.586
v /[m^3/kg]	0.03562	0.04035	0.04665	0.05213	0.05721	0.06205	0.06674	0.07133	0.07585	0.08031	0.08472

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	**6**	**6**									
t /[°C]	275.6	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**
u /[kJ/kg]	2589.9	2668.4	2790.4	2893.7	2989.9	3083.1	3175.2	3267.2	3359.6	3453.0	3547.5
h /[kJ/kg]	2784.6	2885.5	3043.9	3178.2	3302.9	3423.1	3541.3	3658.7	3776.2	3894.3	4013.2
s /[kJ/kgK]	5.890	6.070	6.336	6.543	6.722	6.883	7.031	7.169	7.300	7.425	7.544
v /[m^3/kg]	0.03245	0.03619	0.04225	0.04742	0.05217	0.05667	0.06102	0.06527	0.06943	0.07355	0.07761
p /[MPa]	6.417	6.417									
t /[°C]	**280**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**
u /[kJ/kg]	2586.4	2654.5	2782.1	2887.8	2985.4	3079.4	3172.1	3264.6	3357.4	3451.0	3545.7
h /[kJ/kg]	2779.9	2867.3	3032.9	3170.4	3296.9	3418.3	3537.3	3655.4	3773.3	3891.8	4011.0
s /[kJ/kgK]	5.858	6.013	6.291	6.503	6.685	6.847	6.996	7.135	7.267	7.392	7.511
v /[m^3/kg]	0.03015	0.03317	0.03908	0.04403	0.04854	0.05280	0.05691	0.06090	0.06482	0.06868	0.07250
p /[MPa]	**7**	**7**									
t /[°C]	285.8	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**
u /[kJ/kg]	2581.0	2633.5	2770.1	2879.5	2979.0	3074.3	3167.9	3260.9	3354.3	3448.3	3543.3
h /[kJ/kg]	2772.6	2839.9	3016.9	3159.2	3288.3	3411.4	3531.6	3650.6	3769.3	3888.2	4007.9
s /[kJ/kgK]	5.815	5.934	6.230	6.450	6.635	6.800	6.951	7.091	7.223	7.349	7.469
v /[m^3/kg]	0.02738	0.02949	0.03526	0.03996	0.04419	0.04816	0.05197	0.05566	0.05929	0.06285	0.06637
p /[MPa]	7.442	7.442									
t /[°C]	**290**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**
u /[kJ/kg]	2576.5	2616.2	2760.7	2873.0	2974.1	3070.4	3164.6	3258.2	3351.9	3446.2	3541.4
h /[kJ/kg]	2766.7	2817.5	3004.4	3150.5	3281.7	3406.2	3527.3	3647.0	3766.2	3885.6	4005.6
s /[kJ/kgK]	5.783	5.873	6.186	6.412	6.600	6.767	6.918	7.060	7.192	7.318	7.438
v /[m^3/kg]	0.02555	0.02705	0.03276	0.03729	0.04134	0.04512	0.04874	0.05224	0.05567	0.05904	0.06237

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	**8**	**8**									
t /[°C]	295.0	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**
u /[kJ/kg]	2570.5	2592.3	2748.3	2864.6	2967.8	3065.4	3160.5	3254.7	3348.9	3443.6	3539.1
h /[kJ/kg]	2758.7	2786.5	2988.1	3139.4	3273.3	3399.5	3521.8	3642.4	3762.3	3882.2	4002.6
s /[kJ/kgK]	5.745	5.794	6.132	6.366	6.558	6.727	6.880	7.022	7.156	7.282	7.403
v /[m^3/kg]	0.02353	0.02428	0.02997	0.03434	0.03819	0.04177	0.04517	0.04846	0.05168	0.05483	0.05794
p /[MPa]	8.588	8.588									
t /[°C]	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2563.6	2734.8	2855.6	2961.1	3060.0	3156.1	3251.0	3345.7	3440.8	3536.6	3633.5
h /[kJ/kg]	2749.6	2970.3	3127.4	3264.4	3392.4	3516.0	3637.5	3758.1	3878.6	3999.5	4121.1
s /[kJ/kgK]	5.706	6.076	6.319	6.516	6.687	6.842	6.985	7.119	7.247	7.368	7.484
v /[m^3/kg]	0.02166	0.02742	0.03165	0.03532	0.03870	0.04191	0.04501	0.04803	0.05098	0.05390	0.05677
p /[MPa]	**9**	**9**									
t /[°C]	303.3	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2558.5	2724.9	2849.2	2956.3	3056.3	3153.0	3248.4	3343.4	3438.8	3534.9	3632.0
h /[kJ/kg]	2742.9	2957.3	3118.8	3258.0	3387.4	3512.0	3634.1	3755.2	3876.1	3997.3	4119.1
s /[kJ/kgK]	5.679	6.038	6.288	6.487	6.660	6.816	6.960	7.095	7.223	7.344	7.461
v /[m^3/kg]	0.02049	0.02582	0.02996	0.03352	0.03679	0.03989	0.04286	0.04575	0.04859	0.05138	0.05413
p /[MPa]	9.865	9.865									
t /[°C]	**310**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2547.1	2703.2	2835.3	2946.1	3048.3	3146.4	3242.8	3338.7	3434.7	3531.2	3628.7
h /[kJ/kg]	2727.9	2928.7	3100.4	3244.5	3376.8	3503.3	3626.9	3749.1	3870.8	3992.7	4115.1
s /[kJ/kgK]	5.624	5.958	6.224	6.430	6.607	6.766	6.912	7.048	7.176	7.298	7.415
v /[m^3/kg]	0.01833	0.02286	0.02687	0.03024	0.03330	0.03618	0.03893	0.04160	0.04421	0.04678	0.04931

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	**10**	**10**									
t /[°C]	311.0	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2545.2	2699.6	2833.1	2944.5	3047.0	3145.4	3242.0	3337.9	3434.0	3530.7	3628.2
h /[kJ/kg]	2725.5	2924.0	3097.4	3242.3	3375.1	3502.0	3625.8	3748.1	3870.0	3992.0	4114.5
s /[kJ/kgK]	5.616	5.946	6.214	6.422	6.599	6.758	6.904	7.041	7.169	7.292	7.408
v /[m^3/kg]	0.01803	0.02244	0.02644	0.02978	0.03281	0.03565	0.03838	0.04102	0.04360	0.04613	0.04863
p /[MPa]	**11**	**11**									
t /[°C]	318.1	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2530.5	2672.0	2816.3	2932.4	3037.6	3137.8	3235.6	3332.4	3429.2	3526.4	3624.4
h /[kJ/kg]	2706.3	2887.9	3075.2	3226.3	3362.7	3491.9	3617.4	3741.0	3863.9	3986.7	4109.8
s /[kJ/kgK]	5.554	5.854	6.144	6.361	6.543	6.705	6.853	6.991	7.120	7.243	7.361
v /[m^3/kg]	0.01599	0.01963	0.02354	0.02671	0.02955	0.03219	0.03471	0.03714	0.03951	0.04184	0.04413
p /[MPa]	11.284	11.284									
t /[°C]	**320**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2526.0	2663.6	2811.4	2928.9	3034.9	3135.6	3233.7	3330.9	3427.9	3525.2	3623.3
h /[kJ/kg]	2700.6	2877.0	3068.7	3221.6	3359.1	3489.0	3615.0	3739.0	3862.1	3985.1	4108.5
s /[kJ/kgK]	5.537	5.828	6.125	6.344	6.528	6.691	6.839	6.977	7.107	7.230	7.348
v /[m^3/kg]	0.015	0.019	0.023	0.026	0.029	0.031	0.034	0.036	0.038	0.041	0.043
p /[MPa]	**12**	**12**									
t /[°C]	324.7	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2514.3	2641.4	2798.7	2920.0	3028.1	3130.0	3229.1	3326.9	3424.4	3522.2	3620.6
h /[kJ/kg]	2685.4	2848.1	3052.0	3209.8	3350.0	3481.7	3608.9	3733.8	3857.7	3981.3	4105.1
s /[kJ/kgK]	5.494	5.761	6.076	6.303	6.490	6.655	6.805	6.945	7.075	7.199	7.317
v /[m^3/kg]	0.01426	0.01722	0.02111	0.02415	0.02683	0.02930	0.03165	0.03391	0.03611	0.03826	0.04037

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	12.858	12.858									
t /[°C]	**330**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2499.2	2612.3	2783.0	2909.1	3019.7	3123.3	3223.5	3322.1	3420.2	3518.5	3617.4
h /[kJ/kg]	2666.0	2810.3	3031.2	3195.4	3339.0	3472.8	3601.6	3727.7	3852.4	3976.7	4101.1
s /[kJ/kgK]	5.442	5.678	6.020	6.255	6.447	6.615	6.767	6.907	7.039	7.164	7.282
v /[m^3/kg]	0.01298	0.01540	0.01931	0.02226	0.02483	0.02718	0.02941	0.03154	0.03361	0.03563	0.03762
p /[MPa]	**13**	**13**									
t /[°C]	330.9	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2496.5	2607.2	2780.3	2907.3	3018.3	3122.2	3222.5	3321.3	3419.6	3517.9	3616.9
h /[kJ/kg]	2662.7	2803.7	3027.7	3193.0	3337.1	3471.3	3600.4	3726.6	3851.5	3976.0	4100.4
s /[kJ/kgK]	5.434	5.664	6.011	6.248	6.440	6.609	6.761	6.902	7.033	7.158	7.277
v /[m^3/kg]	0.01278	0.01512	0.01903	0.02197	0.02452	0.02686	0.02906	0.03118	0.03323	0.03523	0.03720
p /[MPa]	**14**	**14**									
t /[°C]	336.7	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2477.1	2567.8	2761.0	2894.2	3008.4	3114.2	3216.0	3315.7	3414.7	3513.7	3613.1
h /[kJ/kg]	2637.9	2753.1	3002.3	3175.7	3324.1	3460.9	3591.8	3719.4	3845.3	3970.6	4095.8
s /[kJ/kgK]	5.373	5.560	5.946	6.195	6.393	6.565	6.719	6.861	6.994	7.120	7.239
v /[m^3/kg]	0.01149	0.01323	0.01724	0.02010	0.02254	0.02476	0.02684	0.02884	0.03076	0.03264	0.03448
p /[MPa]	14.601	14.601									
t /[°C]	**340**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2464.4	2540.8	2748.9	2886.2	3002.4	3109.4	3212.0	3312.3	3411.8	3511.1	3610.8
h /[kJ/kg]	2621.8	2718.5	2986.5	3165.1	3316.1	3454.6	3586.6	3715.0	3841.6	3967.4	4092.9
s /[kJ/kgK]	5.336	5.492	5.907	6.164	6.366	6.539	6.695	6.838	6.972	7.098	7.218
v /[m^3/kg]	0.01078	0.01217	0.01627	0.01910	0.02149	0.02364	0.02566	0.02758	0.02944	0.03125	0.03302

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**									
p /[MPa]	**15**	**15**									
t /[°C]	342.2	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2455.6	2520.9	2740.6	2880.7	2998.4	3106.2	3209.3	3310.1	3409.8	3509.4	3609.2
h /[kJ/kg]	2610.7	2693.1	2975.7	3157.9	3310.8	3450.4	3583.1	3712.1	3839.1	3965.2	4091.1
s /[kJ/kgK]	5.311	5.444	5.882	6.143	6.348	6.523	6.680	6.823	6.957	7.084	7.204
v /[m^3/kg]	0.01034	0.01148	0.01567	0.01848	0.02083	0.02294	0.02492	0.02680	0.02862	0.03039	0.03212
p /[MPa]	**16**	**16**									
t /[°C]	347.4	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2431.8	2460.7	2719.1	2866.9	2988.1	3098.1	3202.6	3304.4	3404.9	3505.1	3605.4
h /[kJ/kg]	2580.8	2617.0	2947.6	3139.7	3297.3	3439.8	3574.4	3704.8	3832.9	3959.8	4086.3
s /[kJ/kgK]	5.246	5.304	5.818	6.094	6.305	6.483	6.642	6.787	6.922	7.050	7.170
v /[m^3/kg]	0.00931	0.00977	0.01428	0.01705	0.01932	0.02135	0.02324	0.02503	0.02675	0.02842	0.03006
p /[MPa]	16.529	16.529									
t /[°C]	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**	
u /[kJ/kg]	2418.1	2707.1	2859.4	2982.6	3093.8	3199.1	3301.4	3402.3	3502.8	3603.4	
h /[kJ/kg]	2563.6	2932.1	3129.8	3290.1	3434.1	3569.8	3700.9	3829.6	3957.0	4083.9	
s /[kJ/kgK]	5.211	5.784	6.068	6.282	6.463	6.623	6.769	6.905	7.032	7.153	
v /[m^3/kg]	0.00880	0.01361	0.01636	0.01860	0.02059	0.02243	0.02417	0.02585	0.02748	0.02907	
p /[MPa]	**17**	**17**									
t /[°C]	352.3	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**	
u /[kJ/kg]	2405.2	2696.2	2852.7	2977.7	3089.9	3195.9	3298.7	3400.0	3500.8	3601.6	
h /[kJ/kg]	2547.5	2917.9	3121.0	3283.6	3429.0	3565.7	3697.5	3826.6	3954.4	4081.6	
s /[kJ/kgK]	5.179	5.754	6.045	6.263	6.445	6.606	6.753	6.889	7.017	7.139	
v /[m^3/kg]	0.00837	0.01304	0.01578	0.01799	0.01995	0.02175	0.02346	0.02510	0.02669	0.02824	

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**								
p /[MPa]	**18**	**18**								
t /[°C]	357.0	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2374.8	2671.9	2838.0	2967.1	3081.6	3189.1	3292.9	3395.0	3496.4	3597.8
h /[kJ/kg]	2509.8	2886.4	3101.8	3269.7	3418.2	3556.8	3690.1	3820.4	3949.0	4076.9
s /[kJ/kgK]	5.106	5.688	5.998	6.222	6.408	6.572	6.720	6.858	6.987	7.109
v /[m^3/kg]	0.00750	0.01192	0.01465	0.01681	0.01870	0.02043	0.02206	0.02363	0.02514	0.02662
p /[MPa]	18.666	18.666								
t /[°C]	**360**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2351.8	2654.8	2827.9	2959.9	3076.0	3184.5	3289.1	3391.7	3493.5	3595.2
h /[kJ/kg]	2481.5	2864.3	3088.7	3260.3	3410.9	3550.9	3685.2	3816.2	3945.4	4073.8
s /[kJ/kgK]	5.054	5.644	5.966	6.196	6.385	6.550	6.700	6.838	6.967	7.090
v /[m^3/kg]	0.00695	0.01122	0.01397	0.01609	0.01794	0.01963	0.02122	0.02274	0.02421	0.02564
p /[MPa]	**19**	**19**								
t /[°C]	361.5	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2339.1	2645.9	2822.8	2956.3	3073.2	3182.2	3287.2	3390.1	3492.1	3593.9
h /[kJ/kg]	2466.0	2852.8	3082.0	3255.5	3407.2	3548.0	3682.7	3814.1	3943.6	4072.2
s /[kJ/kgK]	5.026	5.621	5.951	6.183	6.373	6.539	6.689	6.828	6.958	7.080
v /[m^3/kg]	0.00668	0.01089	0.01364	0.01575	0.01758	0.01925	0.02082	0.02232	0.02376	0.02517
p /[MPa]	**20**	**20**								
t /[°C]	365.7	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2295.0	2617.9	2807.2	2945.3	3064.7	3175.3	3281.4	3385.1	3487.7	3590.1
h /[kJ/kg]	2412.3	2816.9	3061.7	3241.2	3396.1	3539.0	3675.3	3807.8	3938.1	4067.5
s /[kJ/kgK]	4.931	5.553	5.904	6.145	6.339	6.507	6.659	6.799	6.930	7.053
v /[m^3/kg]	0.00587	0.00995	0.01272	0.01479	0.01657	0.01818	0.01969	0.02113	0.02252	0.02387

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**								
p /[MPa]	**20.5**	**20.5**								
t /[°C]	367.8	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2267.6	2603.0	2799.3	2939.7	3060.4	3171.8	3278.5	3382.6	3485.6	3588.1
h /[kJ/kg]	2379.2	2797.8	3051.3	3233.9	3390.6	3534.5	3671.5	3804.6	3935.4	4065.1
s /[kJ/kgK]	4.875	5.517	5.881	6.126	6.322	6.492	6.645	6.785	6.916	7.040
v /[m^3/kg]	0.00545	0.00951	0.01229	0.01435	0.01610	0.01769	0.01917	0.02059	0.02195	0.02327
p /[MPa]	**21**	**21**								
t /[°C]	369.8	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2233.7	2587.4	2791.1	2934.1	3056.1	3168.4	3275.5	3380.1	3483.4	3586.2
h /[kJ/kg]	2338.6	2778.0	3040.7	3226.6	3385.0	3530.0	3667.8	3801.4	3932.7	4062.7
s /[kJ/kgK]	4.808	5.481	5.858	6.107	6.306	6.477	6.630	6.771	6.903	7.027
v /[m^3/kg]	0.00500	0.00908	0.01189	0.01393	0.01566	0.01722	0.01868	0.02006	0.02140	0.02269
p /[MPa]	21.044	21.044								
t /[°C]	**370**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2230.3	2586.1	2790.4	2933.6	3055.8	3168.1	3275.3	3379.9	3483.2	3586.0
h /[kJ/kg]	2334.5	2776.3	3039.8	3225.9	3384.5	3529.6	3667.5	3801.2	3932.5	4062.5
s /[kJ/kgK]	4.801	5.478	5.856	6.106	6.304	6.476	6.629	6.770	6.902	7.026
v /[m^3/kg]	0.00495	0.00904	0.01185	0.01389	0.01562	0.01718	0.01864	0.02002	0.02135	0.02264
p /[MPa]	**21.5**	**21.5**								
t /[°C]	371.8	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2186.9	2571.2	2782.9	2928.5	3051.8	3164.9	3272.6	3377.6	3481.2	3584.3
h /[kJ/kg]	2283.1	2757.4	3030.1	3219.2	3379.3	3525.5	3664.1	3798.3	3930.0	4060.4
s /[kJ/kgK]	4.718	5.443	5.836	6.089	6.290	6.462	6.616	6.758	6.890	7.014
v /[m^3/kg]	0.00447	0.00866	0.01150	0.01352	0.01523	0.01677	0.01821	0.01957	0.02087	0.02214

Table E-2 Superheat properties of water substance

	Dry sat.	**Superheated**								
p /[MPa]	**21.8**	**21.8**								
t /[°C]	372.9	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2144.2	2561.1	2777.9	2925.0	3049.2	3162.8	3270.9	3376.1	3479.9	3583.1
h /[kJ/kg]	2232.9	2744.5	3023.6	3214.8	3375.9	3522.8	3661.8	3796.4	3928.3	4058.9
s /[kJ/kgK]	4.638	5.421	5.822	6.078	6.280	6.453	6.608	6.750	6.882	7.007
v /[m^3/kg]	0.00407	0.00842	0.01127	0.01329	0.01499	0.01652	0.01793	0.01928	0.02057	0.02183
p /[MPa]	**22**	**22**								
t /[°C]	373.7	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2092.8	2554.2	2774.5	2922.7	3047.4	3161.3	3269.7	3375.1	3479.0	3582.4
h /[kJ/kg]	2173.1	2735.8	3019.2	3211.8	3373.7	3521.0	3660.3	3795.1	3927.3	4058.0
s /[kJ/kgK]	4.545	5.405	5.813	6.071	6.274	6.447	6.603	6.745	6.877	7.002
v /[m^3/kg]	0.00365	0.00826	0.01112	0.01314	0.01483	0.01635	0.01776	0.01909	0.02038	0.02162
p /[MPa]	22.064	Critical pressure 22.064								
t /[°C]	373.946	400	450	500	550	600	650	700	750	800
u /[kJ/kg]	2015.7	2551.9	2773.4	2922.0	3046.9	3160.9	3269.3	3374.7	3478.7	3582.1
h /[kJ/kg]	2084.3	2732.9	3017.8	3210.8	3373.0	3520.4	3659.8	3794.7	3926.9	4057.7
s /[kJ/kgK]	4.407	5.400	5.810	6.068	6.272	6.445	6.601	6.743	6.876	7.000
v /[m^3/kg]	0.00311	0.00820	0.01108	0.01309	0.01478	0.01629	0.01770	0.01903	0.02031	0.02155

Table E-3 High and supercritical pressure properties of water substance

p /[MPa]					**1**			higher temperatures ⟶	
t /[°C]	**0.01**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
u /[kJ/kg]	0.0	209.2	418.8	631.4	2622.2	2710.4	2793.6	2875.7	2957.9
h /[kJ/kg]	1.0	210.2	419.8	632.5	2828.3	2943.1	3051.6	3158.2	3264.5
s /[kJ/kgK]	0.000	**0.703**	1.307	1.841	6.696	6.926	7.125	7.303	7.467
v /[m^3/kg]	0.001000	0.001012	0.001043	0.001090	0.206022	0.232747	0.257988	0.282504	0.306606
p /[MPa]					**2**			higher temperatures ⟶	
t /[°C]	**0.01**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
u /[kJ/kg]	0.0	209.0	418.5	630.9	850.1	2680.2	2773.2	2860.5	2945.9
h /[kJ/kg]	2.0	211.1	420.6	633.1	852.5	2903.2	3024.2	3137.7	3248.3
s /[kJ/kgK]	0.000	0.703	1.306	1.840	2.330	6.547	6.768	6.958	7.129
v /[m^3/kg]	0.000999	0.001011	0.001042	0.001089	0.001156	0.111496	0.125507	0.138600	0.151215
p /[MPa]					**4**			higher temperatures ⟶	
t /[°C]	**0.01**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
u /[kJ/kg]	0.1	208.7	417.9	630.0	848.6	1080.8	2726.2	2827.4	2920.7
h /[kJ/kg]	4.1	212.8	422.1	634.4	853.3	1085.8	2961.7	3093.3	3214.5
s /[kJ/kgK]	0.000	0.702	1.304	1.838	2.327	2.793	6.364	6.584	6.771
v /[m^3/kg]	0.000998	0.001010	0.001041	0.001088	0.001154	0.001252	0.058870	0.066473	0.073431
p /[MPa]					**6**			higher temperatures ⟶	
t /[°C]	**0.01**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
u /[kJ/kg]	0.1	208.4	417.4	629.1	847.2	1078.2	2668.4	2790.4	2893.7
h /[kJ/kg]	6.1	214.5	423.6	635.6	854.1	1085.7	2885.5	3043.9	3178.2
s /[kJ/kgK]	0.000	0.701	1.303	1.836	2.324	2.789	6.070	6.336	6.543
v /[m^3/kg]	0.000997	0.001009	0.001040	0.001087	0.001152	0.001248	0.036189	0.042251	0.047419

Table E-3 High and supercritical pressure properties of water substance

p /[MPa]	⟵ lower temperatures				**1**				
t /[°C]	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2957.9	3040.9	3125.0	3210.5	3297.5	3386.0	3476.2	3568.1	3661.7
h /[kJ/kg]	3264.5	3371.3	3479.1	3588.1	3698.6	3810.5	3924.1	4039.3	4156.1
s /[kJ/kgK]	7.467	7.620	7.764	7.901	8.031	8.156	8.275	6.000	2.000
v /[m^3/kg]	0.306606	0.330447	0.354113	0.377655	0.401108	0.424494	0.447828	0.471121	0.000000
p /[MPa]	⟵ lower temperatures				**2**				
t /[°C]	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2945.9	3031.1	3116.9	3203.6	3291.5	3380.8	3471.6	3564.0	3658.0
h /[kJ/kg]	3248.3	3358.2	3468.2	3579.0	3690.7	3803.8	3918.2	4034.1	4151.5
s /[kJ/kgK]	7.129	7.287	7.434	7.572	7.704	7.830	7.951	8.067	8.179
v /[m^3/kg]	0.151215	0.163542	0.175683	0.187695	0.199615	0.211465	0.223262	0.235019	0.246743
p /[MPa]	⟵ lower temperatures				**4**				
t /[°C]	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2920.7	3011.0	3100.3	3189.5	3279.4	3370.3	3462.4	3555.8	3650.6
h /[kJ/kg]	3214.5	3331.2	3446.0	3560.3	3674.9	3790.1	3906.3	4023.6	4142.3
s /[kJ/kgK]	6.771	6.939	7.092	7.235	7.371	7.499	7.621	7.739	7.852
v /[m^3/kg]	0.073431	0.080043	0.086442	0.092700	0.098859	0.104945	0.110976	0.116966	0.122922
p /[MPa]	⟵ lower temperatures				**6**				
t /[°C]	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2893.7	2989.9	3083.1	3175.2	3267.2	3359.6	3453.0	3547.5	3643.2
h /[kJ/kg]	3178.2	3302.9	3423.1	3541.3	3658.7	3776.2	3894.3	4013.2	4133.1
s /[kJ/kgK]	6.543	6.722	6.883	7.031	7.169	7.300	7.425	7.544	7.658
v /[m^3/kg]	0.047419	0.052166	0.056671	0.061021	0.065265	0.069434	0.073545	0.077614	0.081648

Table E-3 High and supercritical pressure properties of water substance

p /[MPa]					**8**			higher temperatures ⟶	
t /[°C]	**0.01**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
u /[kJ/kg]	0.1	208.2	416.8	628.2	845.7	1075.8	2592.3	2748.3	2864.6
h /[kJ/kg]	8.1	216.2	425.1	636.9	854.9	1085.7	2786.5	2988.1	3139.4
s /[kJ/kgK]	0.000	0.700	1.301	1.834	2.320	2.784	5.794	6.132	6.366
v /[m^3/kg]	0.000996	0.001009	0.001039	0.001086	0.001150	0.001245	0.024279	0.029975	0.034344
p /[MPa]					**10**			higher temperatures ⟶	
t /[°C]	**0.01**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
u /[kJ/kg]	0.2	207.9	416.2	627.3	844.3	1073.4	1329.4	2699.6	2833.1
h /[kJ/kg]	10.1	217.9	426.6	638.1	855.8	1085.8	1343.3	2924.0	3097.4
s /[kJ/kgK]	0.000	0.699	1.300	1.831	2.317	2.779	3.249	5.946	6.214
v /[m^3/kg]	0.000995	0.001008	0.001038	0.001084	0.001148	0.001241	0.001398	0.022440	0.026436
p /[MPa]					**20**			higher temperatures ⟶	
t /[°C]	**0.01**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
u /[kJ/kg]	0.3	206.4	413.5	622.9	837.5	1062.2	1307.1	1612.7	2617.9
h /[kJ/kg]	20.1	226.5	434.2	644.4	860.3	1086.7	1334.4	1646.0	2816.9
s /[kJ/kgK]	0.001	0.695	1.292	1.821	2.303	2.757	3.209	3.729	5.553
v /[m^3/kg]	0.000990	0.001003	0.001034	0.001078	0.001139	0.001225	0.001361	0.001665	0.009950
p /[MPa]	Critical pressure				22.064			higher temperatures ⟶	
t /[°C]	**0.01**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
u /[kJ/kg]	0.3	206.2	412.9	622.0	836.1	1060.0	1303.1	1599.6	2551.9
h /[kJ/kg]	22.1	228.3	435.7	645.8	861.2	1087.0	1333.0	1635.6	2732.9
s /[kJ/kgK]	0.001	0.694	1.291	1.819	2.300	2.753	3.202	3.707	5.400
v /[m^3/kg]	0.000989	0.001003	0.001033	0.001077	0.001137	0.001222	0.001355	0.001634	0.008205

Table E-3 High and supercritical pressure properties of water substance

p /[MPa]	⟵ lower temperatures				**8**				
t /[°C]	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2864.6	2967.8	3065.4	3160.5	3254.7	3348.9	3443.6	3539.1	3635.7
h /[kJ/kg]	3139.4	3273.3	3399.5	3521.8	3642.4	3762.3	3882.2	4002.6	4123.8
s /[kJ/kgK]	6.366	6.558	6.727	6.880	7.022	7.156	7.282	7.403	7.518
v /[m^3/kg]	0.034344	0.038194	0.041767	0.045172	0.048463	0.051675	0.054828	0.057937	0.061011
p /[MPa]	⟵ lower temperatures				**10**				
t /[°C]	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2833.1	2944.5	3047.0	3145.4	3242.0	3337.9	3434.0	3530.7	3628.2
h /[kJ/kg]	3097.4	3242.3	3375.1	3502.0	3625.8	3748.1	3870.0	3992.0	4114.5
s /[kJ/kgK]	6.214	6.422	6.599	6.758	6.904	7.041	7.169	7.292	7.408
v /[m^3/kg]	0.026436	0.029782	0.032811	0.035654	0.038378	0.041018	0.043597	0.046131	0.048629
p /[MPa]	⟵ lower temperatures				**20**				
t /[°C]	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2617.9	2807.2	2945.3	3064.7	3175.3	3281.4	3385.1	3487.7	3590.1
h /[kJ/kg]	2816.9	3061.7	3241.2	3396.1	3539.0	3675.3	3807.8	3938.1	4067.5
s /[kJ/kgK]	5.553	5.904	6.145	6.339	6.507	6.659	6.799	6.930	7.053
v /[m^3/kg]	0.009950	0.012721	0.014793	0.016571	0.018185	0.019695	0.021133	0.022521	0.023869
p /[MPa]	⟵ lower temperatures				22.064	Critical pressure			
t /[°C]	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2551.9	2773.4	2922.0	3046.9	3160.9	3269.3	3374.7	3478.7	3582.1
h /[kJ/kg]	2732.9	3017.8	3210.8	3373.0	3520.4	3659.8	3794.7	3926.9	4057.7
s /[kJ/kgK]	5.400	5.810	6.068	6.272	6.445	6.601	6.743	6.876	7.000
v /[m^3/kg]	0.008205	0.011076	0.013090	0.014779	0.016293	0.017700	0.019033	0.020313	0.021555

Table E-3 High and supercritical pressure properties of water substance

p /[MPa]					30			higher temperatures ⟶	
t /[°C]	**0.01**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
u /[kJ/kg]	0.3	205.1	410.9	618.7	831.1	1052.0	1288.9	1562.2	2068.9
h /[kJ/kg]	29.9	235.1	441.7	650.9	865.0	1088.4	1328.9	1608.8	2152.8
s /[kJ/kgK]	0.000	0.690	1.285	1.811	2.289	2.737	3.176	3.644	4.476
v /[m^3/kg]	0.000986	0.000999	0.001029	0.001072	0.001130	0.001211	0.001332	0.001553	0.002798
p /[MPa]					40			higher temperatures ⟶	
t /[°C]	**0.01**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
u /[kJ/kg]	0.3	203.7	408.4	614.8	825.1	1042.7	1273.3	1529.3	1854.9
h /[kJ/kg]	39.6	243.6	449.3	657.4	870.0	1090.7	1325.6	1588.8	1931.4
s /[kJ/kgK]	0.000	0.686	1.278	1.801	2.275	2.719	3.147	3.587	4.114
v /[m^3/kg]	0.000981	0.000995	0.001024	0.001066	0.001122	0.001199	0.001308	0.001488	0.001911
p /[MPa]					50			higher temperatures ⟶	
t /[°C]	**0.01**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
u /[kJ/kg]	0.3	202.5	405.9	611.0	819.4	1034.2	1259.6	1503.9	1787.8
h /[kJ/kg]	49.2	252.0	456.9	664.0	875.2	1093.5	1324.0	1576.1	1874.4
s /[kJ/kgK]	-0.001	0.681	1.271	1.791	2.263	2.701	3.122	3.543	4.003
v /[m^3/kg]	0.000977	0.000991	0.001020	0.001061	0.001115	0.001187	0.001288	0.001442	0.001731
p /[MPa]					60			higher temperatures ⟶	
t /[°C]	**0.01**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
u /[kJ/kg]	0.3	201.2	403.6	607.4	814.1	1026.2	1247.3	1483.1	1745.2
h /[kJ/kg]	58.6	260.5	464.6	670.7	880.6	1096.8	1323.5	1567.5	1843.2
s /[kJ/kgK]	-0.002	0.676	1.264	1.782	2.251	2.685	3.099	3.507	3.932
v /[m^3/kg]	0.000972	0.000988	0.001016	0.001056	0.001108	0.001176	0.001270	0.001407	0.001633

Table E-3 High and supercritical pressure properties of water substance

p /[MPa]	⟵ lower temperatures				**30**				
t /[°C]	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	2068.9	2618.9	2824.0	2974.5	3103.4	3221.7	3334.3	3443.6	3551.2
h /[kJ/kg]	2152.8	2821.0	3084.7	3279.7	3446.7	3599.4	3743.9	3883.4	4020.0
s /[kJ/kgK]	4.476	5.442	5.796	6.040	6.237	6.407	6.560	6.700	6.830
v /[m^3/kg]	0.002798	0.006737	0.008690	0.010175	0.011445	0.012589	0.013653	0.014661	0.015628
p /[MPa]	⟵ lower temperatures				**40**				
t /[°C]	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	1854.9	2364.2	2681.6	2875.0	3026.8	3159.5	3282.0	3398.6	3511.8
h /[kJ/kg]	1931.4	2511.8	2906.5	3154.4	3350.4	3521.6	3679.1	3828.4	3972.6
s /[kJ/kgK]	4.114	4.945	5.474	5.786	6.017	6.208	6.374	6.524	6.661
v /[m^3/kg]	0.001911	0.003691	0.005623	0.006985	0.008089	0.009053	0.009930	0.010747	0.011521
p /[MPa]	⟵ lower temperatures				**50**				
t /[°C]	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	1787.8	2160.3	2528.1	2769.5	2947.1	3095.6	3228.7	3353.1	3472.2
h /[kJ/kg]	1874.4	2284.7	2722.6	3025.3	3252.5	3443.4	3614.6	3773.9	3925.8
s /[kJ/kgK]	4.003	4.590	5.176	5.556	5.825	6.037	6.218	6.378	6.523
v /[m^3/kg]	0.001731	0.002487	0.003890	0.005117	0.006108	0.006957	0.007717	0.008416	0.009072
p /[MPa]	⟵ lower temperatures				**60**				
t /[°C]	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	1745.2	2055.1	2393.2	2664.5	2866.8	3031.3	3175.4	3307.6	3432.6
h /[kJ/kg]	1843.2	2180.2	2570.3	2901.9	3156.8	3366.7	3551.3	3720.5	3880.0
s /[kJ/kgK]	3.932	4.414	4.936	5.352	5.653	5.887	6.081	6.251	6.403
v /[m^3/kg]	0.001633	0.002085	0.002952	0.003955	0.004833	0.005591	0.006265	0.006881	0.007456

Table E-3 High and supercritical pressure properties of water substance

p /[MPa]					**70**			higher temperatures ⟶	
t /[°C]	0.01	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
u /[kJ/kg]	0.2	200.0	401.4	603.9	809.0	1018.8	1236.1	1465.2	1713.3
h /[kJ/kg]	68.0	268.9	472.2	677.4	886.1	1100.5	1323.9	1561.6	1822.9
s /[kJ/kgK]	-0.003	0.672	1.257	1.773	2.239	2.670	3.077	3.475	3.878
v /[m^3/kg]	0.000968	0.000984	0.001012	0.001050	0.001101	0.001167	0.001254	0.001377	0.001566
p /[MPa]					**80**			higher temperatures ⟶	
t /[°C]	**0.01**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
u /[kJ/kg]	0.1	198.8	399.2	600.6	804.2	1011.8	1225.9	1449.5	1687.5
h /[kJ/kg]	77.2	277.3	479.8	684.2	891.7	1104.4	1325.1	1557.7	1808.8
s /[kJ/kgK]	-0.005	0.668	1.250	1.764	2.228	2.655	3.058	3.447	3.834
v /[m^3/kg]	0.000964	0.000980	0.001008	0.001046	0.001095	0.001157	0.001240	0.001352	0.001516
p /[MPa]					**90**			higher temperatures ⟶	
t /[°C]	**0.01**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
u /[kJ/kg]	-0.1	197.7	397.1	597.4	799.6	1005.3	1216.4	1435.5	1665.7
h /[kJ/kg]	86.4	285.6	487.5	691.1	897.5	1108.7	1326.8	1555.3	1798.6
s /[kJ/kgK]	-0.006	0.663	1.244	1.756	2.217	2.641	3.039	3.421	3.797
v /[m^3/kg]	0.000960	0.000977	0.001004	0.001041	0.001088	0.001149	0.001227	0.001331	0.001476
p /[MPa]					**100**			higher temperatures ⟶	
t /[°C]	**0.01**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
u /[kJ/kg]	-0.2	196.6	395.1	594.3	795.1	999.1	1207.6	1422.8	1646.8
h /[kJ/kg]	95.4	293.9	495.1	697.9	903.4	1113.1	1329.1	1554.0	1791.1
s /[kJ/kgK]	-0.008	0.659	1.237	1.748	2.206	2.628	3.022	3.398	3.764
v /[m^3/kg]	0.000957	0.000973	0.001000	0.001036	0.001083	0.001141	0.001215	0.001312	0.001443

Table E-3 High and supercritical pressure properties of water substance

p /[MPa]	⟵ lower temperatures				70				
t /[°C]	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	1713.3	1991.2	2293.6	2569.2	2789.2	2968.1	3122.6	3262.6	3393.5
h /[kJ/kg]	1822.9	2123.7	2466.1	2794.9	3067.4	3293.5	3490.3	3668.9	3835.7
s /[kJ/kgK]	3.878	4.308	4.766	5.178	5.500	5.752	5.960	6.139	6.298
υ /[m^3/kg]	0.001566	0.001892	0.002463	0.003224	0.003975	0.004648	0.005252	0.005804	0.006317
p /[MPa]	⟵ lower temperatures				80				
t /[°C]	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	1687.5	1945.9	2222.4	2489.1	2717.4	2907.5	3071.4	3218.6	3355.1
h /[kJ/kg]	1808.8	2087.8	2397.4	2709.9	2988.1	3225.5	3432.7	3619.7	3793.3
s /[kJ/kgK]	3.834	4.233	4.647	5.039	5.367	5.632	5.851	6.038	6.204
υ /[m^3/kg]	0.001516	0.001774	0.002188	0.002760	0.003384	0.003975	0.004517	0.005014	0.005477
p /[MPa]	⟵ lower temperatures				90				
t /[°C]	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	1665.7	1910.7	2169.0	2423.9	2653.5	2850.9	3022.4	3176.0	3317.8
h /[kJ/kg]	1798.6	2062.9	2350.3	2645.1	2920.7	3164.3	3379.3	3573.4	3753.0
s /[kJ/kgK]	3.797	4.175	4.559	4.929	5.254	5.525	5.752	5.947	6.118
υ /[m^3/kg]	0.001476	0.001691	0.002014	0.002457	0.002969	0.003483	0.003966	0.004416	0.004836
p /[MPa]	⟵ lower temperatures				100				
t /[°C]	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
u /[kJ/kg]	1646.8	1881.9	2126.9	2371.0	2597.9	2798.9	2976.1	3135.2	3281.7
h /[kJ/kg]	1791.1	2044.7	2316.2	2595.9	2865.1	3110.5	3330.7	3530.5	3715.3
s /[kJ/kgK]	3.764	4.127	4.490	4.841	5.158	5.431	5.664	5.864	6.041
υ /[m^3/kg]	0.001443	0.001628	0.001893	0.002249	0.002672	0.003115	0.003546	0.003953	0.004336

Appendix F Properties of Refrigerant 134a

The thermodynamic properties in these tables were calculated using the Excel add-in of the REFPROP software[12], Version 9.1, 2013, National Institute of Standards and Technology, Gaithersburg MD, 20899. The underlying formulation has been described by Tillner-Roth and Baehr[13].

While care has been taken in preparing the tables, no warranty of accuracy or fitness for purpose is made for the data.

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[12] Lemmon, E.W., Huber, M.L., McLinden, M.O. NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 9.1, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg, 2013.

[13] Tillner-Roth, R. and Baehr, H.D., ‘An international standard formulation of the thermodynamic properties of 1,1,1,2-tetrafluoroethane (HFC-134a) for temperatures from 170 K to 455 K at pressures up to 70 MPa’, J. Phys. Chem. Ref. Data, 23:657-729, 1994.

Table F-1 Saturation and superheat properties of refrigerant 134a ($C_2H_2F_4$)

Saturated								**Superheated** ($t{-}t_s$)								
								10 K			30 K			70 K		
p_s [MPa]	t_s [°C]	h_f [kJ/kg]	s_f [kJ/kgK]	v_f [m^3/kg]	h_g [kJ/kg]	s_g [kJ/kgK]	v_g [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	v [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	v [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	v [m^3/kg]
0.0512	**-40**	0.0	0.000	0.000705	225.9	0.969	0.3611	233.4	1.000	0.3783	248.8	1.061	0.4119	281.5	1.177	0.4778
0.0540	**-39**	1.3	0.005	0.000707	226.5	0.967	0.3438	234.1	0.999	0.3598	249.5	1.060	0.3918	282.3	1.175	0.4544
0.055	-38.6	1.7	0.007	0.000707	226.7	0.967	0.3377	234.3	0.998	0.3538	249.8	1.059	0.3852	282.7	1.175	0.4466
0.0568	**-38**	2.5	0.011	0.000708	227.1	0.966	0.3276	234.7	0.998	0.3432	250.2	1.058	0.3736	283.1	1.174	0.4332
0.0598	**-37**	3.8	0.016	0.000710	227.8	0.965	0.3122	235.4	0.996	0.3270	251.0	1.057	0.3560	283.9	1.172	0.4126
0.06	-36.9	3.9	0.016	0.000710	227.8	0.964	0.3112	235.4	0.996	0.3260	251.0	1.057	0.3549	284.0	1.172	0.4114
0.0629	**-36**	5.0	0.021	0.000711	228.4	0.963	0.2977	236.0	0.995	0.3119	251.7	1.056	0.3395	284.7	1.171	0.3934
0.0661	**-35**	6.3	0.027	0.000713	229.0	0.962	0.2840	236.7	0.994	0.2977	252.4	1.054	0.3240	285.6	1.170	0.3754
0.0695	**-34**	7.6	0.032	0.000714	229.7	0.961	0.2711	237.4	0.992	0.2840	253.1	1.053	0.3091	286.4	1.168	0.3580
0.07	-33.9	7.7	0.033	0.000714	229.7	0.960	0.2693	237.4	0.992	0.2820	253.2	1.053	0.3069	286.4	1.168	0.3556
0.0730	**-33**	8.8	0.037	0.000716	230.3	0.959	0.2588	238.0	0.991	0.2712	253.8	1.052	0.2951	287.2	1.167	0.3418
0.0767	**-32**	10.1	0.043	0.000717	230.9	0.958	0.2473	238.7	0.990	0.2588	254.5	1.050	0.2817	288.0	1.165	0.3262
0.08	-31.1	11.2	0.047	0.000719	231.5	0.957	0.2376	239.3	0.989	0.2488	255.2	1.049	0.2708	288.7	1.164	0.3135
0.0804	**-31**	11.4	0.048	0.000719	231.5	0.957	0.2363	239.3	0.989	0.2477	255.3	1.049	0.2695	288.8	1.164	0.3120
0.0844	**-30**	12.6	0.053	0.000720	232.2	0.956	0.2259	240.0	0.987	0.2366	256.0	1.048	0.2575	289.6	1.163	0.2981
0.0885	**-29**	13.9	0.058	0.000722	232.8	0.955	0.2161	240.7	0.986	0.2263	256.7	1.047	0.2462	290.4	1.162	0.2850
0.09	-28.6	14.4	0.060	0.000722	233.0	0.954	0.2126	240.9	0.986	0.2228	257.0	1.047	0.2424	290.7	1.161	0.2806
0.0927	**-28**	15.2	0.063	0.000723	233.4	0.954	0.2068	241.3	0.985	0.2166	257.4	1.046	0.2357	291.2	1.160	0.2728
0.0971	**-27**	16.5	0.069	0.000725	234.1	0.953	0.1980	242.0	0.984	0.2074	258.1	1.045	0.2257	292.0	1.159	0.2611
0.10	-26.4	17.3	0.072	0.000726	234.5	0.952	0.1926	242.4	0.983	0.2017	258.5	1.044	0.2195	292.5	1.158	0.2539
0.1017	**-26**	17.8	0.074	0.000727	234.7	0.952	0.1896	242.6	0.983	0.1985	258.8	1.044	0.2160	292.8	1.158	0.2500
0.1064	**-25**	19.0	0.079	0.000728	235.3	0.950	0.1816	243.3	0.982	0.1903	259.5	1.043	0.2071	293.6	1.157	0.2395
0.11	-24.3	20.0	0.083	0.000729	235.8	0.950	0.1760	243.7	0.981	0.1844	260.0	1.042	0.2006	294.2	1.156	0.2321
0.1113	**-24**	20.3	0.084	0.000730	235.9	0.949	0.1741	244.0	0.981	0.1824	260.2	1.042	0.1985	294.4	1.156	0.2296
0.1164	**-23**	21.6	0.089	0.000731	236.6	0.949	0.1669	244.6	0.980	0.1748	261.0	1.041	0.1903	295.3	1.155	0.2201

Table F-1 Saturation and superheat properties of refrigerant 134a ($C_2H_2F_4$)

Saturated								**Superheated** ($t-t_s$)								
								10 K			30 K			70 K		
p_s	t_s	h_f	s_f	v_f	h_g	s_g	v_g	h	s	v	h	s	v	h	s	v
[MPa]	[°C]	[kJ/kg]	[kJ/kgK]	[m^3/kg]	[kJ/kg]	[kJ/kgK]	[m^3/kg]	[kJ/kg]	[kJ/kgK]	[m^3/kg]	[kJ/kg]	[kJ/kgK]	[m^3/kg]	[kJ/kg]	[kJ/kgK]	[m^3/kg]
0.12	-22.3	22.5	0.093	0.000732	237.0	0.948	0.1621	245.1	0.979	0.1699	261.5	1.040	0.1849	295.8	1.154	0.2138
0.1216	**-22**	22.9	0.094	0.000733	237.2	0.948	0.1601	245.3	0.979	0.1678	261.7	1.040	0.1826	296.1	1.154	0.2112
0.1271	**-21**	24.2	0.100	0.000735	237.8	0.947	0.1536	245.9	0.978	0.1609	262.4	1.039	0.1751	296.9	1.153	0.2025
0.13	-20.5	24.9	0.102	0.000735	238.1	0.946	0.1503	246.2	0.978	0.1575	262.7	1.038	0.1714	297.3	1.152	0.1983
0.1327	**-20**	25.5	0.105	0.000736	238.4	0.946	0.1474	246.6	0.977	0.1545	263.1	1.038	0.1682	297.7	1.152	0.1945
0.1386	**-19**	26.8	0.110	0.000738	239.0	0.945	0.1415	247.2	0.976	0.1483	263.8	1.037	0.1614	298.5	1.151	0.1866
0.14	-18.8	27.1	0.111	0.000738	239.2	0.945	0.1401	247.3	0.976	0.1469	263.9	1.037	0.1598	298.6	1.151	0.1849
0.1446	**-18**	28.1	0.115	0.000740	239.6	0.944	0.1359	247.9	0.976	0.1425	264.5	1.036	0.1551	299.3	1.150	0.1793
0.1508	**-17**	29.4	0.120	0.000741	240.3	0.943	0.1306	248.5	0.975	0.1369	265.2	1.035	0.1491	300.1	1.149	0.1724
0.1573	**-16**	30.7	0.125	0.000743	240.9	0.942	0.1255	249.2	0.974	0.1316	265.9	1.034	0.1432	300.9	1.148	0.1656
0.16	-15.6	31.2	0.127	0.000744	241.1	0.942	0.1235	249.4	0.974	0.1295	266.2	1.034	0.1409	301.2	1.148	0.1630
0.1639	**-15**	32.0	0.130	0.000745	241.5	0.941	0.1207	249.8	0.973	0.1265	266.6	1.034	0.1378	301.7	1.148	0.1593
0.1708	**-14**	33.3	0.135	0.000746	242.1	0.941	0.1161	250.5	0.972	0.1217	267.4	1.033	0.1325	302.5	1.147	0.1532
0.1779	**-13**	34.6	0.140	0.000748	242.7	0.940	0.1116	251.1	0.972	0.1171	268.1	1.032	0.1275	303.3	1.146	0.1475
0.18	-12.7	35.0	0.141	0.000749	242.9	0.940	0.1104	251.3	0.971	0.1158	268.3	1.032	0.1261	303.6	1.146	0.1458
0.1852	**-12**	35.9	0.145	0.000750	243.3	0.939	0.1074	251.8	0.971	0.1127	268.8	1.031	0.1228	304.2	1.145	0.1420
0.1928	**-11**	37.2	0.150	0.000752	243.9	0.938	0.1034	252.4	0.970	0.1085	269.5	1.031	0.1182	305.0	1.145	0.1367
0.20	-10.1	38.5	0.155	0.000753	244.5	0.938	0.0999	253.0	0.969	0.1048	270.1	1.030	0.1141	305.7	1.144	0.1320
0.2006	**-10**	38.6	0.155	0.000754	244.5	0.938	0.0996	253.0	0.970	0.1045	270.2	1.030	0.1138	305.8	1.144	0.1317
0.2086	**-9**	39.9	0.160	0.000755	245.1	0.937	0.0959	253.7	0.969	0.1007	270.9	1.029	0.1097	306.6	1.143	0.1269
0.217	**-8**	41.2	0.165	0.000757	245.7	0.936	0.0924	254.3	0.968	0.0970	271.6	1.029	0.1057	307.4	1.142	0.1222
0.22	-7.6	41.7	0.167	0.000758	245.9	0.936	0.0912	254.6	0.968	0.0957	271.9	1.029	0.1043	307.7	1.142	0.1207
0.2255	**-7**	42.5	0.170	0.000759	246.3	0.936	0.0891	255.0	0.968	0.0935	272.3	1.028	0.1019	308.2	1.142	0.1179
0.2343	**-6**	43.8	0.175	0.000761	246.9	0.935	0.0859	255.6	0.967	0.0901	273.0	1.027	0.0983	309.0	1.141	0.1137
0.24	-5.4	44.7	0.178	0.000762	247.3	0.935	0.0839	256.0	0.966	0.0881	273.4	1.027	0.0960	309.5	1.141	0.1111

Table F-1 Saturation and superheat properties of refrigerant 134a ($C_2H_2F_4$)

Saturated								**Superheated** ($t-t_s$)								
								10 K			30 K			70 K		
p_s	t_s	h_f	s_f	v_f	h_g	s_g	v_g	h	s	v	h	s	v	h	s	v
[MPa]	[°C]	[kJ/kg]	[kJ/kgK]	[m^3/kg]	[kJ/kg]	[kJ/kgK]	[m^3/kg]	[kJ/kg]	[kJ/kgK]	[m^3/kg]	[kJ/kg]	[kJ/kgK]	[m^3/kg]	[kJ/kg]	[kJ/kgK]	[m^3/kg]
0.2433	**-5**	45.2	0.180	0.000763	247.5	0.934	0.0828	256.2	0.966	0.0869	273.7	1.027	0.0948	309.8	1.141	0.1097
0.2527	**-4**	46.5	0.185	0.000765	248.1	0.934	0.0799	256.9	0.966	0.0839	274.4	1.026	0.0915	310.6	1.140	0.1058
0.26	-3.2	47.5	0.189	0.000766	248.6	0.933	0.0777	257.4	0.965	0.0816	274.9	1.026	0.0890	311.3	1.140	0.1030
0.2623	**-3**	47.8	0.190	0.000767	248.7	0.933	0.0771	257.5	0.965	0.0809	275.1	1.026	0.0883	311.4	1.139	0.1022
0.2722	**-2**	49.2	0.195	0.000768	249.3	0.933	0.0744	258.1	0.965	0.0781	275.8	1.025	0.0852	312.2	1.139	0.0987
0.28	-1.2	50.2	0.198	0.000770	249.7	0.932	0.0724	258.6	0.964	0.0760	276.3	1.025	0.0830	312.9	1.139	0.0961
0.2823	**-1**	50.5	0.199	0.000770	249.9	0.932	0.0718	258.7	0.964	0.0754	276.5	1.025	0.0823	313.0	1.138	0.0953
0.2928	**0**	51.9	0.204	0.000772	250.5	0.931	0.0693	259.4	0.964	0.0728	277.2	1.024	0.0795	313.8	1.138	0.0921
0.30	0.7	52.8	0.208	0.000774	250.9	0.931	0.0677	259.8	0.963	0.0712	277.7	1.024	0.0777	314.4	1.138	0.0900
0.3036	**1**	53.2	0.209	0.000774	251.0	0.931	0.0669	260.0	0.963	0.0703	277.9	1.024	0.0768	314.6	1.137	0.0890
0.3146	**2**	54.5	0.214	0.000776	251.6	0.930	0.0647	260.6	0.963	0.0680	278.6	1.023	0.0743	315.4	1.137	0.0860
0.32	2.5	55.2	0.216	0.000777	251.9	0.930	0.0636	260.9	0.962	0.0669	278.9	1.023	0.0731	315.8	1.137	0.0847
0.3260	**3**	55.9	0.219	0.000778	252.2	0.930	0.0625	261.2	0.962	0.0657	279.2	1.023	0.0718	316.2	1.136	0.0832
0.3377	**4**	57.3	0.224	0.000780	252.8	0.929	0.0604	261.9	0.962	0.0635	279.9	1.022	0.0694	317.0	1.136	0.0804
0.34	4.2	57.5	0.225	0.000781	252.9	0.929	0.0600	262.0	0.961	0.0631	280.1	1.022	0.0690	317.2	1.136	0.0799
0.3497	**5**	58.6	0.229	0.000782	253.3	0.929	0.0584	262.5	0.961	0.0614	280.6	1.022	0.0671	317.9	1.136	0.0778
0.36	5.8	59.8	0.233	0.000784	253.8	0.928	0.0567	263.0	0.961	0.0597	281.2	1.022	0.0653	318.5	1.135	0.0757
0.3620	**6**	60.0	0.234	0.000785	253.9	0.928	0.0564	263.1	0.961	0.0594	281.3	1.022	0.0649	318.7	1.135	0.0753
0.3746	**7**	61.3	0.238	0.000787	254.5	0.928	0.0546	263.7	0.960	0.0575	282.0	1.021	0.0629	319.5	1.135	0.0729
0.38	7.4	61.9	0.240	0.000787	254.7	0.928	0.0538	263.9	0.960	0.0567	282.3	1.021	0.0620	319.8	1.135	0.0719
0.3876	**8**	62.7	0.243	0.000789	255.1	0.927	0.0528	264.3	0.960	0.0556	282.7	1.021	0.0608	320.3	1.134	0.0706
0.40	8.9	64.0	0.248	0.000791	255.6	0.927	0.0512	264.8	0.959	0.0539	283.3	1.020	0.0590	321.0	1.134	0.0685
0.4009	**9**	64.1	0.248	0.000791	255.6	0.927	0.0511	264.9	0.959	0.0538	283.4	1.020	0.0589	321.1	1.134	0.0684
0.4146	**10**	65.4	0.253	0.000793	256.2	0.927	0.04944	265.5	0.959	0.0521	284.0	1.020	0.0570	321.9	1.134	0.0662
0.4286	**11**	66.8	0.258	0.000795	256.7	0.926	0.04786	266.1	0.959	0.0504	284.7	1.020	0.0552	322.6	1.133	0.0642

Table F-1 Saturation and superheat properties of refrigerant 134a ($C_2H_2F_4$)

Saturated								**Superheated** (t−t_s)								
								10 K			30 K			70 K		
p_s [MPa]	t_s [°C]	h_f [kJ/kg]	s_f [kJ/kgK]	v_f [m^3/kg]	h_g [kJ/kg]	s_g [kJ/kgK]	v_g [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	v [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	v [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	v [m^3/kg]
0.4430	**12**	68.2	0.262	0.000797	257.3	0.926	0.04633	266.7	0.958	0.04884	285.4	1.019	0.0535	323.4	1.133	0.0622
0.45	12.5	68.8	0.265	0.000799	257.5	0.925	0.04562	267.0	0.958	0.04811	285.7	1.019	0.0527	323.8	1.133	0.0613
0.4578	**13**	69.6	0.267	0.000800	257.8	0.925	0.04486	267.3	0.958	0.04731	286.1	1.019	0.0519	324.2	1.133	0.0603
0.4729	**14**	70.9	0.272	0.000802	258.4	0.925	0.04345	267.9	0.957	0.04583	286.8	1.019	0.0503	325.0	1.132	0.0584
0.488	**15**	72.3	0.277	0.000804	258.9	0.924	0.04209	268.5	0.957	0.04445	287.4	1.019	0.0488	325.8	1.132	0.0567
0.50	15.7	73.4	0.280	0.000806	259.3	0.924	0.04112	268.9	0.957	0.04340	287.9	1.018	0.0476	326.4	1.132	0.0554
0.504	**16**	73.7	0.282	0.000807	259.5	0.924	0.04078	269.1	0.957	0.04307	288.1	1.018	0.0473	326.6	1.132	0.0550
0.521	**17**	75.1	0.286	0.000809	260.0	0.924	0.03952	269.7	0.956	0.04169	288.8	1.018	0.0458	327.4	1.132	0.0533
0.537	**18**	76.5	0.291	0.000811	260.5	0.923	0.03830	270.3	0.956	0.04048	289.4	1.018	0.0445	328.2	1.131	0.0518
0.55	18.8	77.6	0.295	0.000813	260.9	0.923	0.03741	270.8	0.956	0.03954	290.0	1.018	0.0435	328.9	1.131	0.0506
0.554	**19**	77.9	0.296	0.000814	261.1	0.923	0.03713	270.9	0.956	0.03926	290.1	1.017	0.0431	329.0	1.131	0.05025
0.572	**20**	79.3	0.301	0.000816	261.6	0.922	0.03600	271.4	0.955	0.03803	290.8	1.017	0.0418	329.8	1.131	0.04874
0.590	**21**	80.7	0.305	0.000819	262.1	0.922	0.03491	272.0	0.955	0.03689	291.4	1.017	0.0406	330.6	1.131	0.04732
0.60	21.6	81.5	0.308	0.000820	262.4	0.922	0.03430	272.4	0.955	0.03629	291.8	1.017	0.0399	331.1	1.131	0.04657
0.608	**22**	82.1	0.310	0.000821	262.6	0.922	0.03385	272.6	0.955	0.03581	292.1	1.017	0.0394	331.4	1.131	0.04598
0.627	**23**	83.6	0.315	0.000824	263.2	0.921	0.03284	273.2	0.955	0.03474	292.7	1.016	0.0383	332.2	1.130	0.04465
0.646	**24**	85.0	0.320	0.000826	263.7	0.921	0.03186	273.7	0.954	0.03373	293.4	1.016	0.0372	332.9	1.130	0.04339
0.65	24.2	85.3	0.321	0.000827	263.8	0.921	0.03165	273.9	0.954	0.03352	293.5	1.016	0.0369	333.1	1.130	0.04314
0.665	**25**	86.4	0.324	0.000829	264.2	0.921	0.03091	274.3	0.954	0.03278	294.1	1.016	0.0361	333.7	1.130	0.04221
0.685	**26**	87.8	0.329	0.000831	264.7	0.920	0.03000	274.9	0.954	0.03182	294.7	1.016	0.0351	334.5	1.130	0.04103
0.70	26.7	88.8	0.332	0.000833	265.1	0.920	0.02937	275.3	0.954	0.03114	295.2	1.016	0.0344	335.1	1.130	0.04019
0.706	**27**	89.3	0.334	0.000834	265.2	0.920	0.02912	275.4	0.953	0.03088	295.4	1.016	0.0341	335.3	1.130	0.03986
0.727	**28**	90.7	0.338	0.000837	265.7	0.920	0.02826	276.0	0.953	0.02999	296.0	1.016	0.0331	336.1	1.130	0.03876
0.748	**29**	92.1	0.343	0.000839	266.2	0.919	0.02744	276.6	0.953	0.02915	296.7	1.015	0.0322	336.9	1.130	0.03771
0.75	29.1	92.2	0.344	0.000840	266.2	0.919	0.02737	276.6	0.953	0.02907	296.7	1.015	0.0321	336.9	1.130	0.03762

Table F-1 Saturation and superheat properties of refrigerant 134a ($C_2H_2F_4$)

Saturated								**Superheated** ($t-t_s$)								
								10 K			30 K			70 K		
p_s [MPa]	t_s [°C]	h_f [kJ/kg]	s_f [kJ/kgK]	v_f [m^3/kg]	h_g [kJ/kg]	s_g [kJ/kgK]	v_g [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	v [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	v [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	v [m^3/kg]
0.770	**30**	93.6	0.348	0.000842	266.7	0.919	0.02664	277.1	0.953	0.02831	297.3	1.015	0.0313	337.6	1.130	0.03668
0.793	**31**	95.0	0.353	0.000845	267.2	0.919	0.02587	277.6	0.952	0.02748	297.9	1.015	0.0304	338.4	1.129	0.03565
0.80	31.3	95.5	0.354	0.000846	267.3	0.918	0.02562	277.8	0.952	0.02724	298.1	1.015	0.0302	338.6	1.129	0.03535
0.815	**32**	96.5	0.357	0.000848	267.6	0.918	0.02513	278.2	0.952	0.02674	298.6	1.015	0.0296	339.2	1.129	0.03473
0.839	**33**	97.9	0.362	0.000851	268.1	0.918	0.02441	278.7	0.952	0.02596	299.2	1.015	0.0288	340.0	1.129	0.03378
0.85	33.5	98.6	0.364	0.000852	268.3	0.918	0.02407	279.0	0.952	0.02563	299.5	1.015	0.0284	340.4	1.129	0.03336
0.863	**34**	99.4	0.367	0.000854	268.6	0.918	0.02371	279.3	0.952	0.02523	299.8	1.015	0.0280	340.7	1.129	0.03287
0.887	**35**	100.9	0.371	0.000857	269.0	0.917	0.02303	279.8	0.952	0.02454	300.5	1.015	0.0272	341.5	1.129	0.03202
0.90	35.5	101.6	0.374	0.000858	269.3	0.917	0.02269	280.0	0.951	0.02418	300.8	1.014	0.0269	341.9	1.129	0.03157
0.912	**36**	102.3	0.376	0.000860	269.5	0.917	0.02238	280.3	0.951	0.02386	301.1	1.014	0.0265	342.3	1.129	0.03117
0.937	**37**	103.8	0.381	0.000863	270.0	0.916	0.02175	280.9	0.951	0.02321	301.7	1.014	0.0258	343.1	1.129	0.03037
0.95	37.5	104.5	0.383	0.000864	270.2	0.916	0.02144	281.1	0.951	0.02289	302.0	1.014	0.0255	343.4	1.129	0.02997
0.963	**38**	105.3	0.385	0.000866	270.4	0.916	0.02113	281.4	0.951	0.02257	302.4	1.014	0.0251	343.8	1.129	0.02958
0.990	**39**	106.8	0.390	0.000869	270.8	0.916	0.02054	281.9	0.951	0.02194	303.0	1.014	0.0244	344.6	1.129	0.02880
1.00	39.4	107.4	0.392	0.000870	271.0	0.916	0.02032	282.1	0.951	0.02172	303.2	1.014	0.0242	344.9	1.129	0.02852
1.017	**40**	108.3	0.395	0.000872	271.3	0.915	0.01997	282.4	0.950	0.02134	303.6	1.014	0.0238	345.4	1.129	0.02806
1.044	**41**	109.8	0.400	0.000875	271.7	0.915	0.01941	282.9	0.950	0.02077	304.2	1.014	0.0232	346.1	1.129	0.02736
1.05	41.2	110.1	0.401	0.000876	271.8	0.915	0.01929	283.0	0.950	0.02065	304.3	1.014	0.0230	346.3	1.129	0.02721
1.072	**42**	111.3	0.404	0.000879	272.1	0.915	0.01887	283.4	0.950	0.02022	304.8	1.014	0.0226	346.9	1.129	0.02667
1.10	43.0	112.7	0.409	0.000882	272.5	0.914	0.01836	283.9	0.950	0.01969	305.4	1.014	0.0220	347.7	1.129	0.02601
1.101	**43**	112.8	0.409	0.000882	272.6	0.914	0.01834	283.9	0.950	0.01966	305.4	1.014	0.0220	347.6	1.129	0.02599
1.130	**44**	114.3	0.414	0.000885	273.0	0.914	0.01784	284.4	0.949	0.01914	306.0	1.014	0.0214	348.4	1.129	0.02534
1.15	44.7	115.3	0.417	0.000888	273.2	0.914	0.01751	284.8	0.949	0.01880	306.5	1.014	0.0210	348.9	1.129	0.02492
1.160	**45**	115.8	0.418	0.000889	273.4	0.914	0.01734	284.9	0.949	0.01862	306.6	1.014	0.0209	349.2	1.129	0.02471
1.190	**46**	117.3	0.423	0.000892	273.8	0.913	0.01687	285.4	0.949	0.01814	307.2	1.014	0.0203	349.9	1.129	0.02410

Table F-1 Saturation and superheat properties of refrigerant 134a ($C_2H_2F_4$)

Saturated								**Superheated** ($t-t_s$)								
								10 K			30 K			70 K		
p_s	t_s	h_f	s_f	v_f	h_g	s_g	v_g	h	s	v	h	s	v	h	s	v
[MPa]	[°C]	[kJ/kg]	[kJ/kgK]	[m^3/kg]	[kJ/kg]	[kJ/kgK]	[m^3/kg]	[kJ/kg]	[kJ/kgK]	[m^3/kg]	[kJ/kg]	[kJ/kgK]	[m^3/kg]	[kJ/kg]	[kJ/kgK]	[m^3/kg]
1.20	46.3	117.8	0.425	0.000894	273.9	0.913	0.01672	285.5	0.949	0.01797	307.4	1.013	0.0202	350.1	1.129	0.02391
1.221	**47**	118.9	0.428	0.000896	274.2	0.913	0.01640	285.8	0.949	0.01765	307.8	1.014	0.0198	350.7	1.129	0.02351
1.25	47.9	120.2	0.432	0.000899	274.5	0.912	0.01599	286.3	0.949	0.01722	308.4	1.013	0.0193	351.3	1.129	0.02298
1.253	**48**	120.4	0.432	0.000900	274.5	0.912	0.01595	286.3	0.949	0.01718	308.4	1.013	0.0193	351.4	1.129	0.02292
1.285	**49**	121.9	0.437	0.000903	274.9	0.912	0.01551	286.8	0.948	0.01673	309.0	1.013	0.0188	352.2	1.129	0.02237
1.30	49.5	122.6	0.439	0.000905	275.1	0.912	0.01532	287.0	0.948	0.01653	309.3	1.013	0.0186	352.6	1.130	0.02212
1.318	**50**	123.5	0.442	0.000907	275.3	0.912	0.01509	287.2	0.948	0.01628	309.6	1.013	0.0183	352.9	1.129	0.02182
1.35	51.0	125.0	0.446	0.000911	275.6	0.911	0.01469	287.7	0.948	0.01588	310.2	1.013	0.0179	353.7	1.130	0.02132
1.351	**51**	125.0	0.447	0.000911	275.7	0.911	0.01468	287.7	0.948	0.01586	310.2	1.013	0.0179	353.7	1.130	0.02130
1.385	**52**	126.6	0.451	0.000915	276.0	0.911	0.01428	288.2	0.948	0.01545	310.8	1.013	0.0174	354.4	1.130	0.02079
1.40	52.4	127.3	0.453	0.000917	276.2	0.911	0.01411	288.3	0.947	0.01527	311.0	1.013	0.0172	354.7	1.130	0.02057
1.420	**53**	128.2	0.456	0.000919	276.3	0.910	0.01389	288.6	0.947	0.01504	311.4	1.013	0.0170	355.2	1.130	0.02029
1.45	53.8	129.5	0.460	0.000923	276.6	0.910	0.01357	288.9	0.947	0.01470	311.8	1.013	0.0166	355.7	1.130	0.01988
1.455	**54**	129.7	0.461	0.000923	276.7	0.910	0.01351	289.1	0.947	0.01466	311.9	1.013	0.0166	355.9	1.130	0.01982
1.492	**55**	131.3	0.465	0.000927	277.0	0.909	0.01314	289.5	0.947	0.01426	312.5	1.013	0.0162	356.6	1.130	0.01933
1.50	55.2	131.7	0.467	0.000928	277.1	0.909	0.01306	289.5	0.947	0.01418	312.6	1.013	0.0161	356.8	1.130	0.01923
1.528	**56**	132.9	0.470	0.000932	277.3	0.909	0.01278	289.9	0.947	0.01390	313.1	1.013	0.0158	357.4	1.130	0.01889
1.55	56.6	133.9	0.473	0.000934	277.5	0.909	0.01258	290.2	0.946	0.01369	313.4	1.013	0.0155	357.8	1.130	0.01863
1.57	**57**	134.5	0.475	0.000936	277.6	0.908	0.01243	290.2	0.946	0.01349	313.6	1.013	0.0153	358.1	1.130	0.01839
1.60	57.9	136.0	0.479	0.000940	277.9	0.908	0.01213	290.7	0.946	0.01322	314.1	1.013	0.0150	358.8	1.130	0.01806
1.604	**58**	136.1	0.480	0.000941	277.9	0.908	0.01209	290.7	0.946	0.01318	314.2	1.013	0.0150	358.9	1.130	0.01801
1.642	**59**	137.7	0.484	0.000945	278.2	0.907	0.01177	291.2	0.946	0.01285	314.8	1.013	0.0146	359.6	1.130	0.01760
1.65	59.2	138.1	0.485	0.000946	278.3	0.907	0.01170	291.2	0.946	0.01278	314.9	1.013	0.0146	359.7	1.130	0.01752
1.682	**60**	139.4	0.489	0.000950	278.5	0.907	0.01144	291.5	0.945	0.01252	315.3	1.013	0.0143	360.3	1.130	0.01719
1.70	60.5	140.1	0.491	0.000952	278.6	0.907	0.01130	291.8	0.945	0.01238	315.6	1.013	0.0141	360.7	1.131	0.01702

Table F-1 Saturation and superheat properties of refrigerant 134a ($C_2H_2F_4$)

Saturated								Superheated ($t-t_s$)								
								10 K			30 K			70 K		
p_s [MPa]	t_s [°C]	h_f [kJ/kg]	s_f [kJ/kgK]	v_f [m^3/kg]	h_g [kJ/kg]	s_g [kJ/kgK]	v_g [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	v [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	v [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	v [m^3/kg]
1.722	**61**	141.0	0.494	0.000955	278.7	0.906	0.01113	291.9	0.945	0.01220	315.8	1.013	0.0139	361.1	1.131	0.01680
1.75	61.7	142.1	0.497	0.000958	278.9	0.906	0.01092	292.2	0.945	0.01198	316.2	1.013	0.0137	361.6	1.131	0.01654
1.763	**62**	142.6	0.499	0.000960	279.0	0.906	0.01083	292.3	0.945	0.01188	316.4	1.013	0.0136	361.8	1.131	0.01641
1.80	62.9	144.1	0.503	0.000964	279.2	0.905	0.01056	292.7	0.945	0.01161	316.9	1.013	0.0133	362.4	1.131	0.01608
1.804	**63**	144.3	0.504	0.000965	279.2	0.905	0.01053	292.7	0.945	0.01158	316.9	1.013	0.0133	362.5	1.131	0.01605
1.847	**64**	145.9	0.508	0.000970	279.5	0.904	0.01024	293.1	0.944	0.01128	317.5	1.013	0.0130	363.2	1.131	0.01568
1.85	64.1	146.1	0.509	0.000970	279.5	0.904	0.01022	293.1	0.944	0.01126	317.5	1.013	0.0129	363.3	1.131	0.01566
1.890	**65**	147.6	0.513	0.000975	279.7	0.904	0.00996	293.4	0.944	0.01099	318.0	1.012	0.0127	364.0	1.131	0.01533
1.90	65.2	148.0	0.514	0.000976	279.7	0.904	0.00990	293.5	0.944	0.01093	318.1	1.012	0.0126	364.1	1.131	0.01525
1.934	**66**	149.3	0.518	0.000980	279.9	0.903	0.00969	293.8	0.944	0.01071	318.5	1.012	0.0124	364.7	1.131	0.01498
1.95	66.4	149.9	0.520	0.000982	279.9	0.903	0.00959	294.0	0.944	0.01062	318.8	1.013	0.0122	365.0	1.131	0.01486
1.978	**67**	151.0	0.523	0.000986	280.1	0.902	0.00942	294.2	0.943	0.01044	319.1	1.012	0.0121	365.4	1.131	0.01465
2.0	67.5	151.8	0.525	0.000989	280.1	0.902	0.00929	294.3	0.943	0.01031	319.3	1.012	0.0119	365.8	1.131	0.01450
2.024	**68**	152.7	0.528	0.000992	280.2	0.902	0.00916	294.5	0.943	0.01017	319.6	1.012	0.0118	366.1	1.131	0.01432
2.070	**69**	154.4	0.533	0.000998	280.4	0.901	0.00890	294.8	0.942	0.00991	320.1	1.012	0.0115	366.8	1.132	0.01401
2.1	69.6	155.5	0.536	0.001002	280.5	0.900	0.00874	295.0	0.942	0.00975	320.4	1.012	0.0113	367.2	1.132	0.01381
2.117	**70**	156.1	0.538	0.001004	280.5	0.900	0.00865	295.1	0.942	0.00966	320.6	1.012	0.0112	367.5	1.132	0.01370
2.165	**71**	157.9	0.542	0.001010	280.6	0.899	0.00841	295.4	0.942	0.00941	321.1	1.012	0.0110	368.2	1.132	0.01340
2.2	71.7	159.2	0.546	0.001015	280.7	0.899	0.00824	295.6	0.941	0.00924	321.4	1.012	0.0108	368.7	1.132	0.01319
2.213	**72**	159.6	0.547	0.001017	280.7	0.898	0.00817	295.8	0.941	0.00918	321.6	1.012	0.0107	369.0	1.132	0.01311
2.263	**73**	161.4	0.552	0.001023	280.8	0.897	0.00794	296.0	0.941	0.00894	322.1	1.012	0.0105	369.7	1.132	0.01282
2.3	73.7	162.7	0.556	0.001028	280.8	0.897	0.00777	296.2	0.940	0.00877	322.4	1.012	0.0103	370.1	1.132	0.01261
2.313	**74**	163.2	0.557	0.001030	280.9	0.896	0.00771	296.3	0.940	0.00871	322.6	1.012	0.0102	370.4	1.132	0.01255
2.364	**75**	165.0	0.562	0.001037	280.9	0.895	0.00749	296.6	0.940	0.00849	323.1	1.012	0.0100	371.1	1.133	0.01228
2.4	75.7	166.2	0.566	0.001042	280.9	0.895	0.00734	296.8	0.940	0.00834	323.4	1.012	0.00982	371.5	1.133	0.01209

Table F-1 Saturation and superheat properties of refrigerant 134a ($C_2H_2F_4$)

Saturated								**Superheated** ($t-t_s$)								
								10 K			30 K			70 K		
p_s [MPa]	t_s [°C]	h_f [kJ/kg]	s_f [kJ/kgK]	v_f [m^3/kg]	h_g [kJ/kg]	s_g [kJ/kgK]	v_g [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	v [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	v [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	v [m^3/kg]
2.416	**76**	166.8	0.567	0.001045	280.9	0.894	0.00727	296.9	0.939	0.00828	323.5	1.012	0.00975	371.8	1.133	0.01201
2.469	**77**	168.6	0.573	0.001052	280.9	0.893	0.00706	297.1	0.939	0.00806	324.0	1.012	0.00953	372.4	1.133	0.01176
2.5	77.6	169.7	0.576	0.001057	280.9	0.892	0.00694	297.3	0.939	0.00795	324.3	1.012	0.00940	372.9	1.133	0.01161
2.523	**78**	170.5	0.578	0.001060	280.8	0.892	0.00685	297.4	0.938	0.00786	324.5	1.012	0.00931	373.1	1.133	0.01150
2.578	**79**	172.4	0.583	0.001069	280.8	0.891	0.00665	297.6	0.938	0.00765	324.9	1.011	0.00909	373.8	1.133	0.01126
2.6	79.4	173.1	0.585	0.001072	280.7	0.890	0.00657	297.7	0.938	0.00757	325.1	1.011	0.00901	374.1	1.133	0.01116
2.633	**80**	174.2	0.588	0.001077	280.7	0.889	0.00645	297.8	0.937	0.00746	325.4	1.011	0.00889	374.5	1.133	0.01102
2.690	**81**	176.2	0.593	0.001086	280.5	0.888	0.00625	298.0	0.937	0.00727	325.9	1.011	0.00868	375.2	1.133	0.01079
2.7	81.2	176.5	0.594	0.001088	280.5	0.888	0.00622	298.1	0.937	0.00723	326.0	1.011	0.00865	375.3	1.134	0.01075
2.747	**82**	178.1	0.599	0.001096	280.4	0.887	0.00606	298.2	0.936	0.00708	326.3	1.011	0.00848	375.9	1.134	0.01057
2.8	82.9	179.9	0.603	0.001105	280.2	0.885	0.00589	298.4	0.935	0.00691	326.7	1.011	0.00831	376.5	1.134	0.01036
2.806	**83**	180.1	0.604	0.001106	280.2	0.885	0.00587	298.4	0.935	0.00690	326.7	1.011	0.00829	376.6	1.134	0.01034
2.865	**84**	182.1	0.609	0.001116	279.9	0.883	0.00568	298.5	0.935	0.00672	327.2	1.011	0.00810	377.2	1.134	0.01013
2.9	84.6	183.2	0.612	0.001122	279.7	0.882	0.00558	298.7	0.935	0.00662	327.5	1.011	0.00800	377.6	1.134	0.01001
2.926	**85**	184.1	0.615	0.001127	279.6	0.882	0.00550	298.7	0.934	0.00654	327.6	1.011	0.00792	377.9	1.134	0.00992
2.987	**86**	186.1	0.620	0.001139	279.3	0.880	0.00532	298.8	0.933	0.00637	328.0	1.011	0.00774	378.6	1.134	0.00971
3.0	86.2	186.6	0.621	0.001141	279.2	0.879	0.00528	298.8	0.933	0.00634	328.1	1.010	0.00770	378.7	1.134	0.00967
3.050	**87**	188.2	0.626	0.001151	278.9	0.878	0.00514	299.0	0.933	0.00621	328.4	1.010	0.00756	379.2	1.134	0.00951
3.1	87.8	189.9	0.630	0.001161	278.5	0.876	0.00500	299.1	0.932	0.00608	328.8	1.010	0.00743	379.8	1.135	0.00936
3.114	**88**	190.4	0.632	0.001164	278.4	0.875	0.00496	299.0	0.932	0.00604	328.9	1.010	0.00739	379.9	1.134	0.00931
3.178	**89**	192.5	0.637	0.001178	277.9	0.873	0.00479	299.2	0.931	0.00589	329.3	1.010	0.00722	380.6	1.135	0.00912
3.2	89.3	193.3	0.639	0.001183	277.7	0.872	0.00473	299.1	0.931	0.00583	329.3	1.010	0.00717	380.7	1.135	0.00906
3.244	**90**	194.8	0.643	0.001194	277.3	0.871	0.00461	299.2	0.930	0.00573	329.7	1.010	0.00706	381.2	1.135	0.00894
3.3	90.8	196.7	0.648	0.001207	276.7	0.868	0.00447	299.2	0.929	0.00560	329.9	1.010	0.00692	381.7	1.135	0.00878
3.311	**91**	197.1	0.650	0.001210	276.6	0.868	0.00444	299.3	0.929	0.00558	330.0	1.010	0.00690	381.9	1.135	0.00875

Table F-1 Saturation and superheat properties of refrigerant 134a ($C_2H_2F_4$)

Saturated								Superheated ($t - t_s$)								
								10 K			30 K			70 K		
p_s [MPa]	t_s [°C]	h_f [kJ/kg]	s_f [kJ/kgK]	v_f [m^3/kg]	h_g [kJ/kg]	s_g [kJ/kgK]	v_g [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	v [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	v [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	v [m^3/kg]
3.379	**92**	199.4	0.656	0.001228	275.8	0.865	0.00427	299.3	0.929	0.00543	330.4	1.009	0.00674	382.5	1.135	0.00857
3.4	92.3	200.2	0.658	0.001234	275.5	0.864	0.00422	299.3	0.928	0.00538	330.5	1.009	0.00670	382.7	1.135	0.00852
3.449	**93**	201.9	0.662	0.001248	274.8	0.861	0.00409	299.3	0.928	0.00528	330.8	1.009	0.00659	383.2	1.135	0.00840
3.5	93.7	203.7	0.667	0.001263	274.1	0.859	0.00397	299.3	0.927	0.00518	331.0	1.009	0.00648	383.6	1.135	0.00827
3.519	**94**	204.4	0.669	0.001269	273.8	0.858	0.00392	299.4	0.927	0.00514	331.2	1.009	0.00644	383.8	1.135	0.00823
3.591	**95**	207.1	0.676	0.001294	272.5	0.854	0.00374	299.3	0.926	0.00500	331.5	1.009	0.00630	384.4	1.135	0.00806
3.6	95.1	207.4	0.677	0.001297	272.4	0.853	0.00372	299.3	0.925	0.00498	331.5	1.009	0.00628	384.5	1.135	0.00804
3.664	**96**	209.9	0.683	0.001323	271.0	0.849	0.00356	299.3	0.925	0.00487	331.9	1.008	0.00616	385.1	1.136	0.00790
3.7	96.5	211.4	0.687	0.001338	270.2	0.846	0.00347	299.3	0.924	0.00480	332.1	1.008	0.00609	385.4	1.136	0.00782
3.739	**97**	213.0	0.691	0.001356	269.2	0.843	0.00337	299.2	0.923	0.00473	332.2	1.008	0.00601	385.7	1.136	0.00774
3.8	97.8	215.6	0.698	0.001389	267.5	0.838	0.00321	299.2	0.923	0.00463	332.5	1.008	0.00590	386.2	1.136	0.00761
3.815	**98**	216.3	0.700	0.001398	267.0	0.837	0.00317	299.2	0.922	0.00460	332.5	1.008	0.00588	386.3	1.136	0.00758
3.893	**99**	220.2	0.710	0.001452	264.0	0.828	0.00295	299.0	0.921	0.00447	332.9	1.007	0.00574	386.9	1.136	0.00742
3.9	99.1	220.6	0.711	0.001458	263.7	0.827	0.00293	299.1	0.921	0.00446	332.9	1.007	0.00573	387.0	1.136	0.00741
3.972	**100**	225.2	0.723	0.001536	259.5	0.815	0.00268	298.9	0.920	0.00435	333.2	1.007	0.00561	387.6	1.136	0.00727
4.0	100.3	227.4	0.729	0.001580	257.2	0.809	0.00256	298.8	0.919	0.00430	333.2	1.007	0.00556	387.7	1.136	0.00722
4.054	**101**	236.2	0.752	0.001794	247.3	0.782	0.00215	298.7	0.918	0.00422	333.5	1.007	0.00548	388.2	1.136	0.00712
4.100	101.1	241.5	0.766	0.001954	241.5	0.766	0.00195	297.6	0.915	0.00411	332.9	1.005	0.00539	387.9	1.135	0.00702

Appendix G Further Theory

Polytropic Process in Terms of Volume or Specific Volume

Equation (3-18) describes a polytropic process that takes place from state 1 to state 2:

$$p_1 \mathscr{V}_1^n = p_2 \mathscr{V}_2^n .$$

As the same mass, *m*, is present throughout the process it is possible to divide both sides of the equation by the mass raised to the power of *n*. Hence, on a 'per-unit-mass' basis

$$p_1 \frac{\mathscr{V}_1^n}{m^n} = p_2 \frac{\mathscr{V}_2^n}{m^n}$$

$$p_1 \frac{\mathscr{V}_1^n}{m^n} = p_2 \frac{\mathscr{V}_2^n}{m^n}$$

$$p_1 \left(\frac{\mathscr{V}_1}{m}\right)^{\mathrm{n}} = p_2 \left(\frac{\mathscr{V}_2}{m}\right)^n$$

$$p_1 v_1^n = p_2 v_2^n$$

Thus the polytropic relationship can be written in terms of either the volume or the specific volume.

Volumetric Efficiency of an Ideal Reciprocating Compressor

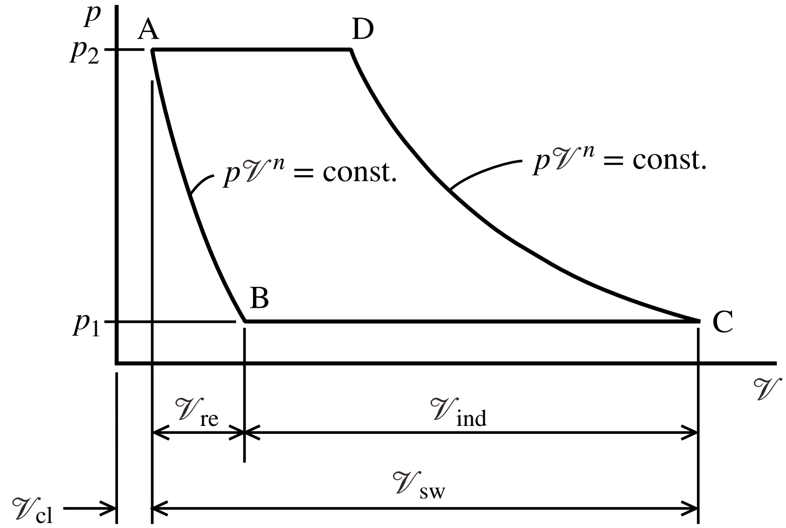


Figure 4-2 (repeated) p-$\mathscr{V}$ diagram for a reciprocating compressor.

The volumetric efficiency and the clearance ratio of a reciprocating compressor are defined by Equations (4-1) and (4-3) respectively. The induced volume and the swept volume are identified in Figure 4-2. It is assumed that the inlet and discharge valves are ideal and do not cause any pressure drop as the gas passes through them. Therefore from D to A in Figure 4-2 the pressure within the cylinder equals the pressure in the discharge pipe. From B to C the pressure within the cylinder equals the pressure in the inlet pipe.

$$E_{vol} = \frac{\mathscr{V}_{ind}}{\mathscr{V}_{sw}} \tag*{(repeated) (4-1)}$$

$$r_{cl} = \frac{\mathscr{V}_{cl}}{\mathscr{V}_{sw}} \tag*{(repeated) (4-3)}$$

where

E_{vol} = volumetric efficiency

$\mathscr{V}_{ind}$ = induced volume m^3

$\mathscr{V}_{\mathrm{sw}}$ = swept volume m^3

r_{cl} = clearance ratio

From Equation (4-1) and referring to Figure 4-2

$$E_{\mathrm{vol}} = \frac{\mathscr{V}_{\mathrm{C}} - \mathscr{V}_{\mathrm{B}}}{\mathscr{V}_C - \mathscr{V}_{\mathrm{A}}}.$$

From Equation (4-3) and referring to Figure 4-2

$$r_{\mathrm{cl}} = \frac{\mathscr{V}_{\mathrm{A}}}{\mathscr{V}_C - \mathscr{V}_{\mathrm{A}}}.$$

Hence,

$$\mathscr{V}_C - \mathscr{V}_{\mathrm{A}} = \frac{\mathscr{V}_{\mathrm{A}}}{r_{\mathrm{cl}}}$$

and

$$\mathscr{V}_C = \frac{\mathscr{V}_{\mathrm{A}}}{r_{\mathrm{cl}}} + \mathscr{V}_{\mathrm{A}}.$$

Applying the polytropic relationship to process AB:

$$p_2 \mathscr{V}_{\mathrm{A}}^n = p_1 \mathscr{V}_{\mathrm{B}}^n$$

$$\frac{\mathscr{V}_{\mathrm{B}}}{\mathscr{V}_{\mathrm{A}}} = \left(\frac{p_2}{p_1}\right)^{\frac{1}{n}}$$

$$\mathscr{V}_{\mathrm{B}} = \mathscr{V}_{\mathrm{A}} \left(\frac{p_2}{p_1}\right)^{\frac{1}{n}}.$$

Therefore

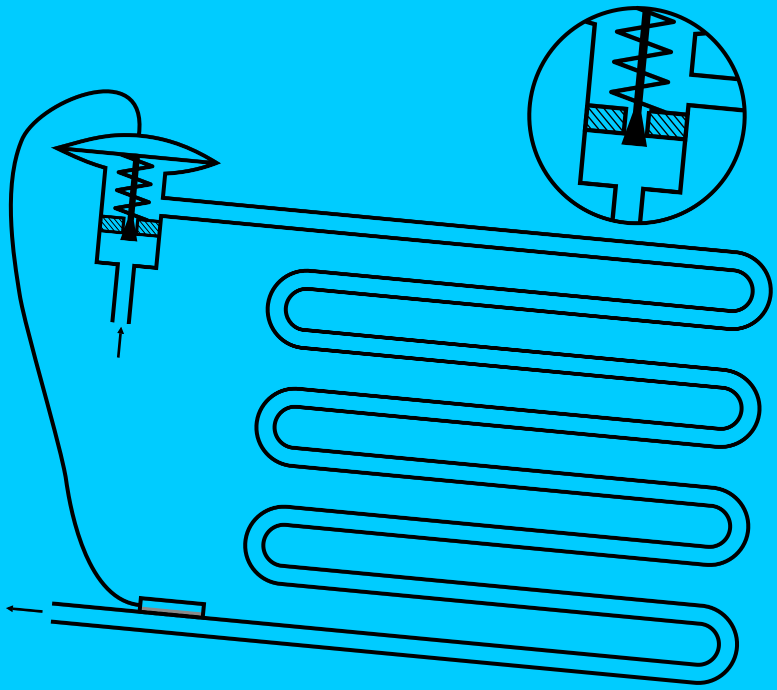
$$E_{\mathrm{vol}} = \frac{\mathscr{V}_{\mathrm{A}}/r_{\mathrm{cl}} + \mathscr{V}_{\mathrm{A}} - \mathscr{V}_{\mathrm{A}}(p_2/p_1)^{1/n}}{\mathscr{V}_{\mathrm{A}}/r_{\mathrm{cl}}}$$

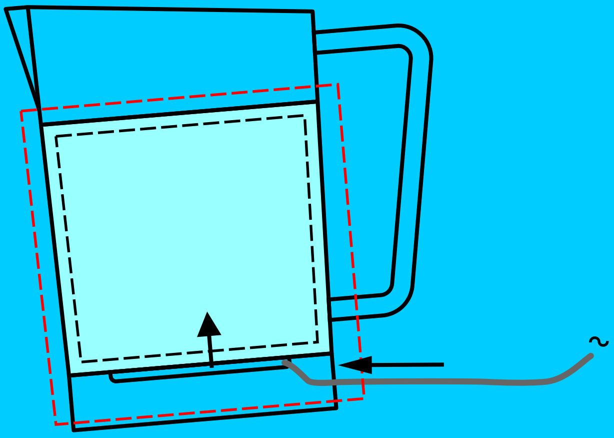
$$= 1 + r_{\mathrm{cl}} - r_{\mathrm{cl}}(\,p_2/p_1)^{1/n}.$$

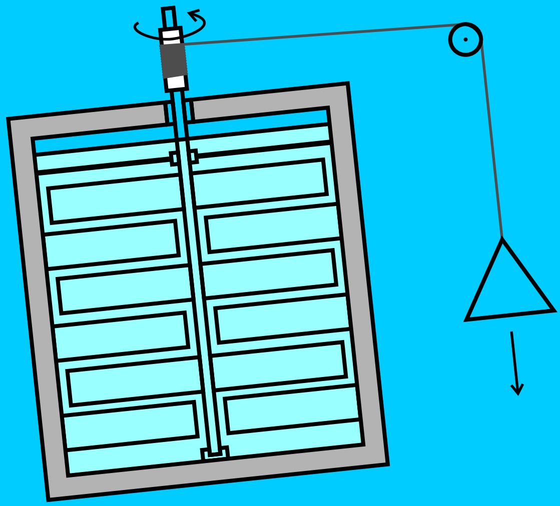
Hence,

$$E_{\mathrm{vol}} = 1 - r_{\mathrm{cl}}\left[\left(\frac{p_2}{p_1}\right)^{1/n} - 1\right].$$

(repeated) (4-2)







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