Winter 2011-01-01

Simulation of Reverse Flow Heat Recovery for Pharmaceutical Clean Rooms in Colombia

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This Report is submitted in partial fulfilment of the requirements of the Master of Engineering in Pharmaceutical Process Control and Automation of the Dublin Institute of Technology

January 10th 2011

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Declaration

I certify that this thesis, which I submit in partial fulfilment of the requirements of the ME Pharmaceutical Process Control and Automation (Programme Ref: DT702/3) of the Dublin Institute of Technology, is entirely my own work and that any content that relates to the work of other individuals, published or otherwise, are acknowledged through appropriate referencing.

I also confirm that this work has not been submitted for assessment in whole or part for an award in any other Institute or University.

Signed: ___________________________

Date: ______________________________

I dedicate this thesis to God and to loving family: my mother Hermencia, my brother Javier, my husband Keith, and my son Anthony. Your constant encouragement and support throughout my life has allowed me to complete my education. Words cannot express the gratitude and appreciation that I feel for all that you have done for me.

Abstract

This dissertation examines, analyses, implements, and evaluates an innovative software heat transfer model for predicting air-to-air heat (energy) recovered in pharmaceutical drying clean rooms in Colombia. The approach provides a synergy between Reverse Flow Heat Recovery technology and activities for the consumption of this energy, not solely within the process, but throughout the whole pharmaceutical complex (e.g. warehouse, office and alternative processes). This novel integrated modelling tool developed using off the shelf software application such as MS Excel combined with MS Visual programming to calculate psychometric points, mass and enthalpy balances for analysing the operation of heat recovery systems. This makes the tool inexpensive and immediately useful "as is". A case study of a drying operation at a pharmaceutical company in Colombia is used to aid in a critical review of the tool from a pragmatic real-world perspective.

Results show dryers are potentially large emission sources of heat in the pharmaceutical industry, not solely within the process, but throughout the whole pharmaceutical complex (e.g. warehouse, office and alternative processes). The project also illustrates that as weather variations are not rapid, when compared to control systems such as ABS breaking on a car or other millisecond control systems, use of MS Excel derived models, which have a greater user friendly interface, can be valid inexpensive tools with immediate energy saving potential. Mathematical models based on these input-output relationships were developed. The assumptions and equations used to arrive to the heat recovered are given in a clear Human Model Interface.

Acknowledgements

I would like to acknowledge my thesis committee advisor Dr. John McGrory who allowed me great flexibility in choosing the direction of this work. Thanks go also to Dr. Hassan Ali for his constant support, encouragement and motivation.

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Nomenclature

ACH	Air changes per hour
API	Active Pharmaceutical Ingredient
BMS	Building Management System
Btu	British Thermal Units
CFM	Cubic feet per minute
cGMP	Current Good Manufacturing Practices
Cp	Specific heat capacity
Dwell	Duration in time of the dampers operation
ELC	Easy Logic Controller
GWh	Gigawatt Hour
HEPA	High Efficiency Particulate Air
HR	Heat Recovery
I/O	Input and Outputs
HVAC	Heating, ventilation, and air conditioning
ISO	International Organization for Standardization
kWh	Kilowatt-hour
MAU	Make-up Air Unit
MBtu	Million British Thermal Units
micron	A unit of length equal to one millionth (10) of a meter.
m3	Cubic meter
ULPA	Ultra-Low Penetration Air

Chapter 1
Introduction

1.1 Introduction

This chapter defines the energy management problem to be investigated, states the context of the research in Colombia focusing in energy usage and requirements for pharmaceutical production areas and clean rooms, and postulates the scope of work.

Considering pharmaceutical drying as a particularly energy-consuming operation and a potential large emission source of heat, the present dissertation studies air-to-air heat (energy) recovery options at pharmaceutical drying clean rooms in Colombia, and proposes user-friendly software of Reverse Flow Heat Recovery to show the heat recovered from the drying operation and the energy savings to the end user

1.2 Background

1.2.1 Structure of Energy in Colombia

The electricity sector in Colombia is dominated by large hydropower generation (65%) and thermal generation (35%), although Colombia electricity is largely generated using renewable energy technologies (i.e. hydropower), further savings in areas such as Reverse Flow Heat Recovery are possible and viable.

Figure 1. Map of Colombia [2]

According to the International Energy Statistics [1], Colombia consumed 381 billions kWh (1.3 quadrillion BTUs) of total energy in 2007. Oil constituted the largest part of this amount, followed by hydroelectricity.

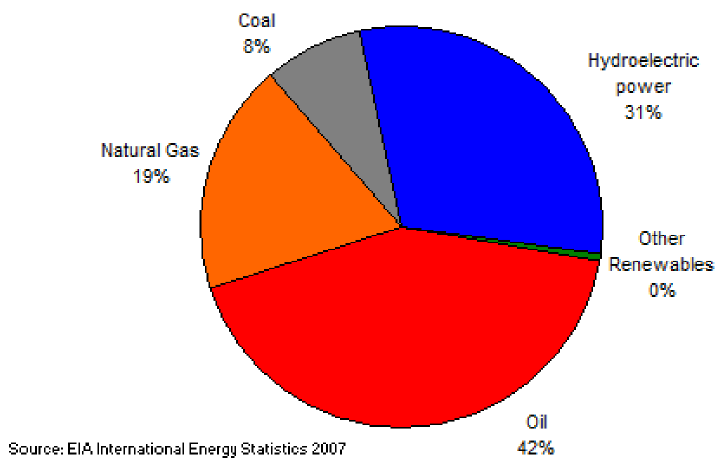
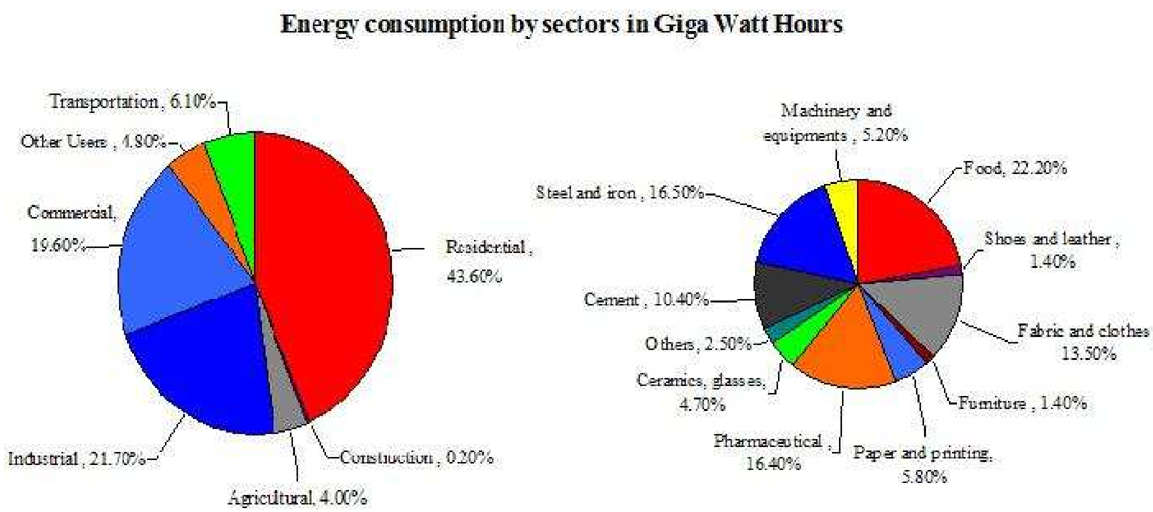


Figure 2. Total Energy Consumption in Colombia, by Type

Colombian Energy Demand

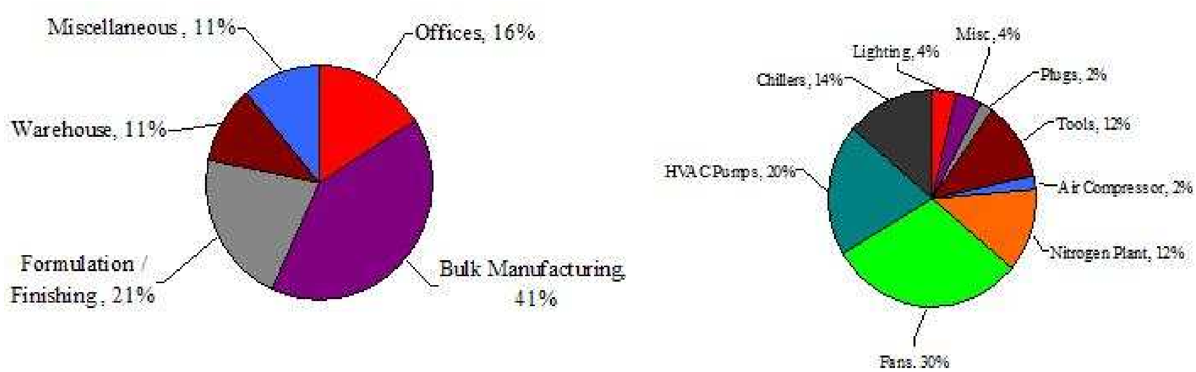
The energy demand by sectors is divided in Giga Watt Hours as shown in Figure 3(a); the industrial sector represents 21.70% [3]. Figure 3(b) shows the most important industries from the electric energy consumption point of view. Pharmaceutical companies' energy consumption represents about 16.40% of the total industrial sector.



(a) (b)

Figure 3. Colombian energy consumption by sectors (GWh)

Although energy costs typically represent a small percentage of total production cost in the pharmaceutical industry, the cost of energy in Figure 4(a) for the pharmaceutical areas and Figure 4(b) for clean rooms are still significant [6, 15].



(a) (b)

Figure 4. Breakdown of energy usages within the pharmaceutical sector (GWh)

The particular processes employed in a pharmaceutical production sequence vary by product and by plant. The key factors affecting a plant energy consumption include facility type (e.g., bulk production), the products produced (e.g. Tablets), the plant location, and the efficiency of the plant. However, from Figure 4(b), it is possible to see that HVAC pumps and fans in Bulk Manufacturing production are the largest consumers of energy. The large demand in energy in HVAC pumps and fans in Bulk Manufacturing production is principally due to the high requirements of air changes per hour for pharmaceutical clean rooms for control of particle contamination, as per International Clean Room Standards such as ISO 14644-1 "Classification of Air Cleanliness" [19].

This dissertation examines, analyses, implements, and evaluates an innovative software heat transfer model for predicting air-to-air heat (energy) recovered in pharmaceutical drying clean rooms in Colombia. Heat recovery analysis is calculated only for the drying operation, as this is the final and more critical operation of the process [18]. Moreover, it is a potential large emission source of heat. The approach provides a synergy between Reverse Flow Heat Recovery technology and activities for the consumption of this energy, not solely within the process, but throughout the whole pharmaceutical complex (e.g. warehouse, office, and alternative processes).

1.3 Objectives

The project objectives are defined as part of an ongoing management review process to ensure that the project finishes on time, meets pre-determined criteria, and meet the requirements for what it was initiated. The project objectives are realistic and measurable so that they can be evaluated at the conclusion of a project to see whether it was achieved or not. The objectives of the project are:

- To identify and evaluate heat recovery options in the pharmaceutical drying operation in Colombia. In particular the mathematical model that permits outputs to be derived or predicted based on inputs.

- To investigate techniques for presenting heat recovery options from the drying operation.

- To develop and implement a system where the model aspects, data storage aspects and visualisation aspects are combined.

- To develop user-friendly virtual simulation application software to show the heat recovered from the drying operation and the energy savings to the end user.

1.4 Summary of other chapters

This dissertation is divided into five chapters.

Chapter 1: Defines the energy management problem to be investigated, states the context of the research and postulate the scope of work focusing on the drying operation, clean rooms, and heating ventilation and air conditioning (HVAC) systems.

Chapter 2: Identifies and evaluates the trends, main production processes, structure, and production characteristics of the Colombian pharmaceutical industry. Next, a description of the controls available is provided. It also identifies potential heat recovery options and reviews common air–to-air heat (energy) recovery technologies, focusing on the Reverse Flow Heat Recovery technology.

Chapter 3: Expands the literature review presented in Chapter 2. It also clearly explains the theoretical framework of the mathematical model used in the proposed software.

Chapter 4: Provides a specific and detailed account of the simulation software implementation.

Chapter 5: Summarised the dissertation with emphasis on the results obtained, and the suggestions for further work.

Chapter 2

State of Art, Literature Review

2.1 Introduction

This chapter outlines the trends, structure, and production characteristics of the Colombian pharmaceutical industry, focusing on the drying operation, clean rooms, and heating ventilation and air conditioning (HVAC) systems. Next, a description of the controls is provided. It also evaluates and identifies potential heat recovery options and finally reviews common air–to-air heat (energy) recovery technologies, focusing on the Reverse Flow Heat Recovery technology.

2.2 Pharmaceutical Industry in Colombia

Today, the Colombian pharmaceutical industry is characterised by being made up of domestic and multinational companies and associated laboratories, which in total, make up more than 300 firms. The largest local manufacturers are Bussié, Genfar, Lafrancol, La Santé, Procaps, and Tecnoquímicas, which produce generic copycats.

Figure 5 . Pharmaceutical Plant in Colombia

2.2.1 Process description

As defined in the U.S. EPA's Profile of the pharmaceutical Manufacturing Industry [7], there are three overall stages in the production of bulk pharmaceutical products. Each of these stages is described in Figure 6.

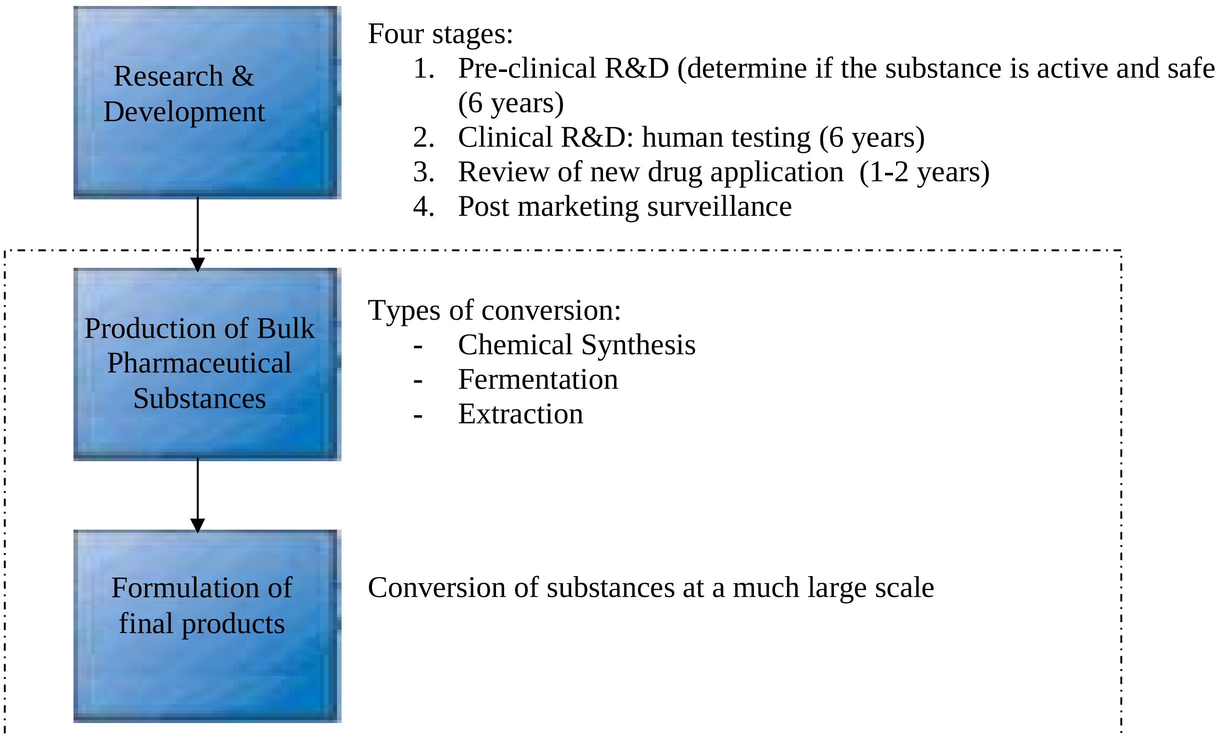


Figure 6. Main process steps in the manufacture of bulk pharmaceutical products (Adaptation from "Profile of the Pharmaceutical Manufacturing Industry [7]")

The regulations which cover this industry have made production and commercialisation of many medicines by Colombia possible. The Colombian Pharmaceutical industry has been able to develop and supply the local market active molecules of original medicines patented in other countries without incurring in Research and Development (R&D) processes for new medicines.

Bulk pharmaceutical substances are produced via chemical synthesis, extraction, fermentation, or a combination of these processes [6, 7].

Chemical synthesis

Figure 7 shows a simplified diagram of the chemical synthesis process for pharmaceuticals [7].

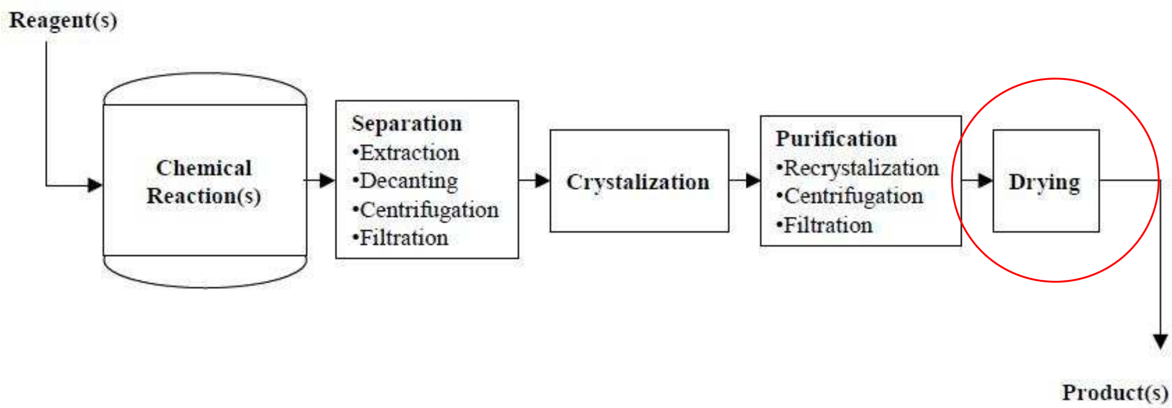


Figure 7. Simplified chemical synthesis diagram

Although all the operations involved in chemical synthesis for the production of bulk pharmaceutical substances in Figure 7, need to be carried out in a chemically controlled area. Heat recovery analysis is calculated only for the drying operation, as this is the final and more critical operation of the process [18]. Moreover, it is a potential large emission source of heat.

Drying Operation

In general, drying means the removal of relatively small amounts of water or other solvent from a material to reduce the content of residual liquid to an acceptably low value. As seen in Figure 7, drying is usually the final step in a series of operations, and the product from the dryer is often ready for final packing [32].

In most cases, drying is accomplished by vaporizing the solvent that is contained in the product, and to do this latent heat of vaporization must be supplied. There are, thus, two important process-controlling factors that enter into the unit operation of drying: (1) Transfer of heat to provide the necessary latent heat of vaporization.

(2) Movement of solvent or solvent vapour through the product material. After the dried product is separated, the moist vapour is exhausted to the atmosphere.

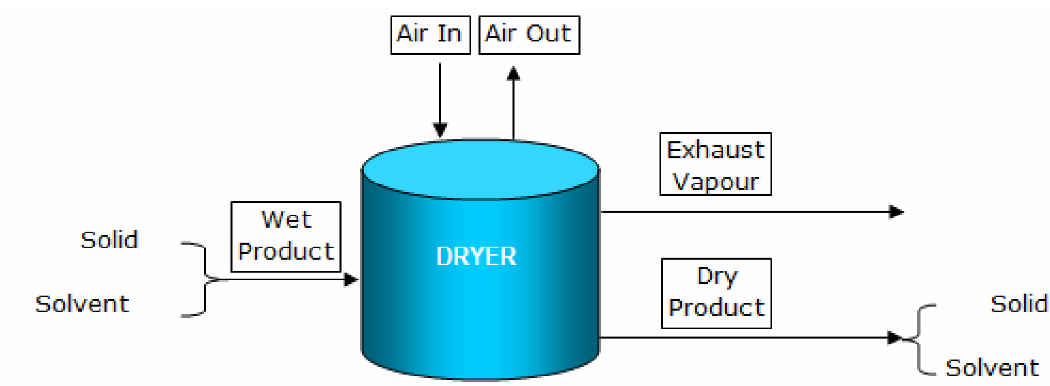


Figure 8 . Drying operation block diagram

Drying processes fall into three categories [30]:

1. Air and contact drying under atmospheric pressure: In air and contact drying, heat is transferred through the product either from heated air or water. i.e. Rotary dryers.
2. Vacuum drying. In vacuum drying, advantage is taken of the fact that evaporation of water occurs more readily at lower pressures than at higher ones. Heat transfer in vacuum drying is generally by conduction, sometimes by radiation.
3. Freeze drying. In freeze drying, the water vapour is sublimed off frozen material. Suitable temperatures and pressures must be established in the dryer to ensure that sublimation occurs.

Several types of dryers are used in pharmaceutical manufacture. The most widely used for pharmaceutical tablets, are rotary dryers.

Rotary Dryer

Rotary dryers are used extensively for drying solids. The rotary dryer consist of a rotating drum with angle lifting blades which lift the feed as the drum rotates and showers it in the stream of hot air flowing through the drum. Both co-current and counter-current configurations are used. Figure 9 shows typical counter-current rotary dryer used to dry tablets.

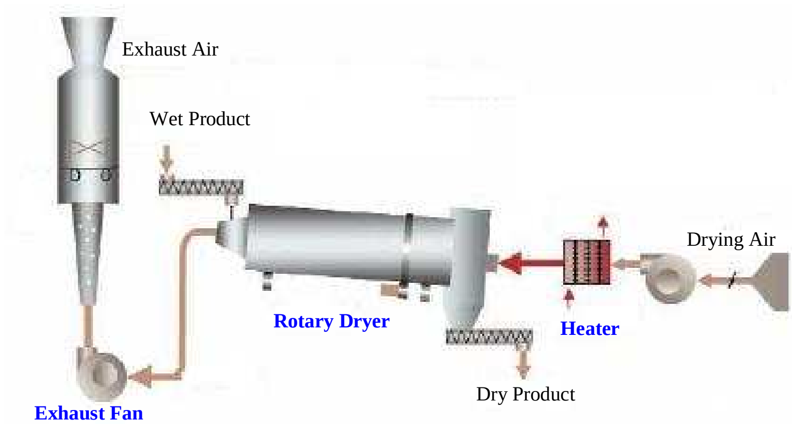


Figure 9. Counter-current rotary dryer

In pharmaceutical applications it is essential that the drying of a given product takes place under extremely clean conditions, yielding a product free from contamination and foreign particle matter [34]. The following sections explain clean room conditions and heating ventilation and air conditioning (HVAC) systems requirements in detail.

Pharmaceutical clean rooms

Federal Standard 200E [20], defines a clean room as a room in which the concentration of airborne particles is controlled to specific limits. British standard 5295 [21], defines a clean room as a room with control of particle contamination, constructed and used as a way to minimize the introduction, generation and retention of particles inside the room and in which the temperature, humidity, airflow patterns, air motion and pressure are controlled.

Pharmaceutical clean rooms are classified according to the required characteristics of the environment. Each manufacturing operation requires an appropriate environmental cleanliness level in the operational state in order to minimize the risks of particulate or microbiological contamination of the product or materials being handled. The highest level of control will be directed to those areas, typically known as critical zones, in which there is contact with the product (or intermediate), and where aseptic manipulation of uncovered containers, closures, or components is present. These areas are designed to comply with Class 5 of ISO 14644 (ISO Class 5 is functionally equivalent to traditional US Federal Standard (FS) 209 E Class 100, and to EU Grade A). These areas are equipped with total-coverage High Efficiency Particulate Arresting (HEPA) filtration, and unidirectional airflow is maintained to the extent it is technically possible to do so. European and United States aseptic processing area zoning differs: In the United States, the area immediately adjacent to the critical zone is typically Class 7 (FS 209 Class 10,000).

Table 1. Airborne particulate classification for manufacture of sterile preparation [35]

Grade	At rest		In operation	
	Maximum number of particles permitted/m^3		Maximum number of particles permitted/m^3	
	0.5–5.0 μm	>5.0 μm	0.5–5.0 μm	>5.0 μm
A	3500	0	3500	0
B	3500	0	350 000	2000
C	350 000	2000	3 500 000	20000
D	3 500 000	20000	Not defined	Not defined

These areas should be designed to reach certain specified air-cleanliness levels in the "at rest" occupancy state. For the manufacture of pharmaceutical preparations, the four grades are as follow [18]:

- Grade A: The local zone for high-risk operations, e.g. drying, filling and making aseptic connections. Normally such conditions are provided by a laminar-airflow workstation. Laminar-airflow systems should provide a homogeneous air speed of approximately 0.45m/s ± 21% at the working position.
- Grade B: In aseptic preparation and filling, the background environment for the grade A zone.
- Grades C and D: Clean areas for carrying out less critical stages in the manufacture of sterile products.

An important part of clean room technology is the pressurization of the controlled area to prevent migration of particulates into the clean area. In a clean room it is important to demonstrate that no particulate will enter (positive) or exit (negative) the controlled area due to construction (wall and/or ceiling utility penetrations, mouse holes and threshold gaps). Differential pressures will indicate that both direction and magnitude of static pressures is sufficient to control migration of particulate from one controlled area to another (or even an uncontrolled area).

Clean Room Standards

Table 2 shows international clean room standards and approximate number of particles per m^3 [19].

Table 2. Air Classification for International Clean Room Standards

Approximate Particles per m³ ≥0.5 mm	US 209E 1992	US 209E Imperial equivalent	EEC CGMP 1989	France AFNOR 1989	Germany VDI 2083 1989	Britain BS 5295 1989	Japan JIS B 9920 1989	ISO EN 14644-1 1999
1								
3.5					0		2	2
10	M 1							
35	M 1.5	1			1		3	3
100	M 2							
353	M 2.5	10			2		4	4
1 000	M 3							
3 530	M 3.5	100	A + B	4 000	3	E or F	5	5
10 000	M 4							
35 300	M 4.5	1 000			4	G or H	6	6
100 000	M 5							
353 000	M 5.5	10 000	C	400 000	5	J	7	7
1 000 000	M 6							
3 530 000	M 6.5	100 000	D	4 000 000	6	K	8	8
10 000 000	M 7							
100 000 000	M 7.5	1 000 000		40 000 000		L	9	9

The simulation software is based on ISO Clean room Standards. ISO - the International Organization for Standardization is an international standard setting body used in Colombia. The ISO Standards cover a wide variety of items ranging from medical equipment to shipbuilding:

- ISO-14644-1 Classification of Air Cleanliness
- ISO-14644-2 Clean room Testing for Compliance
- ISO-14644-3 Methods for Evaluating & Measuring Clean rooms & Associated Controlled Environment
- ISO-14644-4 Clean room Design & Construction
- ISO-14644-5 Clean room Operations
- ISO-14644-6 Terms, Definitions & Units
- ISO-14644-7 Enhanced Clean Devices
- ISO-14644-8 Molecular Contamination
- ISO-14698-1 Bio contamination: Control General Principles
- ISO-14698-2 Bio contamination: Evaluation & Interpretation of Data
- ISO-14698-3 Bio contamination: Methodology for Measuring Efficiency of Cleaning Inert Surfaces

Figure 10 shows the arrangement and distribution of equipment in a drying clean room class 10,000 Non-unidirectional (turbulent flow) and class 100 unidirectional (laminar flow) [17].

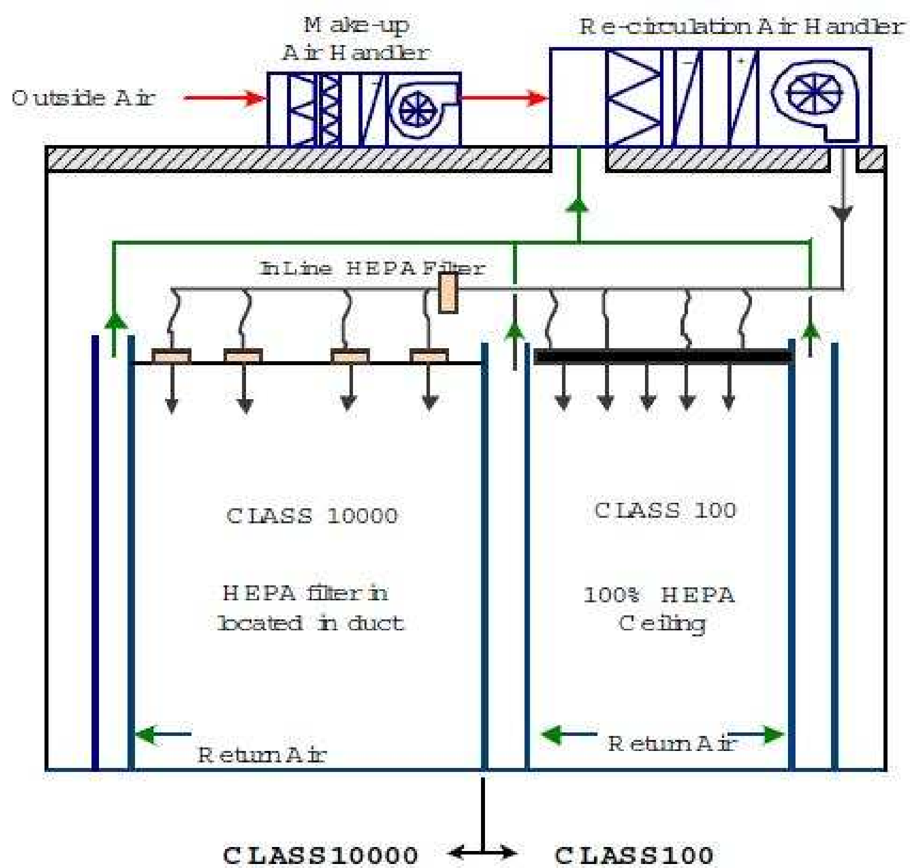


Figure 10. Clean room drying operation - HVAC System [17]

The drying clean room, class 100, has unidirectional (laminar flow) because airflow is an important aspect of particle control for this operation. In unidirectional airflow pattern the entire body of air within a confined area moves with uniform velocity and in single direction with generally parallel streams. In class 10,000, less critical operations are carried out, therefore non directional airflow (turbulent flow), which has a varying velocity, multiple pass circulation or non-parallel flow direction can be use.

Heating, Ventilation, and Air Conditioning (HVAC) System

The purpose of the HVAC system is to add or remove heat and moisture, as well as to remove undesirable air contaminants in order to maintain the desired indoor environment. The components of HVAC systems generally include dampers, supply and exhaust fans, filters, humidifiers, dehumidifiers, heating and cooling coils, ducts, and various sensors [10]. The HVAC system must have a source of cold, to remove the heat and a source of heat to reduce humidity. Moreover, a distribution network is used to deliver the air to the points of use and control the air change rate. In the Colombian pharmaceutical industry, HVAC components are closely supervised by national and international regulation bodies like INVIMA [11] and FDA [5]. Figure 11 shows the main equipment of the HVAC system.

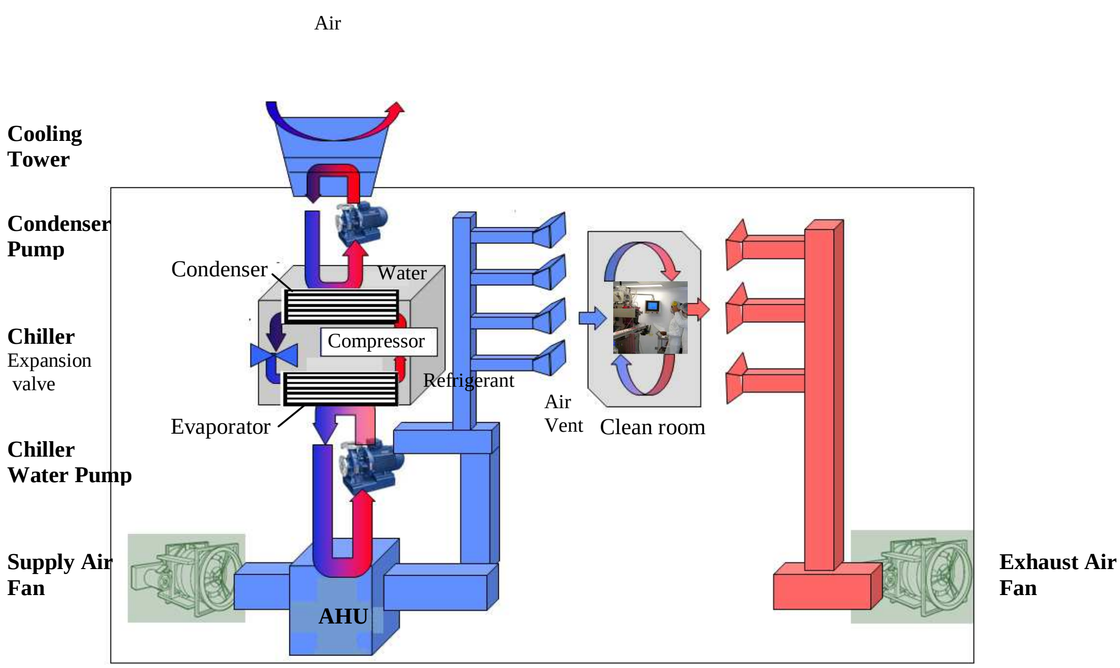


Figure 11. HVAC Main Equipment

The cooling tower is connected to the chillers which are connected to the air-handling unit. The cooling tower is an evaporative cooler that transfers the heat from the water to the outside air through the process of evaporation as the water is sprayed or falls through the air.

The chiller generates cold water which is supplied to areas where AHU’s are used to provide cooling. Figure 12 shows a schematic diagram of the typical cooling process in a water chiller.

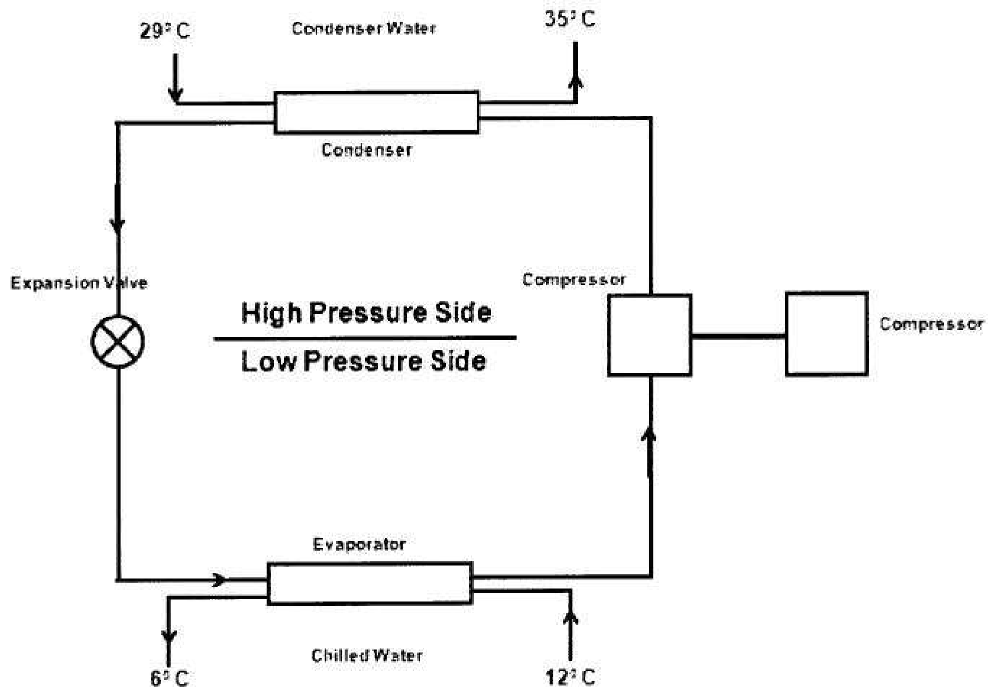


Figure 12. Water Chiller Cooling Process

The condenser is a component where the refrigerant rejects heat to the condenser, causing refrigerant’s phase change from gas to liquid. The condenser is supplied by a closed loop that goes to a cooling tower. High pressure liquid refrigerant passes through the expansion valve, reducing pressure and flashing to a gas within the evaporator, in doing this the refrigerant medium is absorbing energy from the chilled water as it changes from liquid/gas mix to gas. The chilled water produced by the evaporator is circulated in another secondary closed loop to parts of the facility where it is used to provide air conditioning. The secondary closed loop consist of the AHU which is used to handled a large quantity of cooled air and distribute it to various parts of the facility.

The compressor takes the low-pressure vaporized refrigerant coming out of the evaporator, compresses it to a higher pressure, and discharges it into the condenser. There are three types of compressor for chillers: scroll compressor, screw compressor and centrifugal compressor.

The air-handling unit (AHU) contains a set of supply and exhaust fans which take air in and out of spaces or zones within the clean room. Sensors and actuators inside zones serve to provide feedback to the AHU which works to maintain the temperature and air circulation.

The duct work is called a terminal reheat system where outside air enters through dampers, and then mixes with return air. The air is then driven though the cooling coil by a supply fan. The overcooled air, which has lost moisture, is transported along the ductwork. A heat unit then reheat the air to desired temperature, when its relative humidity also drops to the desired level as temperature increases. The air is then supplied as required. If high change rates are required, the overcool-reheat method is used to remove moisture and control temperature with continuous supply of air.

HVAC System Components Identification

Filters: All air entering a clean room is treated by one or more filters. High-Efficiency Particulate Air (HEPA) and Ultra-Low Penetration Air (ULPA) filters are the most common filters used in clean room applications.

HEPA is an acronym for "high efficiency particulate air". The HEPA filters work on diffusion principle to remove particulate matter and are extremely important for maintaining contamination control. There are different categories of HEPA filters. True or absolute HEPA filters must pass a test to be considered HEPA worthy. True HEPA filters will have a serial number assigned to them if they are able to trap at least 99.97 percent of particles of 0.3 microns. HEPA often capture only 85 to 90 percent of particles and that percent can fall even lower for particles of 1 micron and below. HEPA type filters are less expensive than true or absolute HEPA filters.

Terminal Filters: These filters are available in two types of constructions: Box type and Flanged type.

Duct system design and construction: Stainless Steel (SS304) ducting is provided to supply air to the clean room and to bring back air from the return air grilles to the return air fan.

Monitoring devices: Special monitoring devices known as Magnahelic or Photohelic gauges measure the pressure differentials across a diaphragm and depict the value in terms of inches of water or some other convenient scale. These instruments are very accurate and sensitive to very small changes in pressure differential. They are connected directly to an alarm system that will cause a visual signal (flashing light) to report a deviation outside a prescribed range of pressure differential.

Isolators: Barrier isolators minimize the extent of personnel contact.

2.2.2. Company Background (Case Study)

ABC[1] Colombia, with its subsidiaries is a flexible and multi-product company involved in the production and distribution of generic bulk active pharmaceutical ingredients (API's), baby care products, personal care products and animal/veterinary health products. ABC Colombia started operations in 1934 and is based in Bogotá, Colombia. Figure 13 shows the aerial view of the plant in Bogotá.

Active Pharmaceutical Ingredients (API's) are produced in white hygienic zones where direct material handling like chemical reactions, separation, crystallisation, purification and drying are carried out. Bulk active ingredients currently being produced by chemical synthesis in ABC Colombia include tablets such as Aspirin [6].

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[1] The company name has been changed to protect confidentiality.

Figure 13. ABC Bogotá's Company Site Aerial View [6]

According to ABC Colombia (case study, and based on their experience, the drying operation is done in Class 100 with Class 100,000 background. Tables 3 and 4 summarize some of the requirements and typical design criteria used for Active Pharmaceutical Ingredient (API) production in ABC Colombia [16], which are according to the requirements specified in Proceedings Institute of Environmental Sciences and Technology (IEST-RP-CC012) [17].

Table 3. Clean room requirements for API production

Clean Room Class	**Clean Room Dimension**	**Airflow**	**Air changes/hr**
	(m, l. w. h.)	Type	
100	6 x 6 x 3	Unidirectional (Laminar flow)	240 - 480
1,000	6 x 6 x 3	Non-unidirectional (Turbulent flow)	150 – 240
10,000	6 x 6 x 3	Non-unidirectional (Turbulent flow)	60 - 90

Table 4. Typical Design Criteria for API production

Parameter	Design Criteria / Range	Observation
Temperature	21.1°C +/- 1.1 °C (Range: 19 °C - 24 °C)	
Relative Humidity (RH)	50% +/-5% (Range: 50 – 60%)	Rooms for compression, dispensing and blending. In some areas where moisture sensitivity products are processed, even lower relative humidity of 27% +/-5% is needed
Room Pressurization	Normally, the minimum design differential pressure between rooms and the adjacent production corridor shall be maintained at 12.5 Pa with all doors closed.	It is maintained at a negative pressure to the adjacent access corridor in order to reduce cross contamination.
Ventilation	A minimum of 10% fresh air shall be provided in manufacturing areas.	Rooms with high moisture levels or potential odour issues shall be 100% exhausted to avoid humidity and odour.

Hence, according to the Institute of Environmental Sciences and Technology [17], a Class 100 room with dimensions of 6 m x 6 m x 3 m high needs an air flow rate of at least (0.203 x 6 x 6) = 7.3 m^3/s and at most 14.6 ^{m3}/s. A class 100,000 room of the same dimensions would need an air flow rate of (5 x 6 x 6 x 3) / 3600 = 0.15 m^3/s as a minimum or 1.44 m^3/s as a maximum.

2.3 HVAC controls

Feedback control is usually used in the HVAC system. An HVAC control system in a clean room transforms the operating instructions for desired environmental conditions into the air temperatures and ventilation volumes desired in the working environment. The control system has the task of regulating the HVAC system.

Currently ABC Colombia uses a Building Management System (BMS) system using a controller Distech ECP-300 mounted on the make-up air unit (MAU). It sends and receives the signals coming from a remote central control panel to monitor and control different set points.

The existing input and outputs (I/O) from the Distech ECP-300 controller are:

Table 5. ABC's Make-up Air Unit I/O

Signal Description	I/O Type
MAU Start/Stop Command	O
MAU Dampers Close/Status	I
MAU On/Off Status	I
MAU Supply Air Temp.Alarm	I
MAU Heating Burner On/Off Status	I
MAU Filter Differential Pressure Alarm	I
Fire Alarm Status	I
Gas Alarm Status	I
Outdoor Air Temperature Alarm	I
Exhaust Fan Start/Stop Command	O
Exhaust Fan Run Status	I

As showed on table 5, several actuators and control system components can be controlled by the BMS [22]. Appendix 1 provides a control block diagram of the existing HVAC system at ABC Colombia, and Appendix 2 gives technical specifications for the controller Distech ECP-300 installed in the make-up air units [16]. The existing BMS in the case study can be used to control de Reverse Flow Heat Recovery Unit, as well.

2.4 Heat (Energy) Recovery

A primary goal of sustainable energy design is to "make use of all economically available differences in temperature from environmental conditions and facility processes before discarding them to the environment" [36]. Previous discussions have alluded to many sources of renewable or recoverable energy that lend themselves to this application [32].

An essential part of any drying operation is providing ample flow of the drying medium (usually warm air) to accomplish mass transfer, that is, to carry away the air that becomes saturated with moisture.

2.4.1 Energy Audit

In order to find and evaluate heat recovery options and demands, an energy audit was carried out in the project. A heat (energy) audit is a study of how energy is used in a facility. Energy audit is in line with the six-sigma management strategy [13, 14] that many companies have adopted today.

In the project the procedure of the energy audit can involve several standard steps, such as warehouse the data for a period of time. Data mine is used to extract patterns from data and to understand where, when and how energy is being used and how heat wastes from the process are managed. This information is used to find relationships in the data. The patterns, associations, or relationships among all these data are the basis on which the mathematical models are formed and converted into knowledge about historical patterns and future trends.

In the area of energy data mining is being used to know how a system operates. It is the first and most important step to analyse operational costs and their impact. Data mining consists of five major elements:

(1) Extract, transform, and load transaction data onto the data warehouse system.
(2) Store and manage the data in a multidimensional database system.
(3) Provide data access to analysis.
(4) Analyze the data by application software.
(5) Present the data in a useful format, such as a graph or table.

In the project the following mayor types of relationships in the data are:

- Classes: Is an input of the model so it must be defined based on a criterion that leads to an adequate selection. The number of classes represents the different patterns existing among the sample in study.
- Clusters: It is a common technique for statistical data analysis based in a set of observations into subsets.
- Associations: It is a subject-based data mining use to determine what other information is related to that initiating datum.

- Sequential patterns: From a given set of sequences, find the complete set of frequent sub sequences

This, type and cost was identified, heat recovery options were identified and analyzed and lastly, economical analysis was performed using the proposed software. In the data cleaning phase wrong information has been corrected. The outliners and outages were detected using interactive graphics techniques based on the data, which permits replacement by most probable values.

Case Study Energy Overview

Currently ABC Colombia, case study, purchases electricity and natural gas from external suppliers and uses these energy resources to generate all forms of utilities to support the manufacturing process and offices.

Electricity

Electricity is purchased from the electricity transmission Interconexión Eléctrica S.A. E.S.P. (ISA) in Bogotá and is measured in kilowatt-hour (kWh). The substations in the plant distribute electricity to the process where it will be used. In the central utility building, electricity is used by cooling towers and chillers to generate chilled water for the plant’s HVAC system, and by boilers.

Natural Gas

Natural gas is purchased from Ecogás in cubic meters (m^3) which then can be converted to kWh of equivalent value. Natural gas is used in boilers.

Current industrial rates for electricity and natural gas in Colombia are:

Table 6. Commodities - Industrial Rates

	Electricity	**Natural gas**	
	(kWh)	(m3)	(MMBh)
COL $	350	810	22,940
USD $	0.1898	0.4391	12.44
EUR $	0.1453	0.3364	9.53

** MMBh = $1x10^6$ btu/h ≈ 1000 ft^3/h HHV

2.4.2 Heat Recovery Options

Heat recovery units are being developed and implemented in a wide variety of suitable applications, from commercial buildings to chemical industries like food processing applications where high hygienic requirements are required and where waste heat is produced within the process. As defined in section 2.2.1, the drying operation, focus of the present project, is done by evaporating solvents from solids to give the final product (or intermediate). Therefore an air-to-air heat recovery system, like the Reverse Flow Heat Recovery system, can draw the humid air exiting the process through a vent system equipped with a heat exchanger technology.

Common heat recovery systems include heat recovery wheels, heat pipes, and run-around loops. Appendix 3 compares industrial energy-recovery technologies available, including the new Reverse Flow Heat Recovery technology developed by BMK™.

2.5 Previous Work

This section explains previous research works that have been developed for Reverse Flow Heat Recovery, thermal drying and decision support systems in energy systems. Both areas have been examined either in the literature across several research and commercial domains [9, 4, 23, 24].

2.5.1 Reverse Flow Heat Recovery

The heat recovery unit proposed by BMK™ [9] for reverse flow heat recovery consist basically of two heat exchangers and two-position dampers that allow capturing waste heat. Figure 14 shows the major components of the system.

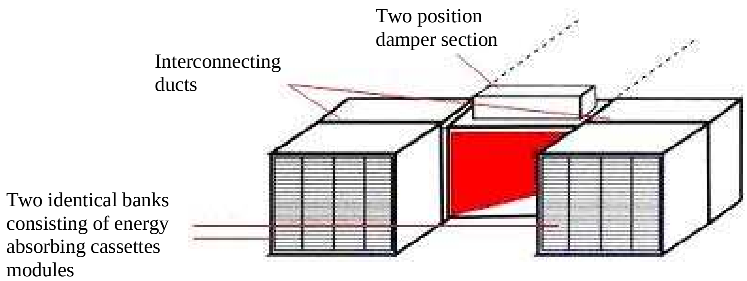


Figure 14. Major components - Reverse Flow Recovery System

As heat is exhausted from the process, the two-position damper directs the flow of air through one of the two banks of aluminium plates whose surface area has been maximised to capture energy from the exhausted air stream. At the same time, outdoor air is being drawn through the opposite heat exchanger bank returning the previously stored energy to the space. As the damper changes position (adjustable cycle, standard is 70 seconds), the entire system now works in reverse flow. Outdoor air is drawn through the newly energized cassette bank where the captured energy is released, returning it to the incoming air stream. Figure 15 shows a schematic diagram of the system.

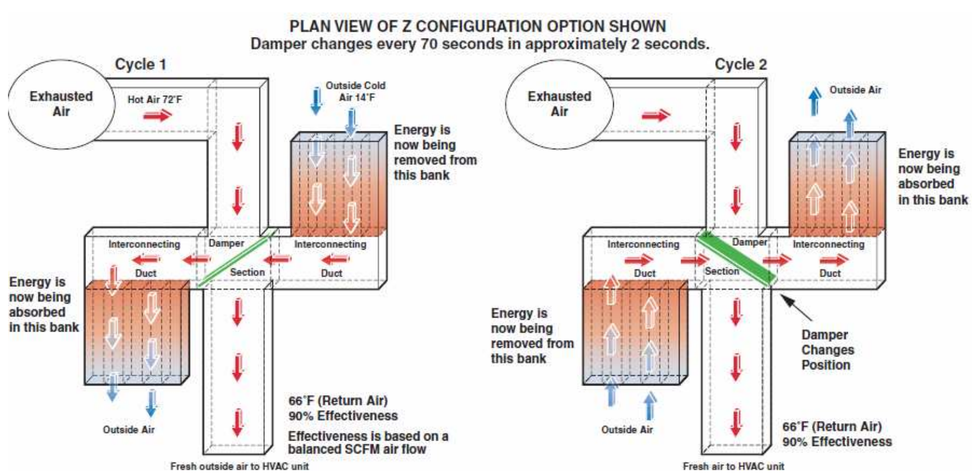


Figure 15. Reverse Flow Heat Recovery schematic diagram

Reverse Flow Recovery Controls

The energy recovery system of the Reverse Flow Heat Recovery unit can be adjusted by changing the phase on the two position damper to control the amount of unwanted moisture retention or recapture exhausted latent moisture in a cold weather.

Figure 16. Reverse Flow Heat Recovery Damper

The damper is controller by a Fuji easy logic controller (ELC). The ELC incorporates a weekly time-setting function that allows configuring several control logic sequences based on time. The ELC is programmed using software in a ladder diagram format that is developed from a traditional relay schematic diagram or directly on the front panel. Appendix 2 gives technical specifications for the Fuji controller [16]. Figure 17 shows the two position damper’s Controller and Figure 18 shows the adjustable energy recovery system for the Reverse Flow Heat Recovery system.

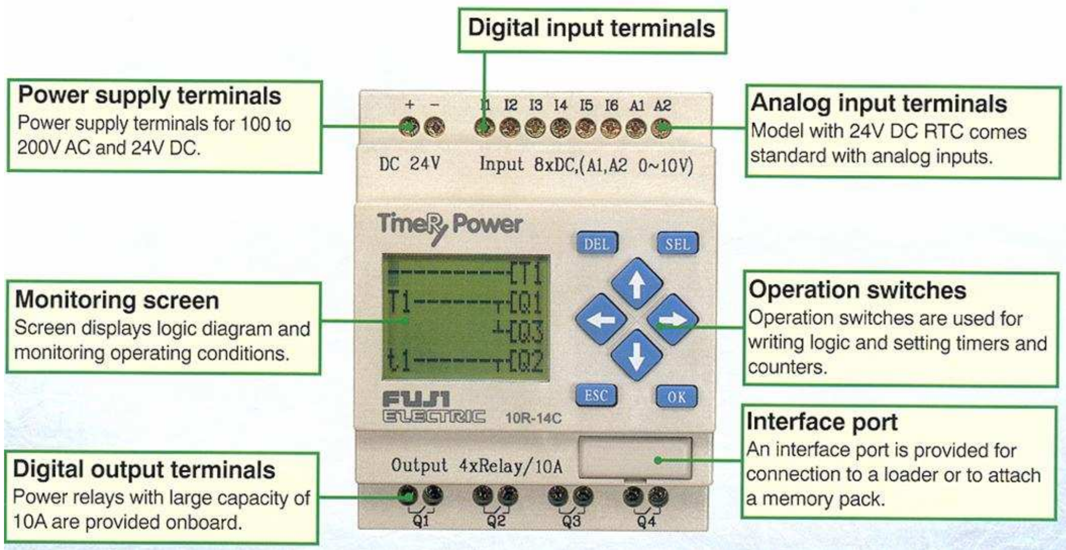


Figure 17. Reverse Flow Heat Recovery (Two position damper's Controller)

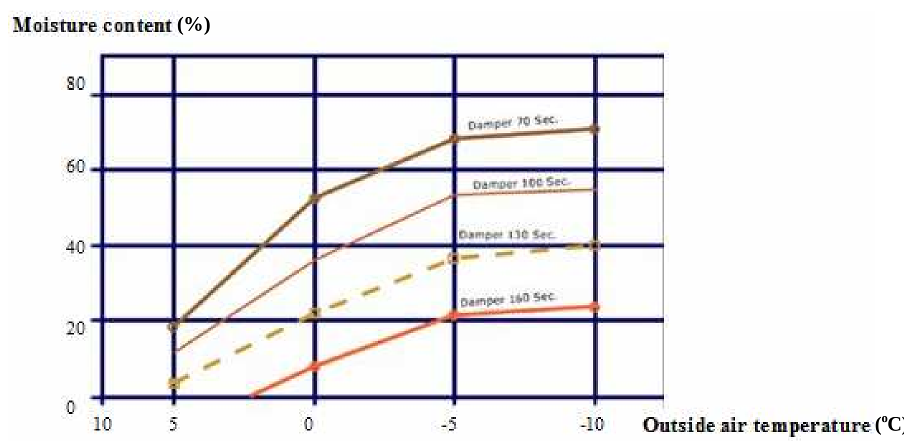


Figure 18. Damper dwell time in seconds

The dwell time relates to the duration in time of the dampers operation. The long period of the damper operation allows the Heat Recovery unit to reverse the air flow through the cassettes periodically to take advantage of the self cleaning properties of the reverse flow arrangement.

2.5.2 Mathematical models

Various models and software programs have been developed for thermal drying [25, 26, 27] and for overview of decision support systems [4, 23, 24]. However, few commercial software packages related to drying have been developed successfully or are well accepted for pharmaceutical clean rooms applications because they can be very expensive in the design, analysis, trouble-shooting, as well as control and optimization of drying systems.

Drying Operation

A search identified only three commercial software packages specifically intended for drying design [28, 29, 8]. *Simprosys* is a Windows-based process simulator. It can be used for flow-sheet design and simulation of drying. It is developed using C++. *dryPAK* is a DOS based dryer design software package for dryer design calculations including heat and mass balance and drying kinetics calculations. dryPAK was developed on the DOS platform and has not been upgraded to Windows yet. *DrySel* is an expert system marketed by Aspen Technology for dryer selection. It is a proprietary software package. Both graphical and numerical display is provided. These software packages are very useful; however they are not affordable for most users since the licensing fees are very expensive.

Table 7. Drying operation software packages overview

Characteristics	**Software Packages for Drying Operation**		
	Cost	**Input type**	**Calculation type**
Simprosys	Free trial version	Manual	Mass balance calculation
dryPAK	Expensive licensing fees	Manual	Heat and mass balance and drying kinetics
DrySel	Expensive licensing fees	Manual	Solids properties and drying kinetics

Energy Analysis

Various models have been developed for overview of decision support systems. Examples include RETScreen [4] and HOMER [23]. *RETScreen* is standardized and integrated renewable energy project analysis software that can be used to evaluate the energy production. HOMER is model that can be modelled by using only basic inputs (annual averages and cost per kW). RETScreen and HOMER are mainly economical for one type of energy.

HOMER is a computer model that assists the design of micro power systems. HOMER models a power system's physical behaviour and its life cycle cost, which is the total cost of installing and operating the system over its life span [37]. HOMER also assists in understanding and quantifying the effects of uncertainty or changes in the inputs. The input windows of HOMER have been designed to minimize the effort required to enter data that describes loads, components performance, and costs. HOMER provides default values for many inputs so that the analysis can be quickly started.

RETScreen [4] can be used to evaluate the energy production, life cycle costs and greenhouse gas emissions reduction for various renewable energy technologies. RETScreen is dedicated to the preparation of pre-feasibility studies. It includes eight technology modules (not linked): wind energy, small hydro, photovoltaic, solar air heating, biomass heating, solar water heating, passive solar heating, and ground source heat pump project analysis. RETScreen has been developed in Microsoft Excel. Each of the eight technology modules includes the following five worksheets: energy model, equipment data, cost analysis, greenhouse gas emissions analysis, and financial summary. Table 8 provides a comparative overview of RETScreen and HOMER.

Table 8. RETScreen and HOMER modelling characteristics

Characteristics	RETScreen		HOMER	
Inputs				
Site conditions	• Project location, latitude of project location, and annual average temperature.	✓	• Site conditions	✓
Loads	• Module type, nominal efficiency, capacity, battery data (if battery exits), load data.	✓	• Primary, deferrable and thermal load	✓
Components	• Wind energy, hydro, generator, grid, battery..	✓	• Wind turbine, hydro, generator, grid, battery	✓
	• Diesel, cogeneration, air / water / solar heating.	✓	• No included	X
Economics	• Initial project cost (feasibility study, development, engineering, equipment, system installation), annual savings / income, and parameters for the economic evaluation of the project (energy cost rate, project life).	✓	• Annual real interest rate, project life time, system fixed capital cost, system fixed operation and maintenance (O&M) cost.	✓
Constrains	• It cannot evaluate systems with more than one renewable technology.	✓	• Do not support multiple criteria analysis.	✓
Optimization	• Not specified.	X	• It contains the values of each optimization variable that are used to build the set of all possible system configurations.	✓
Outputs				
Cost	• Project cost and savings: total initial cost, incentives/grants, periodic cost and credits, total annual cost, total annual savings.	✓	• Total net present cost. Also cost breakdown (initial capital, annualized capital, annualized replacement, annual operation and maintenance, annual fuel, total annualized cost) for each component of the system.	✓
Electrical	• Annual energy balance: renewable energy delivered net green house gas emission reduction.	✓	• Total annual output of ach electrical energy producing component, total amount of energy that went to serve each of the system's electrical loads (plus any storage).	✓
Features				
Simulation	• The energy model uses a user specified power curve to calculate the energy curve of a turbine. Energy production id then adjusted for pressure and temperature effects, as well for various user specified losses.	✓	• Simulates the operation of a system by making energy balance calculations for each of the 8760 hours in a year. Hourly energy flows for each component as well as annual cost and performance summaries can be viewed.	✓
Optimization	• Not specified.	X	• Simulates each system configuration and displays list of systems sorted by Net Present Cost (NPC)	✓
Sensitivity analysis	• Not specified.	X	• Performs and optimization for each sensitivity variable	✓

2.6 Summary

This chapter gave a description of the main production processes in a typical pharmaceutical process focusing on the drying operation, clean rooms, and heating ventilation and air conditioning (HVAC) systems based on a case study. It identified that the drying operation, is realised by evaporating solvents from solids to give the final product (or intermediate).

It described that an air-to-air heat recovery system, like the Reverse Flow Heat Recovery system, can draw the humid air exiting the process through a vent system equipped with a heat exchanger technology. It also described the BMS control system, and identified its potential link to control the Reverse Flow Hear recovery unit.

This chapter then showed the structure, trends and production characteristics of the Colombian pharmaceutical industry and tied it into the generic processes discussed earlier in the chapter. It showed that the drying a final product is the most energy consuming aspect of the whole pharmaceutical industry.

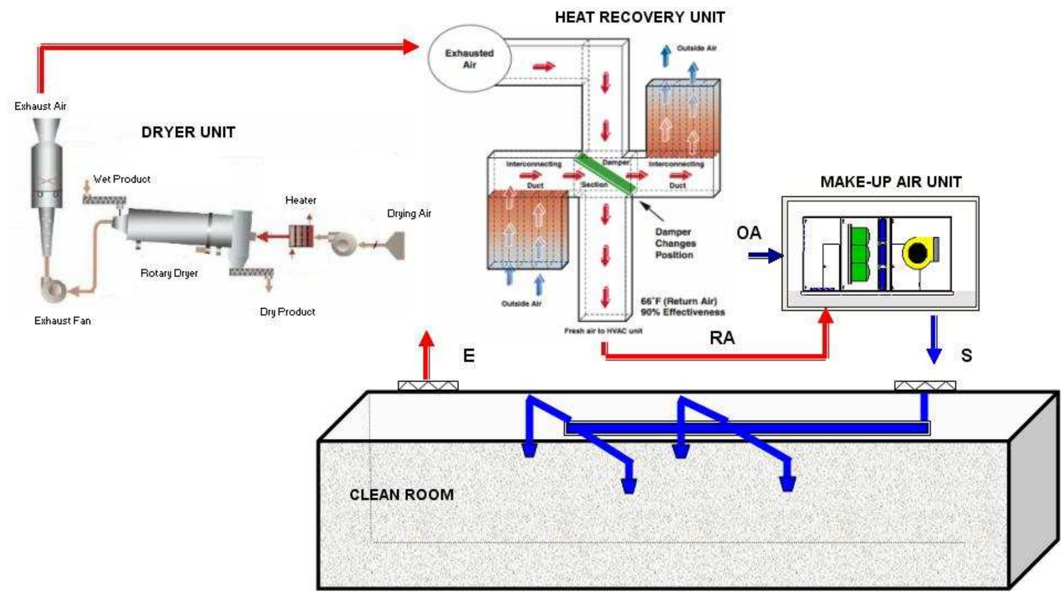
Chapter 3
Design

3.1 Introduction

This chapter expands the literature review presented in Chapter Two. It shows the proposed heat recovery software for pharmaceutical drying clean rooms including the theoretical framework of the mathematical model used in the software. A case study of a drying operation at a pharmaceutical company in Colombia is used to aid in a critical review of the tool from a pragmatic real-world perspective.

3.2 Proposed System

The design of heat recovery systems has been under investigation for many years [9, 4, 23, and 24]. The proposed system consists of a new Human-Model-Interface (HMI) that permits outputs to be derived based on inputs, for predicting the amount of air-to-air heat (energy) that can be recovered in pharmaceutical drying clean rooms in Colombia. The drying cycle was identified in chapter two as a critical operation where large emissions of heat are produced. This waste heat can be recovered using several heat recovery systems such as the Reverse Flow Heat Recovery Technology, which is proposed in the present dissertation to draw the humid air exiting the process through a vent system equipped with a heat exchanger technology. Figure 19 shows a schematic diagram of the proposed system for a typical pharmaceutical counter-current rotary dryer for drying solids completed with a reverse flow heat recovery unit.



** E = Exhaust Air, RA = Recovered Air, OA = Outside Air, S = Supply Tempered Air.

Figure 19. Schematic diagram of a counter-current rotary dryer with heat recovery

As defined in chapter two, bulk active ingredients currently being produced by chemical synthesis in ABC Colombia (case study), include tablets such as acetyl salicylic acid (Aspirin) [6]. In the final operation of the production of acetyl salicylic acid (Aspirin), the drying operation, the output from the purification operation goes through a counter current rotary dryer where the temperature is increased until the excess water is removed as water vapour. From the 2009 British Pharmacopoeia, [33], the final concentration of acetylsalicylic acid must be 99.5% with 0.5% water.

As a case study 1,058,196 kg/year of wet product is fed to the rotary dryer, containing 24.80 % wet product moisture content, to give acetyl salicylic acid (Aspirin) containing 99.5% with 0.5% water. The drying medium consists of air heated at 385 °K. The air leaves the drying operation at 310°K.

The Reverse Flow Recovery unit is used to draw the humid air exiting the process through a vent system equipped with a heat exchanger technology. As noted in the Chapter Two, the Reverse Flow Recovery unit can be essentially controlled by the BMS for ON/OFF operation to indicate whether heat recovered is enabled or not. The process parameters of the production of acetyl salicylic acid (Aspirin) and air in this study, including the heat and mass balance calculations for the drying operation, are defined by manual inputs as listed below in Table 9. Figure 20 show the calculated mass balance of the Counter-current rotary dryer.

Table 9. Acetyl salicylic acid (Aspirin) process parameters

Product: Acetylsalicylic Acid (Aspirin) Pharmacopeia:99.5% with 0.5% water		
	Units	**Value**
Inlet		
Wet Product	kg/Year	1,058,195.9
Wet Product Moisture Content	%	24.8
Dryer type		Counter Current Rotary
Dryer Capacity	kg/s wet stock max	0.03
Wet Product Input Temperature	°K	373.5
Air Supplied	kg water vapour/ kg dry air	0.03
Entering Air Temperature	°K	385
Reference Datum Temperature	°K	273
Outlet		
Dry Product	kg/Year	800,000 (*)
Dry Product Moisture Content	%	0.5
Dry Product Output Temperature	°K	3,085
Leaving Air Temperature	°K	310
Radiation losses	kJ/kg dry air used	20 (**)

* Containing 5% moisture
** Assumed radiation losses amount in kJ per kg of dry air used.

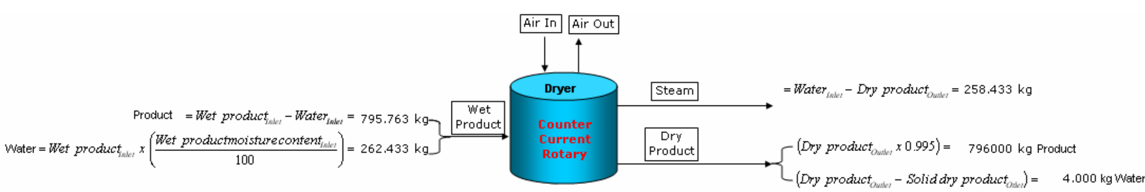


Figure 20. Counter-current rotary dryer block diagram

1. Heat In

(a) Air

Heat content of stream = $\left[\left(C_{p\,(Dry\ air)}G + \left(Air_{(Supplied)}G\ x\ C_{p\,(Water\ vapour)}\right)\right)\right] x \left(T_{In\,(Air)} - T_{Datum}\right)$

= **113,35 G kW**

(b) Wet solid

Mass flow rate of water = $\left(Dryer_{(Capacity)}\ x\ \text{Wet Product}_{(\text{Moisture Content})}\right)$

= **0,007 kg/s**

Mass flow rate of dry solid = $\left(Dryer_{(Capacity)}\ x\ Mass\ flow\ rate_{(Water)}\right)$

= **0,023 kg/s**

Heat content of stream = $\left[\left(Mass\ flow\ rate_{(Dry\ solid)}\ x\ 4.18\right) + \left(Mass\ flow\ rate_{(dry\ solid)}\ x\ C_{p\,(Product)}\right)\right]\left[T_{In\,(Wet\ product)} - T_{In\,(Datum)}\right)$

= **5,10 kW**

2. Heat Out

(a) Air

Heat in exit air = $\left[\left(C_{p\,(Dry\ air)}G + \left(Air_{(Supplied)}G\ x\ C_{p\,(Water\ vapour)}\right)\right)\right] x \left(T_{Out\,(Air)} - T_{Datum}\right)$

37,45 G kW

Water in the dried solids out = $\left(T_{Out\,(Dry\ product\ moisture)}\ x\ Mass\ flow\ rate_{(Dry\ solid)}\right) / \left(1 + T_{Out\,(Dry\ product\ moisture)}\right)$

0,001 kg/s

Water evaporated into gas steam= $\left(T_{Out\,(Dry\ product\ moisture)} - Water_{(In\ dried\ solids\ out)}\right)$

0,049 kg/s

Assuming evaporation takes place at 373 K, then:

Heat in the water vapour = $Water\ evaporated_{(Water\ vapour)}\ x \left[C_{p\,(Water\ vapour)}\ x \left(T_{Out\,(Air)} - T_{Datum}\right) + Latent\ heat_{(Watervapour\ r)} + 4.18\ x \left(T_{In\,(Wet\ product)} - T_{Datum}\right)\right]$

124,70 kW

(b) Dried solids

Heat content of stream = $\left[\left(Mass\ flow\ rate_{(Dry\ solid)}\ x\ C_{p\,(Product)}\right) + \left(Water_{(In\ dried\ solid\ out}\ x\ 4.18\right) / \left(T_{Out\,(Dry\ product)} - T_{Datum}\right)\right]$

0,04 kW

(c) Radiation Losses **20,00 G kW**

3. Heat Balance (In=Out)

Mass Flow rate (G) is:

$$\text{Heat content}_{(\text{Heat in, Air})} + \text{Heat content}_{(\text{Heat in Wet solid})} = \text{Heat in water vapour}_{(\text{Heat out Air})} + \text{Heat in exit air}_{(\text{Heat out Air})} + \text{Heat content of stream}_{(\text{Heat out (Dried solids)})} + \text{Loss}$$

$$G(\text{Heat content}_{(\text{Heat in Air})} - \text{Heat exit air}_{(\text{Heat out Air})} - \text{Loss}) = \text{Heat water vapour}_{(\text{Heat out Air})} + \text{Heat content of stream}_{(\text{Heat out Dried solids})} - \text{Heat content}_{(\text{Heat in Wet solid})}$$

55,90 G	=	119,64
Mass flowrate of dry air supplied to the dryer G	=	**2,14 Kg/s**

4. Heat Recovery

Air Density	=		1,20 Kg/m3	
Leaving Air Temperature	=		310 degC	
Available Airflow for Heat Recovery	=	*Mass flow rate of dry air x 3600 / Air density* =	**6.420 m3/h**	***3.779 cfm***
Leaving Air Temperature for Heat Recovery, dB	=	$\text{Leaving air temperature deg}K - 373 =$	**37 degC**	***98,6 degF***

As seen before the total mass flow rate of dry air supplied to the dryer is calculated in 2.14 kg/s, therefore the available airflow for heat recovery and leaving air temperature for heat recovery is calculated in 6.420 m^3/h and 37°C respectively.

The above information is the basis to carry out the heat recovery unit analysis, heat recovery unit performance, and payback analysis. The heat recovery system is analysed for summer and winter conditions.

For simplicity of the analysis, the proposed simulation software is initially designed and simulated only for the acetyl salicylic acid (Aspirin) drying operation; however this is not a limitation of the software, as it can be used for other wet product compositions and be modified for different requirements.

3.2.1 Heat Recovery Simulation

The proposed system is a novel integrated modelling tool, that combines model aspects, data storage aspects, and visualisation aspects, using off the shelf software application such as MS Excel combined with MS Visual programming to calculate psychometric points, mass, and enthalpy balances for analysing the operation of heat recovery systems.

The new Human-Model-Interface (HMI) is divided in six components which communicate with each other using MS Excel built-in MS Visual programming code. Detail account of each module is given in Chapter Four:

(1) Main (Index) Component
(2) Dryer Heat Recovery (HR) Component
(3) Reverse Flow Heat Recovery (HR) Component Performance
(4) Reverse Flow Heat Recovery (HR) Component Analysis
(5) Psychometric Chart with stated points, i.e. HR Supply, Outside Air, Mixed Air, and Indoor Set Point.
(6) Payback Analysis

The software program calculates the amount of waste heat from the counter-current rotary dryer based on variable psychometric inputs as: intake dry/wet bulb air temperatures, exhaust dry/wet bulb air temperatures, humidity content, airflows, clean room specifications (ISO class, dimensions, etc).

Climate Design Information for Bogotá Colombia is used to calculate local temperatures and humidity ratios. Sensible/latent Heat Analysis is based on ASHRAE Fundamentals Handbook [12]. The inlet conditions and the performance factors of the Reverse Flow Heat Recovery system have to be known. Mathematical models are based on thermodynamic equations. Table 10 shows the general formulae used to calculate sensible heat, latent heat, and total heat. Figure 20 shows a general flow diagram for the proposed software application.

Table 10. General formulae for Sensible and Latent Heat

Heading	**Description**	**SI UNITS (Metric)**
Sensible Heat .	Heat that cause a change in temperature.	$Q = m^3/h.(Cp.\ \rho).\ \Delta t$ Where, Heat, Q (kJ) Density, ρ air (~ 1.2 kg/m^3) Specific Heat Capacity, Cp air (~ 1.005 $kJ/kg.^oK$ $\Delta t = (T_2 - T_1)$ (^oC)
Latent Heat	Heat that causes change of state (e.g. liquid to vapour, or solid to liquid) with no change in temperature.	$Q = [m^3/h.(Hw.\ \rho).(h_2 - h_1)]$ Where, Hw = Water Latent Heat (~ 2465.56 kJ/kg) h_2-h_1 = humidity ratio difference (kgw/kga)
Total Heat	The sum of the sensible and latent heat in a substance or fluid above a base point.	= Sensible + Latent

Psychometric chart

The proposed heat recovery software for pharmaceutical drying clean rooms in Colombia includes two types of psychometric charts: (1) Paper type psychometric chart and (2) Automatic generated psychometric chart on the computer using the mathematical model. The psychometric chart graphically represents the thermodynamic properties of the moist air. The choice of coordinates is arbitrary. The heat transfer mathematical model includes a chart with coordinates of Dry Bulb (degC) and Humidity Ratio (gr/kg) and gives a convenient and useful graphical user interface showing several psychometric set points such as HR Supply, Outside Air, Mixed Air, and Room Indoor Set Point with a minimum of thermodynamics approximations. The computer based psychometric chart also allows saving the file in any of the common formats (xls, bmp, jpg, gif or pdf) so that it can be easily e-mailed or used in reports.

Figure 21 shows a typical paper type psychometric chart. Dry bulb temperatures are show on the charts vertical lines. The horizontal lines represent Dew Point temperatures. Lines representing Wet bulb temperatures are the straight diagonal lines sloping downward from left to right. The curve forming the top edge of the chart is called the “saturation curve”. Air in a condition that falls on any point along this curve is totally saturated with moisture. Any additional, moisture added could not be absorbed and would and would remain in a liquid state as condensation. The sweeping curved lines that follow the saturation curve are relative humidity lines expressed as percentages. These lines represent the degree of volume displace by moisture with respect to the total air volume [12].

Figure 22 shows the automatic generated psychometric chart on the computer using the mathematical model.

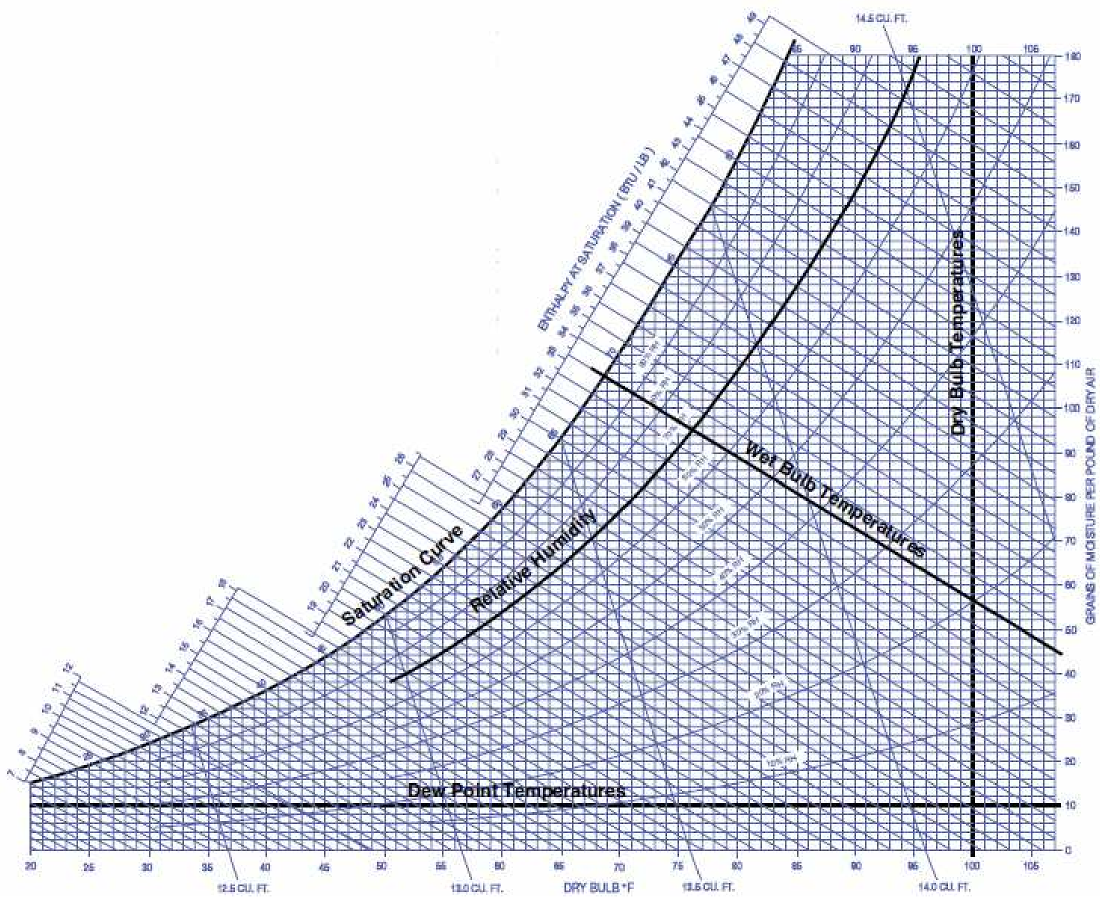


Figure 21. Paper type psychometric Chart [12]

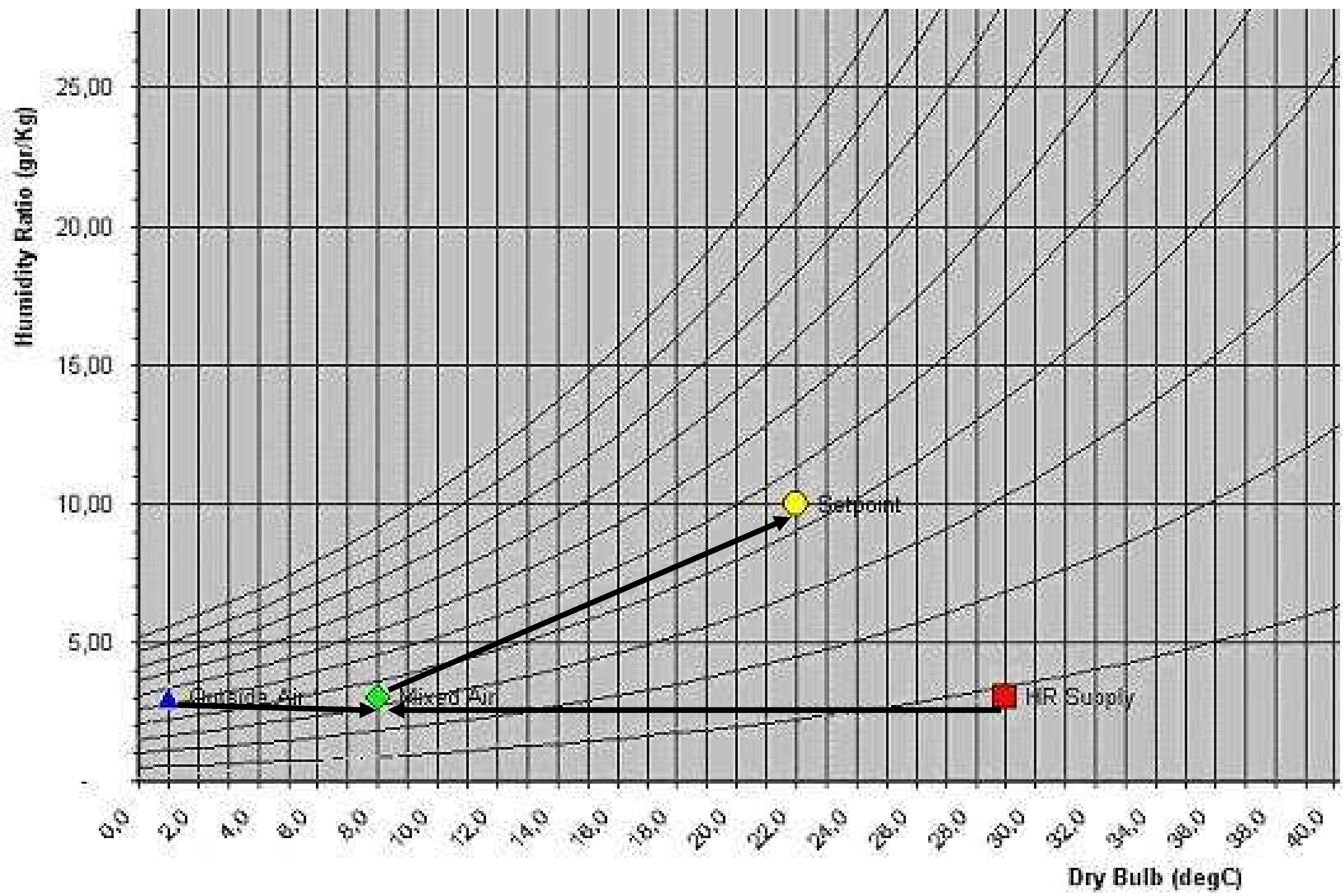


Figure 22. Automatic generated psychometric chart on the computer using the mathematical model

Figure 23 shows a general flow diagram for the proposed software application.

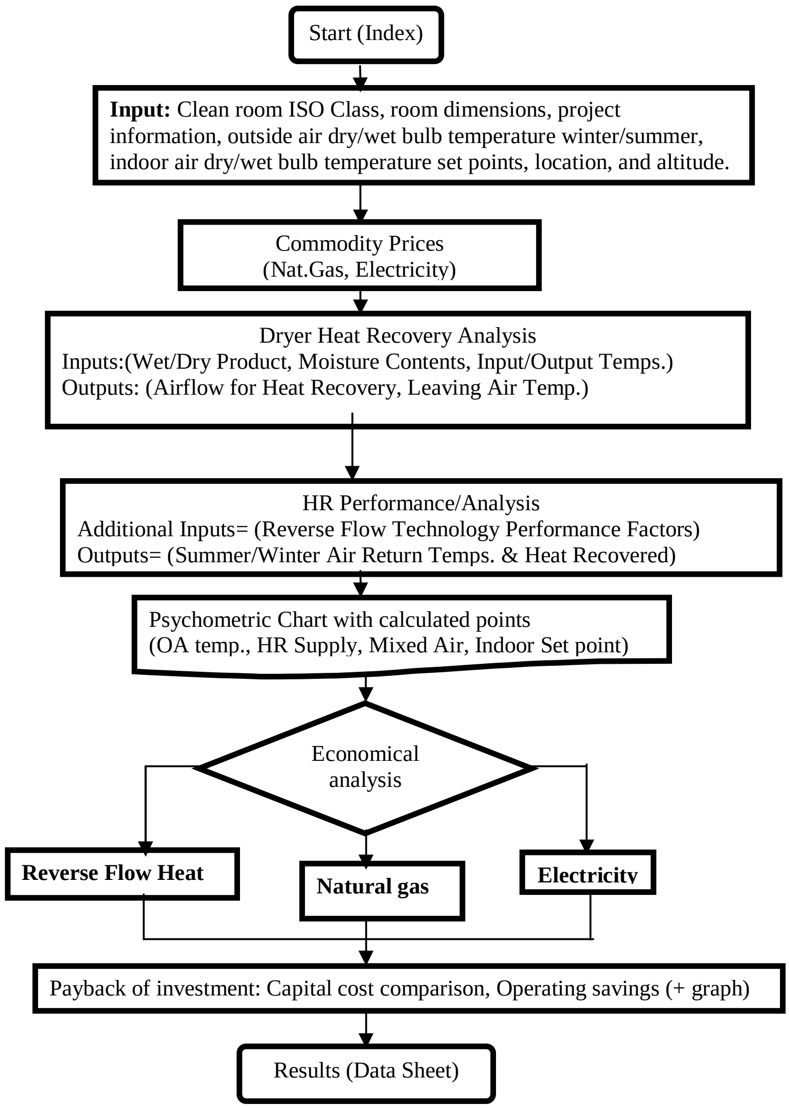


Figure 23. Software Flow Diagram

Modelling Components

The mathematical model is a description of the behaviour of the Reverse flow Heat Recovery system for pharmaceutical drying clean rooms heat recovery in Colombia. It is made up of three components [12]:

(1) **Input variables**, which act on the system. The proposed software includes controllable variable from mathematical formulae (e.g. humidity ratio) and uncontrollable variables (e.g. climate conditions).

(2) **System structure and parameters**, which provide the necessary physical description of the system (e.g. physical properties of the elements).

(3) **Output variables**, which describe the reaction of the system to the input variables (e.g. Reverse Flow Heat Recovery savings).

As one of the objectives of the project is to predict the output variables with known structure and know parameters when subject to specified input variables, the forward (classical) model approach is used. This approach presumes detailed knowledge not only of the various natural phenomena affecting the system behaviour but also of the magnitude of various interactions [12] (e.g. specific heat capacities, etc.).

Specific heat capacities

Specific heat capacities, Cp, are estimated using Kopp's rule of each of the element's involved in the drying operation. Kopp's rule is a simple empirical method for estimating the heat capacity of a liquid at room temperature [38]. According to this rule, a compounds' Cp is equal to the sum of each element's contribution in the compound. Kopp's rule is a rough estimation of the heat capacity, however for the purpose of this project the calculations will be sufficient as the margin of error is less than +/- 5 % [38].

Climate Design Information

Energy calculations are base on average use and typical weather conditions rather than on maximum use and worst case weather. Due to the proximity of Colombia with the equator there are no major seasonal variations. Figure 24 shows the ASHRAE climate design conditions for Bogotá, Colombia [12].

Complete data climate design conditions for Bogotá are provided for convenience in Appendix 5 [12].

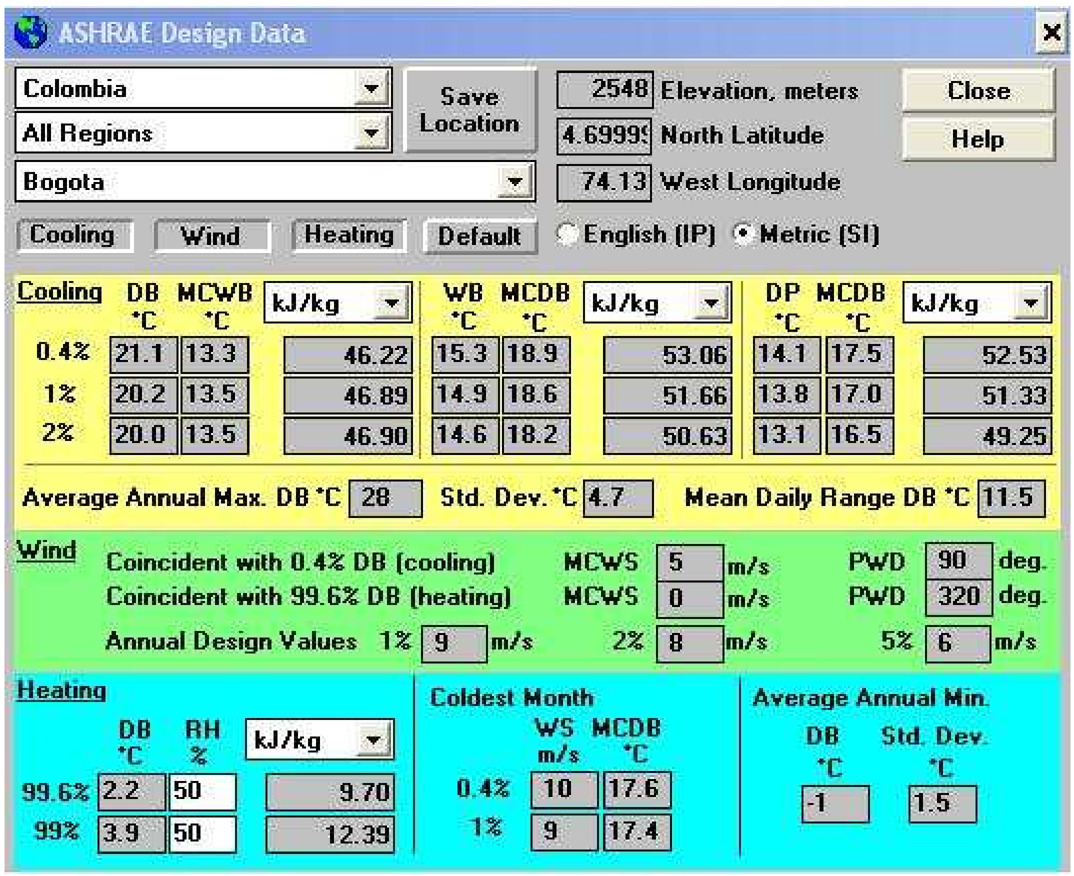


Figure 24 . ASHRAE Design Data for Bogotá, Colombia

Accurate energy calculations cannot be performed without models of the system heat components. In addition to the general formulae for sensible and latent heat described in table 9, the mathematical model for drying operation also comprises heat components (e.g. heat in, heat out, heat balance) in order to identify the available airflow for heat recovery and leaving air temperature for heat recovery from the dryer.

Energy and drying operations are typically described as the sum of sensible and latent loads, plus heat balances. The drying operation and air analysis calculations are based on the textbooks described in Chapter Two [12, 30, 32, and 34].

3.3 Summary

This chapter illustrated the schematic diagram of the proposed heat recovery unit for pharmaceutical clean rooms in Colombia; it showed the climate design conditions for Bogotá, Colombia and gave the main mathematical formulae that are used in the software to calculate the amount of heat recovered by the Reverse Flow unit. The proposed software was defined as a single application for process parameter fitting for pharmaceutical drying operations under clean room conditions and a heat recovery analysis tool.

Chapter 4
Implementation and Results

4.1 Introduction

This chapter contains an overview of the Reverse Flow Heat Recovery mathematical model for pharmaceutical drying clean rooms in Colombia, provides a brief description of the major parts involved on each Human-Machine-Interfaces (HMI´s). Identifies the minimum hardware and software requirements to install and run the proposed software. Provides information of the model validation, testing and finally gives a detail analysis of the result obtained.

4.2 Heat Recovery Human Model Interface

The simulation software is based on hourly profiles for climate conditions and operational characteristics. Calculations of Heat recovered from the drying operation, Heat Recovery (HR) performance and Payback analysis are including establishing the cost-effectiveness of the Reverse Flow Heat Recovery system. Figures 25 to 38 highlight the main components of the Human-Model-Interface (HMI) of the Reverse Flow Heat Recovery software, in terms of purpose and activity. The assumptions and equations used to arrive to the heat recovered are given in each Human Model Interface.

As described before in Chapter Three, the new Human Model Interface that permits outputs to be derived based on inputs for predicting the amount of air-to-air heat (energy) that can be recovered in pharmaceutical drying clean rooms in Colombia, is comprised of the following six components:

(1) Main (Index) Component
(2) Dryer Heat Recovery (HR) Component
(3) Reverse Flow Heat Recovery (HR) Component Performance
(4) Reverse Flow Heat Recovery (HR) Component Analysis
(5) Psychometric Chart with stated points, i.e. HR Supply, Outside Air, Mixed Air, and Indoor Set Point.
(6) Payback Analysis

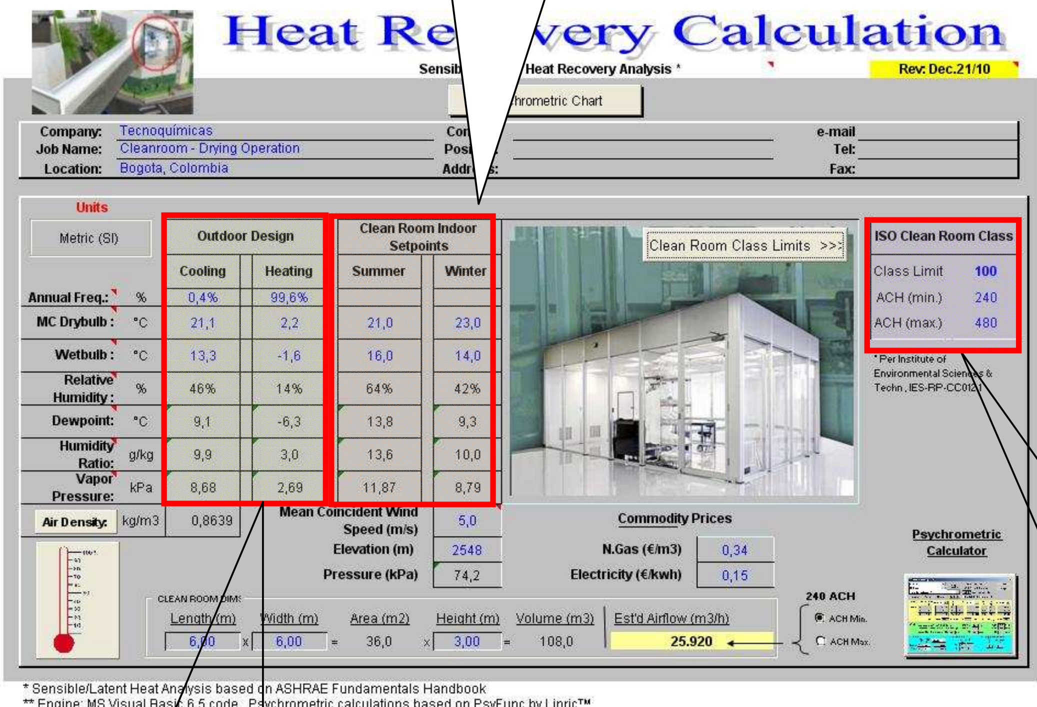
The previous components communicate with each other using MS Excel built-in MS Visual programming code. MS Excel using MS Visual programming was selected as the energy analysis program in this project, as the cost of the computer facilities and the software itself are small compared to similar software packages which are not affordable for most users since the licensing fees are very expensive. Moreover, the mathematical model uses a user friendly Human Model Interface that avoids the cost of learning a complex program. The end result is lower cost, user friendly, flexible, easy to customize, and a higher quality software application.

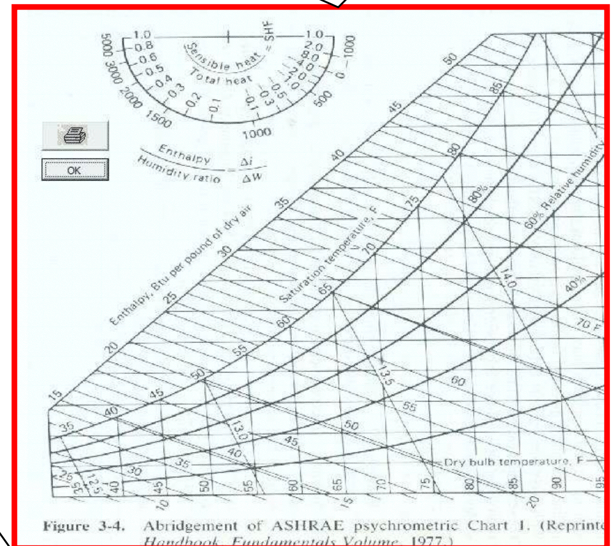
The major parts involved on each Human Machine Interfaces (HMI´s) are as follow:

Tab.1 Main

Aspect 2: Clean Room Set Points
Purpose: Selection of the required clean room set points for summer and winter conditions, in order to calculate Psychrometric Calculations.

Aspect 3: Psychometric Chart (Manual)
Purpose: Generate psychrometric chart from a manual template.





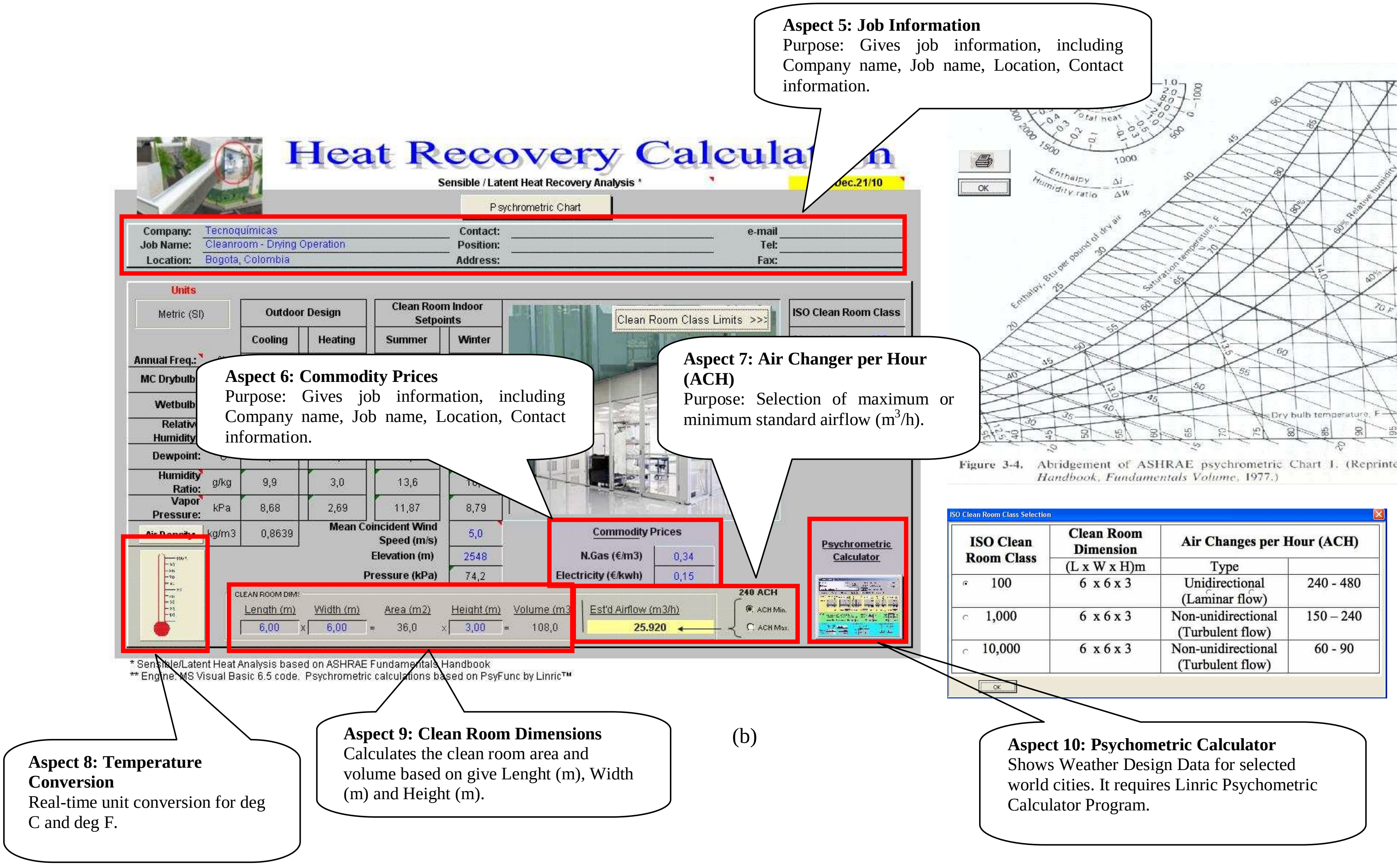
ISO Clean Room Class	Clean Room Dimension (L x W x H)m	Air Changes per Hour (ACH) Type	
100	6 x 6 x 3	Unidirectional (Laminar flow)	240 - 480
1,000	6 x 6 x 3	Non-unidirectional (Turbulent flow)	150 – 240
10,000	6 x 6 x 3	Non-unidirectional (Turbulent flow)	60 - 90

(a)

Aspect 1: Outdoor Design
Selection of the required Annual Frequency, Dry bulb and Wet bulb temperatures for cooling and heating parameters at a particular location in order to calculate Psychrometric Calculations, such as: Relative Humidity, Dew point, Humidity Ratio amd Vapour Pressure.

Figure 25. Main page (Input Variables)

Aspect 4: Outdoor Design
Purpose: Selection of ISO Clean room Class for a given clean room application [40].



Aspect 5: Job Information
Purpose: Gives job information, including Company name, Job name, Location, Contact information.
Heat Recovery Calculation
Sensible / Latent Heat Recovery Analysis *
Psychrometric Chart
Company: Tecnoquímicas
Job Name: Cleanroom - Drying Operation
Location: Bogota, Colombia
Contact:
Position:
Address:
e-mail
Tel:
Fax:
Units
Metric (SI)
Outdoor Design
Cooling
Heating
Clean Room Indoor Setpoints
Summer
Winter
Clean Room Class Limits >>>
ISO Clean Room Class
Aspect 6: Commodity Prices
Purpose: Gives job information, including Company name, Job name, Location, Contact information.
Aspect 7: Air Changer per Hour (ACH)
Purpose: Selection of maximum or minimum standard airflow (m3/h).
Humidity Ratio: g/kg 9,9 3,0 13,6
Vapor Pressure: kPa 8,68 2,69 11,87 8,79
kg/m3 0,8639
Mean Coincident Wind Speed (m/s) 5,0
Elevation (m) 2548
Pressure (kPa) 74,2
Commodity Prices
N.Gas (€/m3) 0,34
Electricity (€/kwh) 0,15
Psychrometric Calculator
Length (m) 6,00 x Width (m) 6,00 = Area (m2) 36,0 x Height (m) 3,00 = Volume (m3) 108,0
Est'd Airflow (m3/h) 25.920
240 ACH
ACH Min.
ACH Max.
* Sensible/Latent Heat Analysis based on ASHRAE Fundamentals Handbook
** Engine: MS Visual Basic 6.5 code. Psychrometric calculations based on PsyFunc by Linric™
Figure 3-4. Abridgement of ASHRAE psychrometric Chart 1. (Reprinte Handbook, Fundamentals Volume, 1977.)
ISO Clean Room Class Selection
ISO Clean Room Class | Clean Room Dimension (L x W x H)m | Air Changes per Hour (ACH) Type
100 | 6 x 6 x 3 | Unidirectional (Laminar flow) | 240 - 480
1,000 | 6 x 6 x 3 | Non-unidirectional (Turbulent flow) | 150 – 240
10,000 | 6 x 6 x 3 | Non-unidirectional (Turbulent flow) | 60 - 90
OK
Aspect 8: Temperature Conversion
Real-time unit conversion for deg C and deg F.
Aspect 9: Clean Room Dimensions
Calculates the clean room area and volume based on give Lenght (m), Width (m) and Height (m).
Aspect 10: Psychometric Calculator
Shows Weather Design Data for selected world cities. It requires Linric Psychometric Calculator Program.

(b)

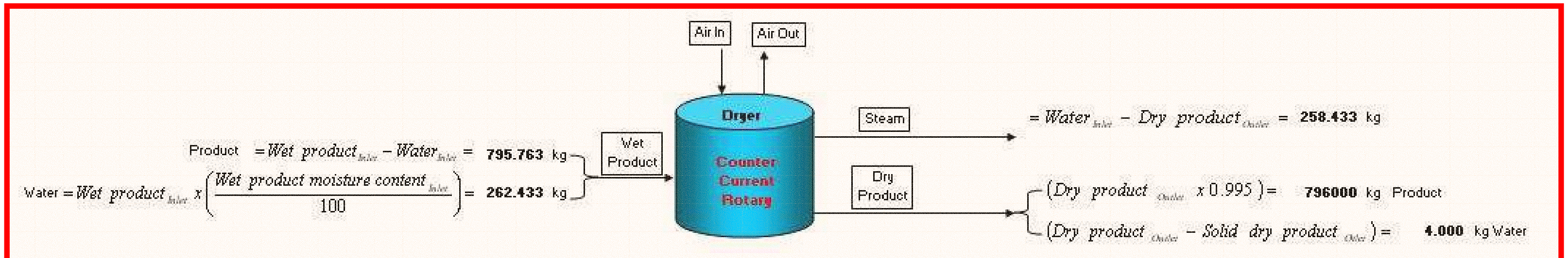
Tab 2. Dryer HR

Aspect 11: Dryer Process Parameters
Purpose: Selection of manual inputs process parameters that affect the properties of the dried product.

Dryer Heat Recovery

Note: Blue Values are Manual Inputs

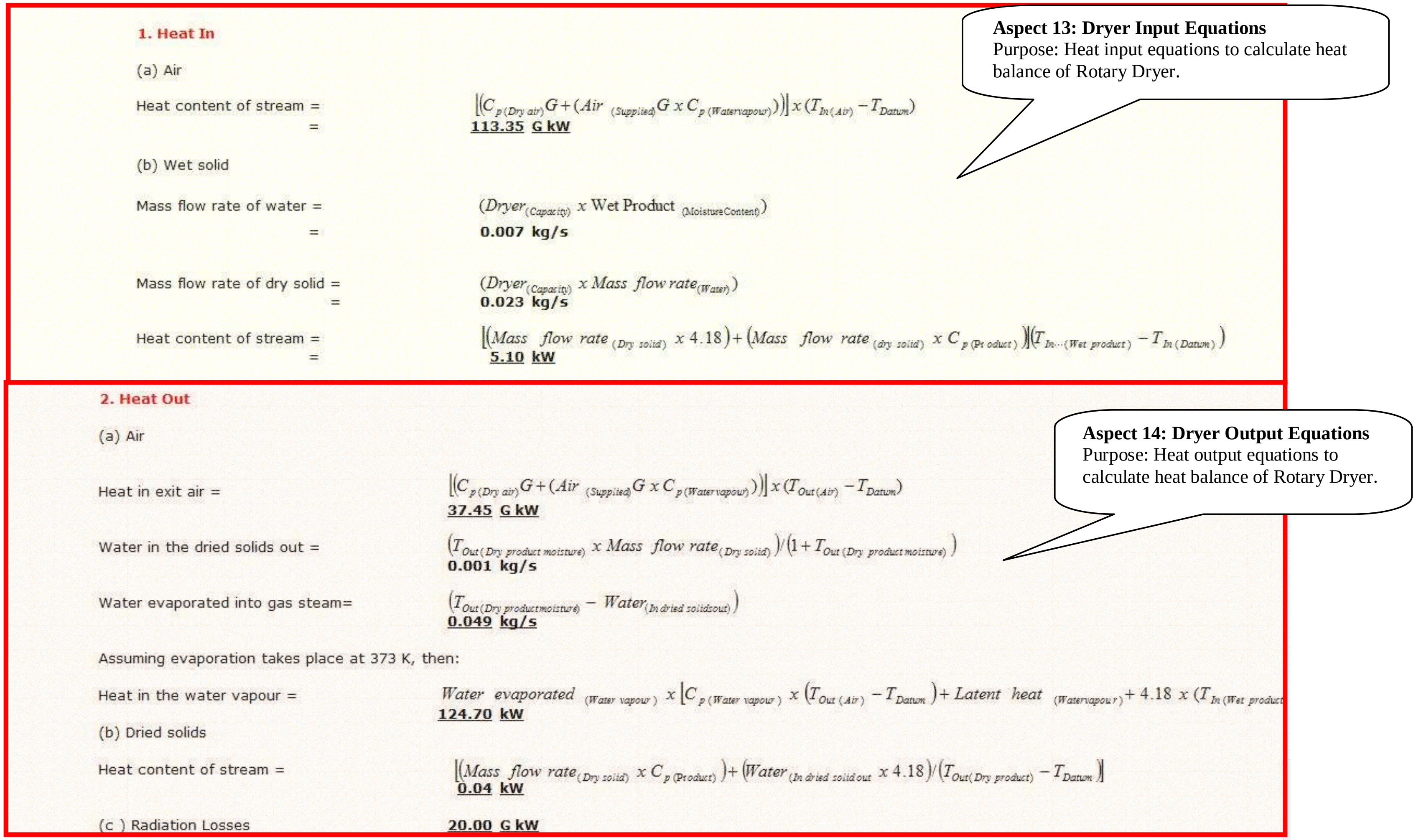
Product: Acetylsalicylic Acid (Aspirin)						
Pharmacopeia:99.5% with 0.5% water						
INLET	**UNITS**	**VALUE**	**OUTLET**	**UNITS**	**VALUE**	
Wet Product	kg/Year	1.058.196	Dry Product	kg/Year	800.000	
Wet Product Moisture Content	%	24,80	Dry Product Moisture Content	%	0,50	
Dryer type		Counter Current Rotary				
Dryer Capacity	kg/s wet stock max	0,0300				
Wet Product Input Temperature	K	373	Dry Product Output Temperature	K	308,5	***Containing 5,0 % moisture*
Air Supplied	kg water vapour/ kg dry air	0,006				
Entering Air Temperature	K	385,0	Leaving Air Temperature	K	310,0	
Reference Datum Temperature	K	273,0				
Cal. Latent Heat based on Tin	kJ/kg	**2.257**	Radiation losses	kJ/kg dry air used	20,0	*Assumed radiation losses amount in kJ per kg of dry air used*



Aspect 12: Dryer Human – Machine – Interface (HMI)

Purpose: Dryer user friendly interface of the process.

Figure 26. Dryer Heat Recovery



Aspect 13: Dryer Input Equations
Purpose: Heat input equations to calculate heat balance of Rotary Dryer.

1. Heat In

(a) Air

Heat content of stream = $\left[\left(C_{p\,(Dry\ air)}G + (Air_{\ (Supplied)}G \ x \ C_{p\,(Watervapour)})\right)\right] x \ (T_{In\,(Air)} - T_{Datum})$

= **113.35 G kW**

(b) Wet solid

Mass flow rate of water = $(Dryer_{(Capacity)} \ x$ Wet Product $_{(MoistureContent)})$

= **0.007 kg/s**

Mass flow rate of dry solid = $(Dryer_{(Capacity)} \ x \ Mass \ \ flow \ rate_{(Water)})$

= **0.023 kg/s**

Heat content of stream = $\left[\left(Mass \ \ flow \ \ rate_{\ (Dry\ solid)} \ x \ 4.18\right) + \left(Mass \ \ flow \ \ rate_{\ (dry\ solid)} \ x \ C_{p\,(Product)}\right)\right]\left(T_{In\cdots(Wet\ product)} - T_{In\,(Datum)}\right)$

= **5.10 kW**

Aspect 14: Dryer Output Equations
Purpose: Heat output equations to calculate heat balance of Rotary Dryer.

2. Heat Out

(a) Air

Heat in exit air = $\left[\left(C_{p\,(Dry\ air)}G + (Air_{\ (Supplied)}G \ x \ C_{p\,(Watervapour)})\right)\right] x \ (T_{Out\,(Air)} - T_{Datum})$

37.45 G kW

Water in the dried solids out = $\left(T_{Out\,(Dry\ product\ moisture)} \ x \ Mass \ \ flow \ rate_{(Dry\ solid)}\right) / \left(1 + T_{Out\,(Dry\ product\ moisture)}\right)$

0.001 kg/s

Water evaporated into gas steam= $\left(T_{Out\,(Dry\ productmoisture)} - Water_{(In\ dried\ solidsout)}\right)$

0.049 kg/s

Assuming evaporation takes place at 373 K, then:

Heat in the water vapour = $Water \ \ evaporated_{\ (Water\ vapour)} \ x \ \left[C_{p\,(Water\ vapour)} \ x \ \left(T_{Out\,(Air)} - T_{Datum}\right) + Latent \ \ heat_{\ (Watervapour)} + 4.18 \ x \ (T_{In\,(Wet\ product}$

124.70 kW

(b) Dried solids

Heat content of stream = $\left[\left(Mass \ \ flow \ rate_{(Dry\ solid)} \ x \ C_{p\,(Product)}\right) + \left(Water_{(In\ dried\ solid\ out} \ x \ 4.18\right) / \left(T_{Out\,(Dry\ product)} - T_{Datum}\right)\right]$

0.04 kW

(c) Radiation Losses **20.00 G kW**

Figure 27. Dryer Heat Recovery

(a)

3. Heat Balance (In=Out)

Mass Flow rate (G) is:

$$Heat\ content_{(Heat\ in,\ Air)} + Heat\ content_{(Heat\ in\ Wet\ solid)} = Heat\ in\ water\ vapour_{(Heat\ out\ Air)} + Heat\ in\ exit\ air_{(Heat\ out\ Air)} + Heat\ content\ of\ stream_{(Heat\ out\ (Dried\ solids))} + Loss$$

$$G(Heat\ content_{(Heat\ in\ Air)} - Heat\ exit\ air_{(Heat\ out\ Air)} - Loss) = Heat\ water\ vapour_{(Heat\ out\ Air)} + Heat\ content\ of\ stream_{(Heat\ out\ Dried\ solids)} - Heat\ content_{(Heat\ in\ Wet\ solid)}$$

55,90 G	=	119,64
Mass flowrate of dry air supplied to the dryer G	=	**2,14 Kg/s**

Aspect 15: Dryer Heat Balance
Purpose: Heat balance and mass flow rate of dry air supplied to the dryer calculations.

4. Heat Recovery

Air Density	=		1,20 Kg/m3	
Leaving Air Temperature	=		310 degC	
Available Airflow for Heat Recovery	=	*Mass flow rate of dry air x 3600 / Air density* =	**6.420 m3/h**	***3.779 cfm***
Leaving Air Temperature for Heat Recovery, dB	=	$Leaving\ air\ temperature\ degK - 373 =$	**37 degC**	***98,6 degF***

Aspect 16: Dyer Heat Recovery
Purpose: Available air flow for Heat Recovery and Leaving Air Temperature for Heat Recovery calculations.

(b)

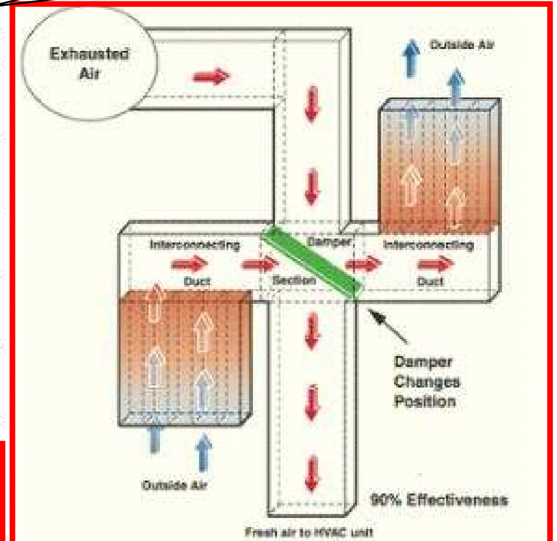
Tab 3. HR Performance

Aspect 17: Heat Recovery Performance
Purpose: To calculate actual and standard CFM (cubic feet per minute) for winter and summer conditions upon the available airflow for heat recovery from the dryer.

REVERSE FLOW TECHNOLOGY

Note: Blue Values are Manual Inputs given by the Manufacturer

		Summer	Winter
	Actual CFM	Standard CFM	
Actual CFM Exhaust	3.779	3.518	3.518
Actual CFM Supply	3.779	3.708	3.963
Minimum Standard CFM		**3.518**	**3.518**
Actual CFM Fresh Air	3.779		
Actual CFM Exhaust	3.779		



Design Data	DB	WB	RH (gr/Lb)
Outdoor Winter (F)	36,0	29,2	21,2
Outdoor Summer (F)	70,0	55,9	69,1
Winter Exhaust (F)	98,6	59,0	39,3
Summer Exhaust (F)	98,6		
Altitude (Ft)	8.359		
Pressure (psi)	10,77		
Effectiveness of Exhaust (%)	90%	+/- 5%	By Heat Recovery Unit Manufacturer
Latent Winter Recovery (%)	70%		

	Summer	Winter
Effective Correction	0,89	1,00
Hum/csfm Ratio Correction	1,00	1,00
Exhaust Air Effectiveness	80,0%	90,0%
	Exhaust Temp.	**Winter Supply Temp.**
Pressure Drop Correction	0,98	0,81

By Heat Recovery Unit Manufacturer

Aspect 19: Heat Recovery Unit
Purpose: Show the major components of the Heat Recovery Unit.

Figure 28. Heat Recovery Performance

Aspect 18: Heat Recovery Performance design data
Purpose: States design data for heat recovery performance analysis.

(a)

Actual CFM Exhaust	3.779			
	Summer Design		Winter Design	
	Exhaust SCFM	Exchanger Static"	Exhaust SCFM	Exchanger Static"
	3.518	0,342	3.518	0,342
	Supply scfm summer	Supply Static"	Supply SCFM winter	Supply Static"
	3.708	0,387	3.963	0,358
	Summer scfm ratio		Winter scfm ratio	
	0,95		0,89	

Airflow (cfm)	Exhaust	Supply
Normal Static (inch)	0,402	0,402
Velocity (fpm)	437	437

Aspect 20: Airflow CFM
Purpose: To calculate actual CFM Exhaust and supply velocity.

Return Temps	Supply to AHU	
	DB (degF)	DB (degC)
Winter Design	86,0	30,0
Summer Design	91,7	33,2

Aspect 21: Return temperatures
Purpose: To calculate return temperatures of the supply AHU for winter and summer design.

Heat Recovered	215.212 btu/h	64,6 kW	1.085 x Scfm x (Temp.supply - Temp. exhaust)

Aspect 22: Heat Recovery Performance
Purpose: To calculate the heat recovered of the supply to AHU.

(b)

HR Performance Equations

	Actual CFM	Summer	Vinter
		Standard CFM	
Actual CFM Exhaust	$=(From\ Dryer)$	$=\left[(Actual\ CFM\ Exhaust)\ x\left(\frac{529.67}{(Summer\ Exhaust\ (F)+460)}\right)x\left(\frac{Hg\ Exhaust}{29.92}\right)\right]$	$=\left[(Actual\ CFM\ Exhaust)\ x\left(\frac{529.67}{(Winter\ Exhaust\ (F)+460)}\right)x\left(\frac{Hg\ Exhaust}{29.92}\right)\right]$
Actual CFM Supply	$=Actual\ CFM\ Exhaust$	$=\left[(Actual\ CFM\ Fresh\ Air)\ x\left(\frac{529.67}{(Outdoor\ Summer\ (F)+460)}\right)x\left(\frac{Hg\ Outside\ Summer}{29.92}\right)\right]$	$=\left[(Actual\ CFM\ Fresh\ Air)\ x\left(\frac{529.67}{(Outdoor\ Winter\ (F)+460)}\right)x\left(\frac{Hg\ Outside\ Winter}{29.92}\right)\right]$
Minimum Standard CFM		$=MIN\ Value\ Actual\ CFM\ (Summer)_{Exhaust\ vs.\ Supply}$	$=MIN\ Value\ Actual\ CFM\ (Winter)_{Exhaust\ vs.\ Supply}$
Actual CFM Fresh Air	$=Actual\ CFM\ Supply$		
Actual CFM Exhaust	$=Actual\ CFM\ Exhaust$		

Summer Design	
Exhaust SCFM	**Exchanger Static"**
$=Actual\ CFM\ Exhaust Summer$	$=\left(\frac{Exhaust\ SCFM\ Summer}{Actual\ CFM\ Exhaust}\right)^2 x\ 0.402\ x\ Pressure\ drop\ correction$
Supply scfm summer	**Supply Static"**
$=Actual\ CFM\ Exhaust\ Summer$	$=\left(\frac{Supply\ SCFM\ Summer}{Actual\ CFM\ Exhaust}\right)^2 x\ 0.402$
Summer scfm ratio	
$=\left(\frac{Exhaust\ SCFM\ Summer}{Supply\ SCFM\ Summer}\right)$	

Winter Design	
Exhaust SCFM	**Exchanger Static"**
$=Actual\ CFM\ Exhaust Winter$	$=\left(\frac{Exhaust\ SCFM\ Winter}{Actual\ CFM\ Exhaust}\right)^2 x\ 0.402\ x\ Pressure\ drop\ correction$
Supply SCFM winter	**Supply Static"**
$=Actual\ CFM\ Supply Winter$	$=\left(\frac{Supply\ SCFM\ Winter}{Actual\ CFM\ Exhaust}\right)^2 x\ 0.402\ x\ Pressure\ drop\ correction$
Winter scfm ratio	
$=\left(\frac{Exhaust\ SCFM\ Winter}{Supply\ SCFM\ Winter}\right)$	

Figure 29. Heat Recovery Performance Equations

(a)

Return Temps	Supply to AHU	
	DB (degF)	DB (degC)
Winter Design	$= \left(\text{Outdoor Winter DB} - \text{Exhaust Air Effectiveness}\right) x \left(\text{Outdoor Winter DB} - \text{Winter Exhaust}\right) x \left(\frac{\text{Min. Standard CFM Winter}}{\text{Actual CFM Supply}}\right)$	
Summer Design	$= \left(\text{Outdoor Summer DB} - \text{Exhaust Air Effectiveness}\right) x \left(\text{Outdoor Summer DB} - \text{Summer Exhaust}\right) x \left(\frac{\text{Min. Standard CFM Summer}}{\text{Actual CFM Supply}}\right)$	

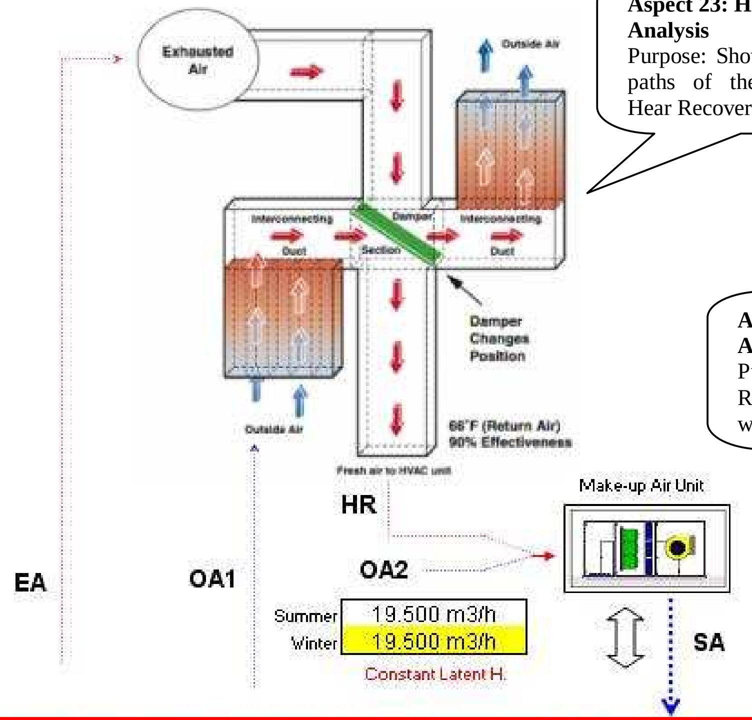
Heat Recovered	$= \left(1.085 \; x \; \text{Exhaust SCFM}\right) x \left(\text{Winter Exhaust DB} - \left(\text{Outdoor Winter DB}\right)\right) x \; \text{Exhaust Air Effectiveness Winter}$	1.085 x Scfm x (Temp.supply - Temp. exhaust)

(b)

Tab 4. HR Analysis

Heat Recovery

Project: **Cleanroom - Drying Operation**
Location: **Bogota, Colombia**
Elevation (m): **2548**
Pressure (kPa): **74,2**
HR Technology: **REVERSE FLOW**
ISO Class: **100**
Req'd Airflow: **25.920 m3/h**



Aspect 23: Heat Recovery Analysis
Purpose: Shows the Air flows paths of the Reverse Flow Hear Recovery Unit.

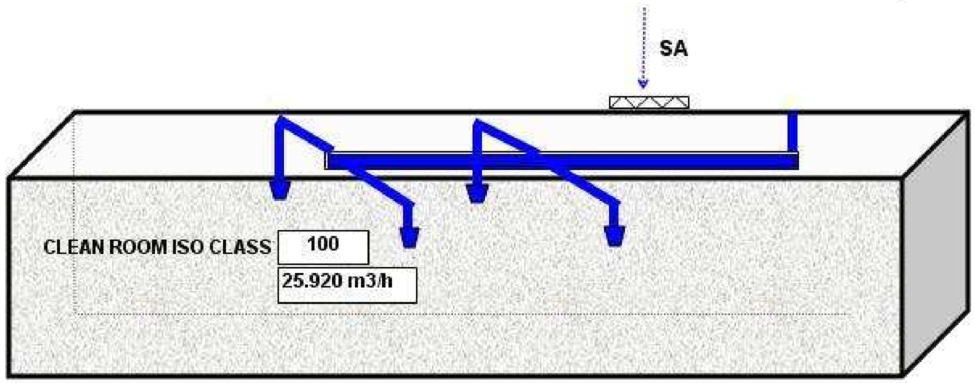
Aspect 24: Heat Recovery Analysis
Purpose: Psychrometric Heat Recovery calculations for winter conditions.

(Winter Conditions)	From Dryer	Outside Air 1	HR Supply	Mixed Air	Setpoints
Air Flow (m3/h)	6.420	6.420	6.420	25.920	25.920
Drybulb, db (°C)	**37,0**	**2,2**	**30,0**	**9,1**	**23,0**
Wetbulb, wb (°C)	**15,0**	**-1,6**	**10,6**	**1,9**	**14,0**
Humidity Ratio, x (g/kg)	5,6	3,0	3,0	3,0	13,6
Relative Humidity, rh (%)	11%	50%	8%	31%	**64%**
Dewpoint, dp (°C)	1,1	-6,3	-6,3	-6,3	13,8
Density, d (kg/m3)	0,825	0,933	0,848	0,911	0,859
Enthalpy, h (kj/kg)	51,6	9,7	37,8	16,7	55,5

Figure 30. Heat Recovery Analysis and Psychometric Points (Winter conditions)

Aspect 25: Heat Recovery Analysis
Purpose: Psychrometric Heat Recovery calculations for summer conditions.

(Summer Conditions)	From Dryer	Outside Air 1	HR Supply	Mixed Air	Setpoints
Air Flow (m3/h)	6.420	6.420	6.420	25.920	25.920
Drybulb, db (°C)	**37,0**	**21,1**	**33,2**	**24,1**	**21,0**
Wetbulb, wb (°C)	**15,0**	**13,3**	**16,9**	**14,2**	**16,0**
Humidity Ratio, x (g/kg)	5,6	9,9	9,9	9,9	13,6
Relative Humidity, rh (%)	11%	46%	23%	39%	**64%**
Dewpoint, dp (°C)	1,1	9,1	9,1	9,1	13,8
Density, d (kg/m3)	0,825	0,864	0,830	0,855	0,859
Enthalpy, h (kj/kg)	51,6	46,2	58,6	49,3	55,5



Floor Dimensions	
Length	6,0 m
Width	6,0 m
Height	3,0 m
Area	**36 m2**
Vol	108 m3

Note: Blue Values are Manual Inputs

VENTILATION PARAMETERS		
Make-up Fresh Air Flow (Ventilation)	25.920 m3/h	*15.257 cfm*
Air Changes per Hour	240 ach	
Room Area	36 m2	
Room Volumen	108 m3	
Clean Room ISO Class Limit	100	

Aspect 26: Ventilation Parameters
Purpose: To describe a summary of the ventilation parameters used in the clean room.

Figure 31 . Heat Recovery Analysis and Psychometric Points (Summer conditions)

HR Analysis Equations

VENTILATION PARAMETERS	
Make-up Fresh Air Flow (Ventilation)	$= Air\ flow\ set\ point_{winter\ conditions}$
Air Changes per Hour	$(From\ Main)$
Room Area	$= Clean\ Room\ Area$
Room Volumen	$= Clean\ Room\ Volume$
Clean Room ISO Class Limit	$(From\ Main)$

Figure 32 . Heat Recovery Analysis (Ventilation Parameters Equations)

Tab 5. Psychometric Chart

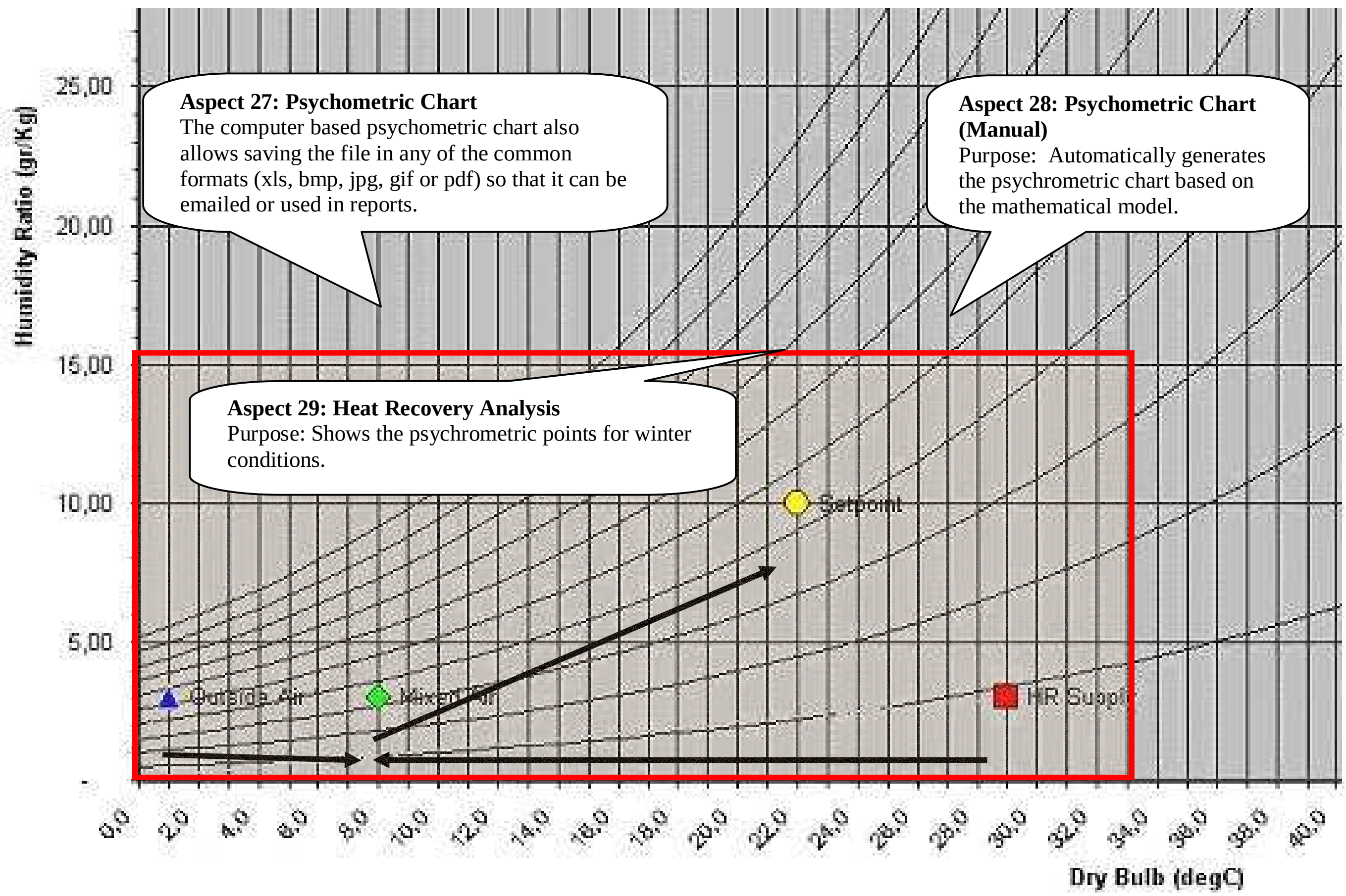


Figure 33. Psychometric Chart

Psychrometric Calculations			
Inputs	HR Supply	Outside Air 1	Mixed Air
Air Flow Rate	6.420 m3/h	9.780 m3/h	**16.200** m3/h
Dry Bulb Temperature	30,0 °C	2,2 °C	13,2 °C
Wet Bulb Temperature	10,6 °C	(1,6) °C	3,8 °C
Altitude	2.548 m.		
Outputs			
Atmospheric Pressure	74,2 kPa		
Dew Point Temperature	(6,3) °C	(6,3) °C	(6,3) °C
Relative Humidity	8,4 Percent	50,0 Percent	23,6 Percent
Humidity Ratio	3,0 grams/kg	3,0 grams/kg	3,0 grams/kg
Enthalpy	37,8 kJ/kg	9,7 kJ/kg	20,2 kJ/kg
Specific Volume (1/d)	1,18 m3/kg	1,07 m3/kg	1,11 m3/kg
Mass Flow Rate, dry air	5.445 kg/h	9.131 kg/h	14.576 kg/h
Mass Flow Rate, water vapor	16.470 kg/h	27.598 kg/h	44.068 kg/h
Mass Flow Rate, moist air	21.915 kg/h	36.730 kg/h	58.644 kg/h

Data to Graph	HR Supply	Outside Air 1	Mixed Air	Setpoint
Dry Bulb Temp. (degC)	30,0	2,0	13,0	23,0
Humidity Ratio (gr/kg)	3,0	3,0	3,0	10,0

Figure 34 . Psychometric Chart data

Tab 6. Payback Analysis

Aspect 30: Payback Analysis - Inputs and Winter Indoor Conditions.
Purpose: Overall measure of the HR unit efficiency, Exhaust Temps., airflow requirements, comodity prices, and Winter Indoor Conditions.

INPUTS

Indoor Air Conditions			
db Temperature of exhaust	23,0	°C	
wb Temperature of exhaust	14,0	°C	
Altitude	2548,0	m	
Total Airflow Requirements	25.920	m3/h	15.293 cfm
Available Dryer Airflow for HR	6.420	m3/h	3.788 cfm
Gas Costs @	0,34	€/m3	→ **0,032 €/kWh**
Electricity Costs @	0,15	€/kWh	
Heating Recovery Effectiveness	90%		By Heat Recovery Unit Manufacturer
Cooling Recovery Effectiveness	80%		
Burner Efficiency	80%		
Cooling Efficiency	80%	kw/ton	
Static Press. added by Unit	100	Pa	
Fan Motor Efficiency	75%		
Reverse Flow Equipment life	21	years	

The system has been designed for a minimum life expectancy of 21 years.

WINTER INDOOR CONDITIONS

Atmospheric Pressure	74,2	kPa
Dew Point Temperature	13,8	°C
Relative Humidity	64%	
Humidity Ratio	13,6	g/kg
Enthalpy	55,5	kJ/kg
Specific Volume	1,16	m3/kg

HR SYSTEM PERFORMANCE

Heating Exhausted (kWh)	Cooling Exhausted (kWh)	Fan Energy Incurred (kWh)	Cooling Recovered (kWh)	Heating Recovered (kWh)
753.615	8.128	8.410	154	167.997

BKM Model # HR unit model **EB 4000**

Aspect 31: Payback Analysis – HR System Performance
Purpose: Overall measure of the heating and cooling capacities of the heat recovery system.

Figure 35. Payback Analysis (Indoor Air Conditions, Winter Indoor Conditions and HR System performance)

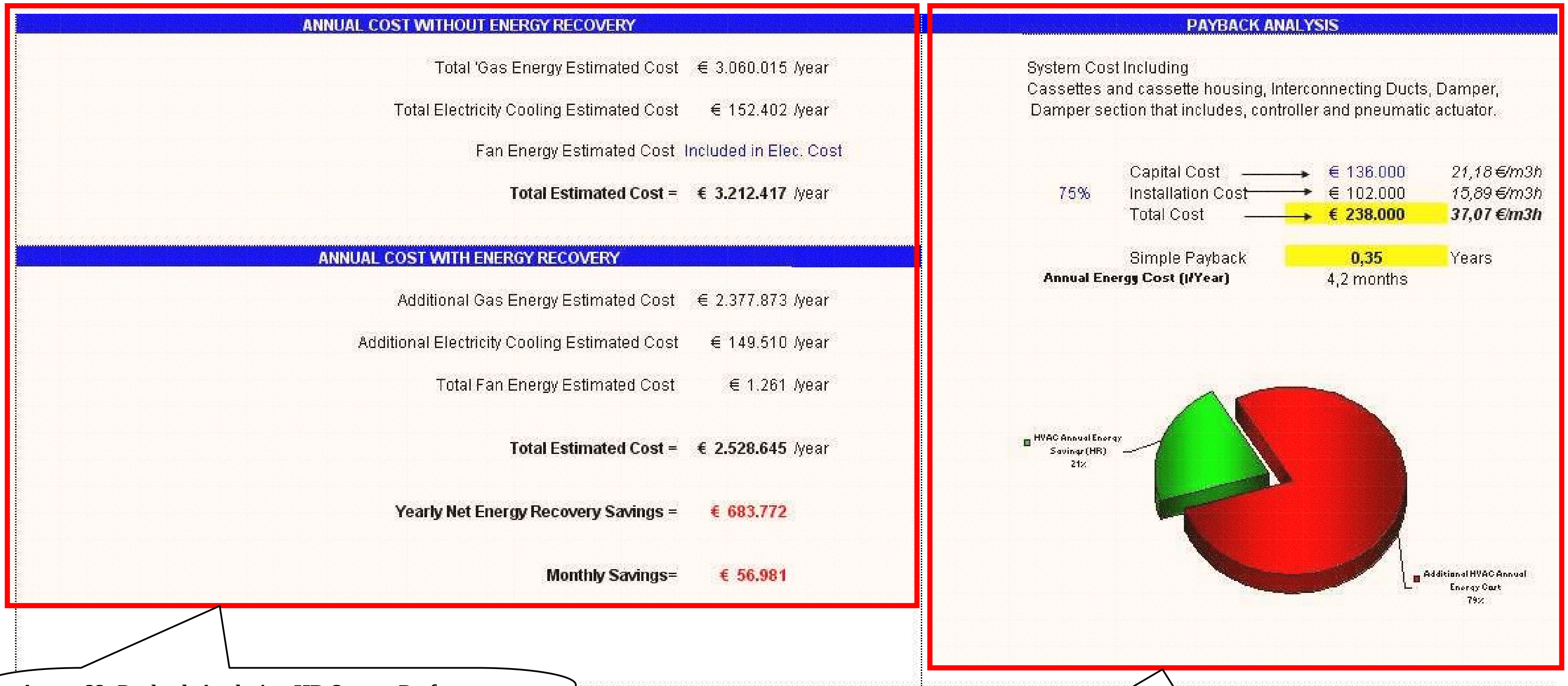
Payback Analysis Equations

INPUTS	
Indoor Air Conditions	
db Temperature of exhaust	*FromHR Analysis(Winter conditionsSP DB)*
wb Temperature of exhaust	*FromHR Analysis(Winter conditionsSPWB)*
Altitude	*From Main (Elevation)*
Total Airflow Requirements	*FromHR Analysis(Winter conditionMixing air flow)*
Available Dryer Airflow for HR	*FromDryerHR(Dryer availableair flow)*
Gas Costs @	*FromMain(Gas cost)*
Electric Costs @	*FromMain(Electricity cost)*
Heating Recovery Effectiveness	By Heat Recovery Unit Manufacturer
Cooling Recovery Effectiveness	By Heat Recovery Unit Manufacturer
Burner Efficiency	By Heat Recovery Unit Manufacturer
Cooling Efficiency	By Heat Recovery Unit Manufacturer
Static Press. added by Unit	By Heat Recovery Unit Manufacturer
Fan Motor Efficiency	By Heat Recovery Unit Manufacturer
Reverse Flow Equipment life	

WINTER INDOOR CONDITIONS	
Atmospheric Pressure	*FromMain(Pressure)*
Dew Point Temperature	*FromHR Analysis(Winter conditionsSP Dewpoint)*
Relative Humidity	*From HR Analysis (Winter conditions SP Relative Humidity)*
Humidity Ratio	*FromHR Analysis(Winter conditionsSP HumidityRatio)*
Enthalpy	*FromHR Analysis(Winter conditionsSP Enthalpy)*
Specific Volume	=1/Density

Heating Exhausted (kWh)	Cooling Exhausted (kWh)	Fan Energy Incurred (kWh)	Cooling Recovered (kWh)	Heating Recovered (kWh)
$=\Sigma\, Heating(kW)$	$=\Sigma\, Cooling(kW)$	$=\Sigma\, Fan\ Power\ Load(kW)$	$=\Sigma\, CoolingRecovered(kW)$	$=\Sigma\, HeatingRecovered(kW)$

Figure 36. Payback Analysis (Indoor Air Conditions, Winter Indoor Conditions and HR System performance Equations)



Aspect 32: Payback Analysis – HR System Performance
Purpose: Economic analysis of the system with or without heat recovery in order to determine savings.

Aspect 33: Payback Analysis – Payback Analysis
Purpose: Shows a simple calculation of how long it would take to recover the investment if a Reverse Flow Heat Recovery unit is used.

Figure 37. Payback Analysis (Annual Cost without Energy Recovery, Annual Cost with Energy Recovery and Payback Analysis)

Without Energy Recovery

Total 'Gas Energy Estimated Cost =(*HeatingExhausted* x *Gas cost*)/(*Burner Efficiency*/100)

Total Electricity Cooling Estimated Cost =(*Cooling Exhausted* x *Electricity cost*)/(*Cooling Efficiency*/100)

With Energy Recovery

Additional Gas Energy Estimated Cost =(((*HeatingExhausted* – *HeatingRecovered*) x *Gascost*) / (*Burner Efficiency*/100)

Additional Electricity Cooling Estimated Cost=(*Cooling Exhausted* – *CoolingRecovered*) x *Electricity cost* /(*CoolingEfficiency*/100)

Total Fan Energy Estimated Cost =(*Fan Energy* x *Electricity cost*

Figure 38. Payback Analysis (Annual Cost without Energy Recovery, Annual Cost with Energy Recovery and Payback Analysis Equations)

4.3 Reverse Flow Heat Recovery Payback Analysis

In engineering, the Payback period is the amount of time required for achieving an amount in profits to offset the cost of a capital expenditure, such as the cost of investment in modifications in an industrial facility for the purpose of conserving energy. The Reverse Flow Heat Recovery Payback depends on a number of factors, such as location, type of heat recovery unit, unit size, efficiency, and, heat recovery unit performance as determined by the Heat Recovery Unit Manufacturer.

As a large number of uncontrolled and unknown factors are involved in the Payback analysis, the bin method is use for annual energy consumption as different temperature intervals and time periods are evaluated separately [12]. Weather bin data for the city of Bogotá Colombia provides the number of hours in a typical year that the outdoor air temperature will fall in to a particular range of temperatures (or bin). The Payback model, as shown in Figures 35, 36, 37 and 38, calculates energy savings based on the heat recovered from the pharmaceutical drying operation. By determining output for given inputs at each hour, the yearly net energy recovery savings are determined.

Table 11 shows weather bin data for Bogotá Colombia and, Figures 39, 40 and 41 show annual Dry bulb temperatures data.

Table 11. Bogotá, Colombia - Weather Bin Data

BOGOTA, COLOMBIA - WEATHER BIN DATA

8760 hours 24/7

TMY-2 Files InterEnergy Software

Dry Bulb (degC)	Bin Hours	MC Wet Bulb (degC)	MC Enthalpy (kJ/kg)	Delta T (degC)	Total Airflow (m3/h)	Heating (kW)	Cooling (kW)	HVAC Unit: Fan Power Load (kWh)	Heat Recovery Unit: Available Dryer Airflow for HR (m3/h)	Heat Recovery Unit: Cooling Recovered (kW)	Heat Recovery Unit: Heating Recovered (kW)
24,0	2	13,6	47,9		25.920		1.787	1,92	6.420	79	
23,0	7	14,1	49,3		25.920		6.341	6,72	6.420	75	
22,0	**21**	13,8	47,6	1,00	25.920	182		20,16	6.420		40,65
21,0	68	13,7	47,5	2,00	25.920	1.181		65,28	6.420		263,25
20,0	200	13,5	47,3	3,00	25.920	5.210		192,00	6.420		1.161
19,0	366	13,4	46,7	4,00	25.920	12.712		351,36	6.420		2.834
18,0	614	13,1	45,8	5,00	25.920	26.657		589,44	6.420		5.943
17,0	663	12,7	44,6	6,00	25.920	34.542		636,48	6.420		7.700
16,0	666	12,5	43,8	7,00	25.920	40.481		639,36	6.420		9.024
15,0	582	12,3	43,1	8,00	25.920	40.429		558,72	6.420		9.012
14,0	632	11,9	42,0	9,00	25.920	49.390		606,72	6.420		11.010
13,0	726	11,5	40,7	10,00	25.920	63.040		696,96	6.420		14.053
12,0	1013	10,9	39,1	11,00	25.920	96.757		972,48	6.420		21.569
11,0	1034	10,1	36,8	12,00	25.920	107.741		992,64	6.420		24.018
10,0	833	9,2	34,6	13,00	25.920	94.030		799,68	6.420		20.961
9,0	485	8,3	32,3	14,00	25.920	58.959		465,60	6.420		13.143
8,0	313	7,4	30	15,00	25.920	40.768		300,48	6.420		9.088
7,0	198	6,4	27,3	16,00	25.920	27.508		190,08	6.420		6.132
6,0	129	5,6	25,4	17,00	25.920	19.042		123,84	6.420		4.245
5,0	85	4,6	23,1	18,00	25.920	13.285		81,60	6.420		2.962
4,0	51	3,9	20,7	19,00	25.920	8.414		48,96	6.420		1.876
3,0	30	2,9	18,7	20,00	25.920	5.210		28,80	6.420		1.161
2,0	21	1,9	16,6	21,00	25.920	3.829		20,16	6.420		854
1,0	10	0,9	14,6	22,00	25.920	1.910		9,60	6.420		426
	5		13,1	23,00	25.920	999		4,80	6.420		223
-1,0	2	-1,0	10,8	24,00	25.920	417		1,92	6.420		93
-2,0	1	-2,0	8,8	25,00	25.920	217		0,96	6.420		48
-3,0	1	-3,0	7,1	26,00	25.920	226		0,96	6.420		50
-4,0	1	-4,0	4,8	27,00	25.920	234		0,96	6.420		52
-5,0	1	-5,0	3,0	28,00	25.920	243		0,96	6.420		54
	8760										

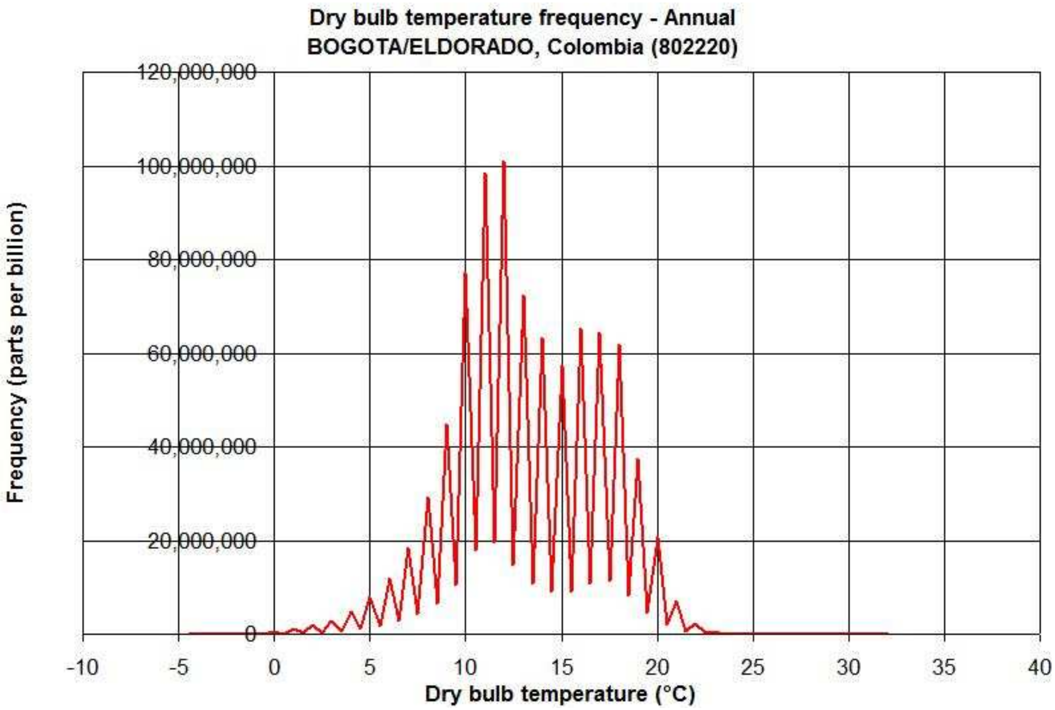


Figure 39. Dry bulb temperature frequency - Annual

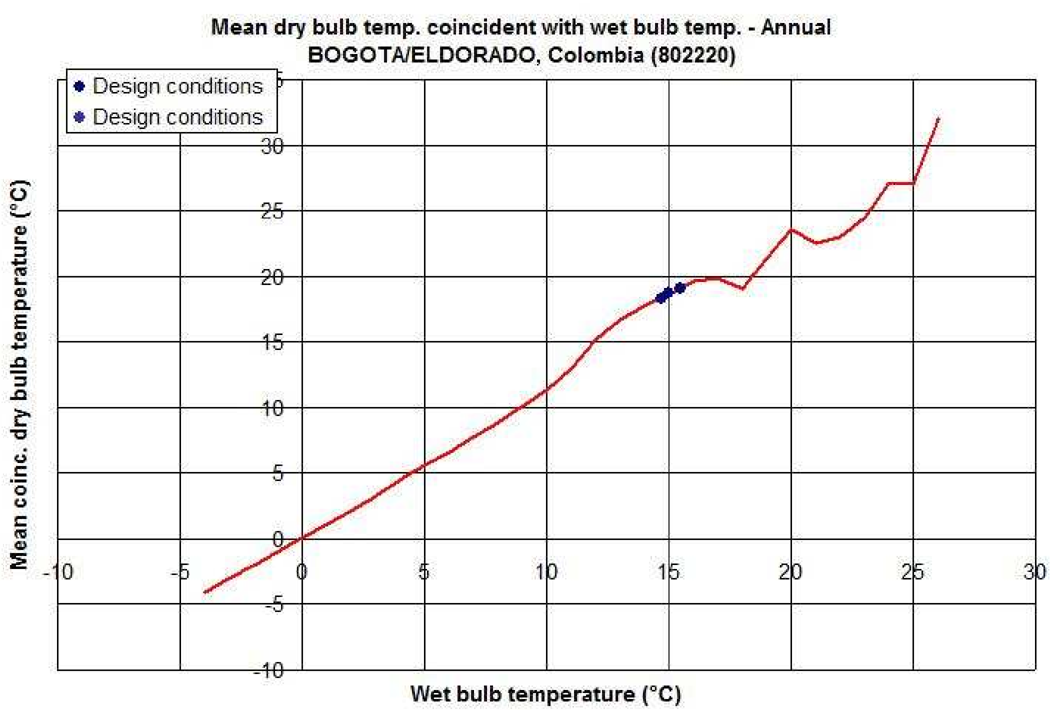


Figure 40. Mean dry bulb temperature with wet bulb temperature - Annual

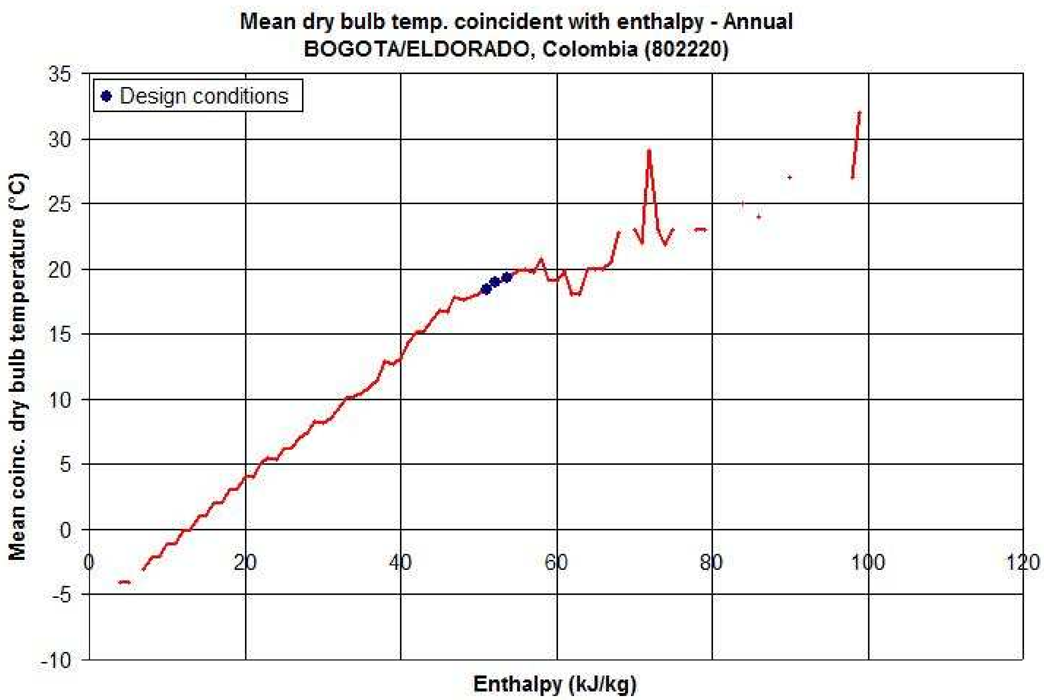


Figure 41. Mean dry bulb temperature coincident with enthalpy - Annual

4.4 Hardware and Software Requirements for Installing the Reverse Flow Heat Transfer Model

This section lists the minimum hardware and software requirements to install and run the proposed software heat transfer model for predicting air-to-air heat (energy) recovered in pharmaceutical drying clean rooms in Colombia. The hardware and software requirements for the proposed heat recovery software for pharmaceutical drying clean rooms in Colombia are derived from industry standard technologies and widely available commercial products.

Table 12. Hardware and Software Requirements

Heading	Description
Software	Microsoft Office Excel 2002 or Microsoft Office Excel 2007. ** To install and run the MS Excel combined with MS Visual programming, the macro security should be set to Medium in order to be able to enable macros. To allow unsigned macros to run, the "Trust all installed add-ins and templates" check box must be selected on the Trusted Publishers tab of the Security dialog box: On the Tools menu, point to Macro, and then click Security. On the Trusted Publishers tab, select the Trust all installed add-ins and templates check box. For more information, see Microsoft Office Support Centre [39].
Hard Disk	At least 5 MB disk space.
Drive	A CD or DVD drive, as appropriate, is required for installation from disc.
Processor	Processor type: Intel® Pentium® 4 Processor or faster Processor speed: Recommended: 3.0 GHz or faster
Operating system	Windows XP or newer
Memory	RAM: Minimum: 1 GB Recommended: 2 GB or more
Display	For the Reverse Flow Heat transfer model graphical tools is recommended Super VGA or higher resolution: at least 1280x1024 pixel resolutions.
Other Devices	Pointing device: A Microsoft mouse or compatible pointing device is required.

4.5 Validation and Testing

The requirements validation techniques have an important role in software development. It is an accurate representation of the real world from the perspective of the intended uses of the software. The proposed software heat transfer model is validated using a comparative technique, which compares several results of the program with each other.

Usually, a software program is tested properly using different test cases before shipment to customer, but this program is tested at final stage after development. A comparative technique is used between two or more factors, e.g. ISO clean room class, wet product moisture content, and commodity prices escalation. These factors are then compared to each others and their results analyzed.

4.6 Results

As seen before, there are several parameters that affect the decision to implement a Reverse Flow Heat Recovery system. This subsection addresses some of the economic considerations which are evaluated and compared in the decision process.

4.6.1 Airflow Heat Recovery vs. Wet Product Moisture Content

Table 13 shows the available Airflow Heat Recovery based on the Wet Product Moisture Content. This relationship provides an indication that this relationship is linear in nature.

Table 13.Airflow Heat Recovery vs. Wet Product Moisture Content

Wet Product Moisture Content	Available Airflow for Heat Recovery	Wet Product Input Temperature
%	m3/h	K
10,0	6.470,0	373
20,0	6.436,0	373
30,0	6.402,0	373
24,8	6.420,0	373
40,0	6.368,0	373
50,0	6.334,0	373
60,0	6.301,0	373
70,0	6.267,0	373
80,0	6.233,0	373
90,0	6.199,0	373

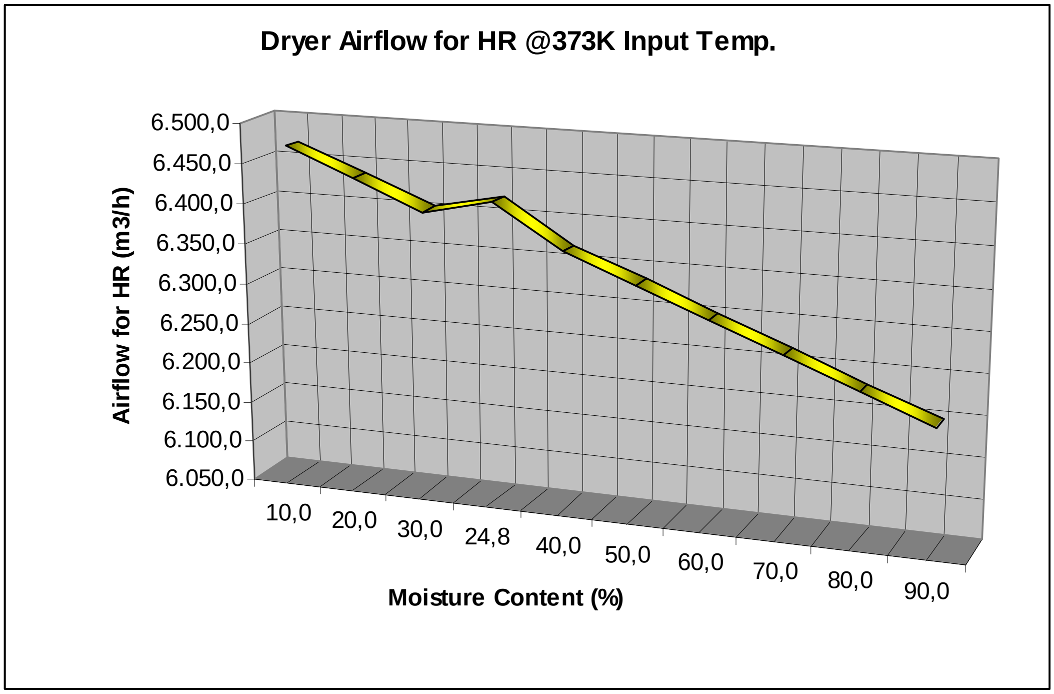


Figure 42. Airflow Heat Recovery vs. Wet Product Moisture Content

4.6.2 Heat Recovery vs. Outside Air Temperature

Table 14. Heat Recovery vs Outside Air Temperature

Outdoor Air DBT (deg C) *	Outdoor Air MCWBT (deg C) *	Heat recovered (kW)
-5	-5	77,9
0	0	69,6
2,1	-1,6	64,7
5	4,6	59,4
10	9,2	50,1
15	12,3	40,8
20	13,7	29,7
25	14,8	22,3
30	18,5	13

* Based on Bin Data

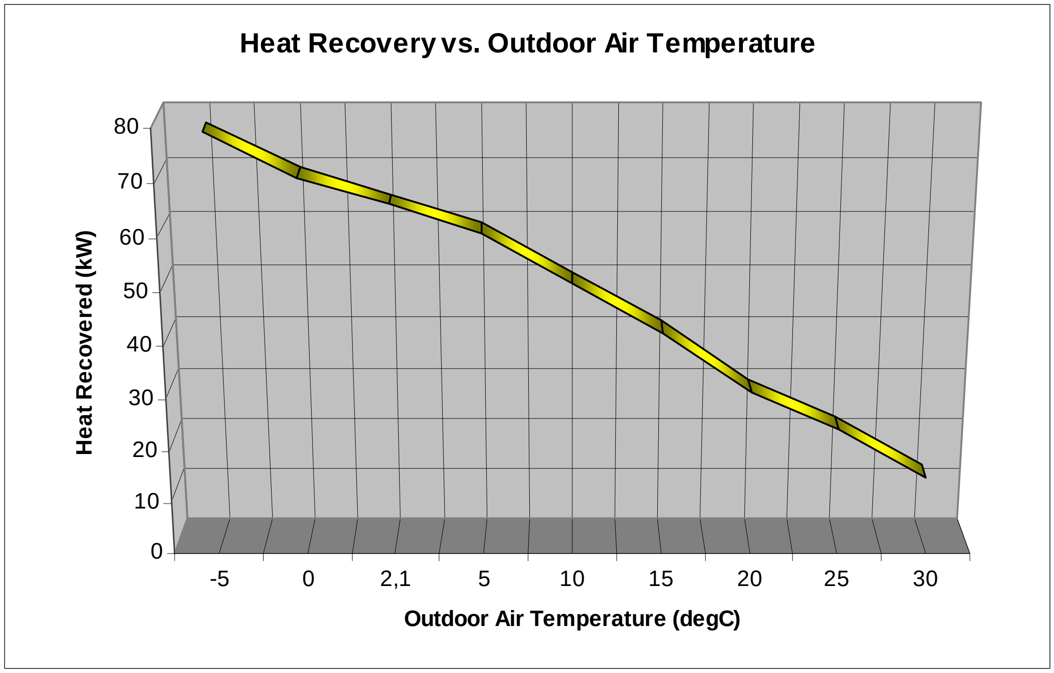


Figure 43. Heat Recovery vs Outside Air Temperature

The above analysis shows that the heat recovery is proportionally inverse to the outdoor air temperature. Thus, the colder the outside air temperature, the more profitable the Heat Recovery system is.

4.6.3 Energy Prices Analysis

Table 15. Energy Prices Analysis

Time (Years)	N.Gas (€/m3)	Electricity (€/kwh)	Heat Recovery Payback (Months)
0	0,34	0,15	4,2
1	0,36	0,18	3,9
2	0,37	0,22	3,8
3	0,39	0,26	3,6
4	0,41	0,31	3,5
5	0,43	0,37	3,3
6	0,46	0,45	3,1
7	0,48	0,54	3
8	0,50	0,64	2,8
9	0,53	0,77	2,7
10	0,55	0,93	2,6

* Annual escalation natural gas price 5%
** Annual escalation electricity price 20%

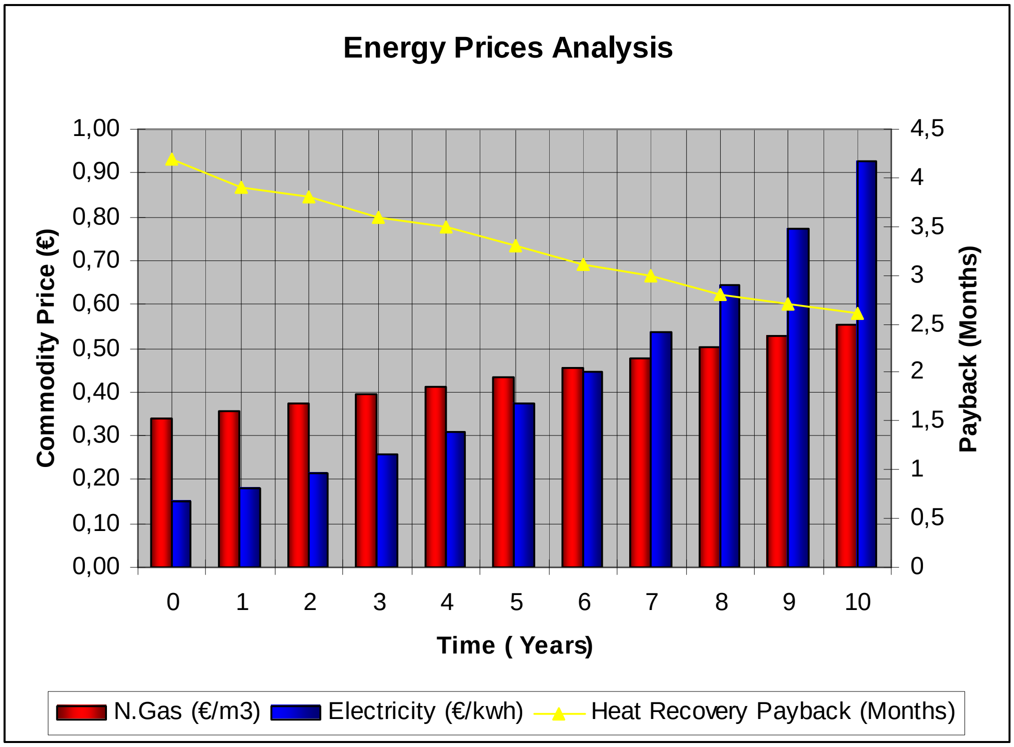


Figure 44. Energy Prices Analysis

As seen in the previous 10-year energy price analysis, with an annual escalation of 20% and 5% on electricity and natural gas respectively, the payback of the Reverse Flow Heat Recovery system reduces substantially.

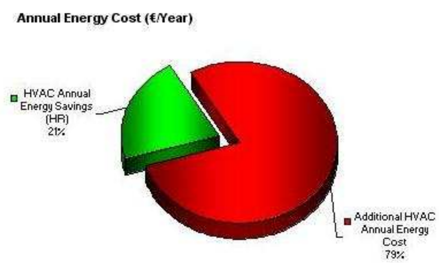
4.6.4 Payback Analysis

The Payback refers to the time period that will elapse before the cumulative cost savings will equal the incremental capital cost of the equipment selected. Using the Bin data and the calculated response of the calculated heat recovered from the Reverse Flow system in pharmaceutical clean rooms ISO Class 100, 1,000 and 10,000 is as follows:

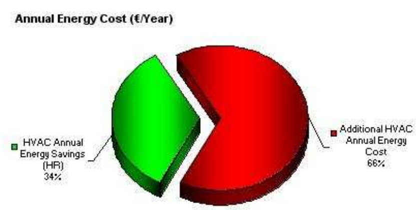
Table 16.Payback Analysis

	Class 100	Class 1000	Class 10000
	(€/Year)		
Additional HVAC Annual Energy Cost	€ 2.528.530	€ 1.324.193	€ 119.856
HVAC Annual Energy Savings (HR)	€ 683.726	€ 683.467	€ 683.208
	€ 3.212.255	**€ 2.007.659**	**€ 803.064**

ISO Class 100 Clean Room



ISO Class 1,000 Clean Room



ISO Class 10,000 Clean Room

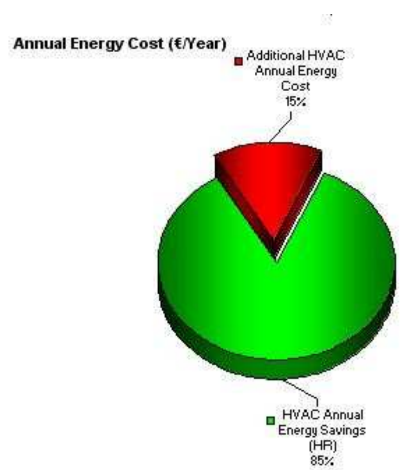


Figure 45. Payback Annual Energy Cost

Assuming a typical boiler efficiency of 85% and a negotiated cost for the gas at 0.34 €/m^3 (0.032 €/kWh) this translates to an average monthly savings of € 567,724. The total project cost including cassettes, cassette housing, interconnecting ducts, damper, controller pneumatic actuator and installation cost (75%) has an average cost of € 238,000. Using a simple Payback analysis the Payback for this project is estimated in 0.35 years (4.2 months), which indicates that the implementation of the Reverse Flow

Heat Recovery system in pharmaceutical drying clean rooms in Colombia is economical and viable.

4.7 Summary

This chapter illustrated the Reverse Flow Heat Recovery mathematical model for pharmaceutical drying clean rooms in Colombia, highlighting the main components of the Human-Model-Interface (HMI) of the Reverse Flow Heat Recovery software, in terms of purpose and activity. It identified the minimum hardware and software requirements to install and run the proposed software. It provided information of the comparative technique validation and testing model. HVAC Monthly Savings were calculated for ISO Class 100, 1,0000 and 10,000 Clean Rooms, giving an estimated Payback of 0.35 years approximately. Results indicated that the implementation of the Reverse Flow Heat Recovery system in pharmaceutical drying clean rooms in Colombia would be cost effective.

Chapter 5
Conclusion and Future Work

5.1 Introduction

This chapter concludes with a summary of the dissertation with; evaluates the objectives of the project, and gives suggestions for further work.

5.2 Evaluation of Objectives

As part of the ongoing management review process to ensure that the project finishes on time, meets pre-determined criteria, and meet the requirements for what it was initiated, this section evaluates at the conclusion of the project each objective to see whether it was achieved or not. The objectives of the project as defined before were:

<u>Objective 1</u>

- To identify and evaluate heat recovery options in the pharmaceutical drying operation in Colombia. In particular the mathematical model that permits outputs to be derived or predicted based on inputs.

Yes, this objective was achieved. This project described and showed the structure, trends and production characteristics of the Colombian pharmaceutical industry and tied it into the generic processes.

It also identified and described thermodynamic equations used in the Mathematical models. The drying operation and air analysis calculations are based on the textbooks described in Chapter Two [12, 30, 32, and 34].

Objective 2

- To investigate techniques for presenting heat recovery options from the drying operation.

Yes, this objective was achieved. This project proposed a new Human-Model-Interface (HMI) that permits outputs to be derived based on inputs, for predicting the amount of air-to-air heat (energy) that can be recovered in pharmaceutical drying clean rooms in Colombia. It identified that the drying cycle is a critical operation where large emissions of heat are produced, and it proposed the use of the Reverse Flow Heat Recovery Technology to draw the humid air exiting the process through a vent system equipped with a heat exchanger technology. Figure 19 showed a schematic diagram of the proposed system for a typical pharmaceutical counter-current rotary dryer for drying solids completed with a reverse flow heat recovery unit.

Objective 3

- To develop and implement a system where the model aspects, data storage aspects and visualisation aspects are combined.

Yes, this objective was achieved. The heat transfer model for predicting air-to-air heat (energy) recovered in pharmaceutical drying clean rooms in Colombia is defined as a single application for process parameter fitting for pharmaceutical drying operations under clean room conditions and a heat recovery analysis tool.

Model aspects are developed using off the shelf software applications such as MS Excel combined with MS Visual programming; data storage files are stored in excel format (xls.), and visualisation aspects are combined in user friendly Human Model Interfaces (HMI´s) that avoids the cost of learning a complex program. In addition, the software includes two types of psychometric charts:

(1) Paper type psychometric chart represents the thermodynamic properties of the moist air. The choice of coordinates is arbitrary. The heat transfer mathematical model includes a chart with coordinates of Dry Bulb (degC) and Humidity Ratio (gr/kg) and gives a convenient and useful graphical user interface showing several psychometric set points such as HR Supply, Outside Air, Mixed Air, and Room Indoor Set Point with a minimum of thermodynamics approximations.

(2) Automatic generated psychometric chart on the computer using the mathematical model represents the thermodynamic properties of several psychometric process set points: i.e. HR Supply, Outside Air, Mixed Air, and Room Indoor Set Points.

Objective 4

- To develop user-friendly virtual simulation application software to show the heat recovered from the drying operation and the energy savings to the end user.

Yes, this objective was achieved. The heat transfer model for predicting air-to-air heat (energy) recovered in pharmaceutical drying clean rooms in Colombia was developed in MS Excel, which have a graphical user friendly interface. The software included a Payback analysis to establish the cost-effectiveness of the Reverse Flow Heat Recovery system.

5.3 Future Work

Although the proposed heat transfer mathematical model for predicting air-to-air heat (energy) recovered in pharmaceutical drying clean rooms in Colombia is based on hourly profiles for climate conditions and operational characteristics, certain phenomena cannot be modelled precisely, like temperature changes during the drying operation, commodity energy prices escalations, different types of dryers and performance, etc. This problem can be partially overcome by using a method where equations are solved simultaneously at each time interval. The results of this modelling strategy are superior, though it demands more computing resources.

5.4 Conclusions

- Pharmaceutical drying clean rooms require careful consideration of its particle concentration, Air Changes per Hour (ACH), location, manufacturing processes, and both equipment and operating costs.

- The drying operation is realised by evaporating solvents from solids to give the final product (or intermediate). There is significant potential for heat recovery from the waste heat exhaust.

- In Colombia further savings in areas such as Reverse Flow Heat Recovery are possible, cost-effective, and viable.

- The particular processes employed in a pharmaceutical production sequence vary by product and by plant. The key factors affecting a plant energy consumption include facility type (e.g., bulk production), the products produced (e.g. Tablets), the plant location, and the efficiency of the plant.

- Thermodynamic equations used in the mathematical models calculate the amount of heat recovered by the proposed Reverse Flow Heat Recovery unit.

- HVAC monthly savings were calculated for ISO Class 100, 1,0000 and 10,000 Clean Rooms, giving a estimated Payback of 0.35 years. Results indicated that the implementation of the Reverse Flow Heat Recovery system in pharmaceutical drying clean rooms in Colombia is highly economical and profitable.

- The proposed heat transfer mathematical model for predicting air-to-air heat (energy) recovered in pharmaceutical drying clean rooms in Colombia provided an indication that the heat recovered is proportionally direct to the clean room ISO Class.

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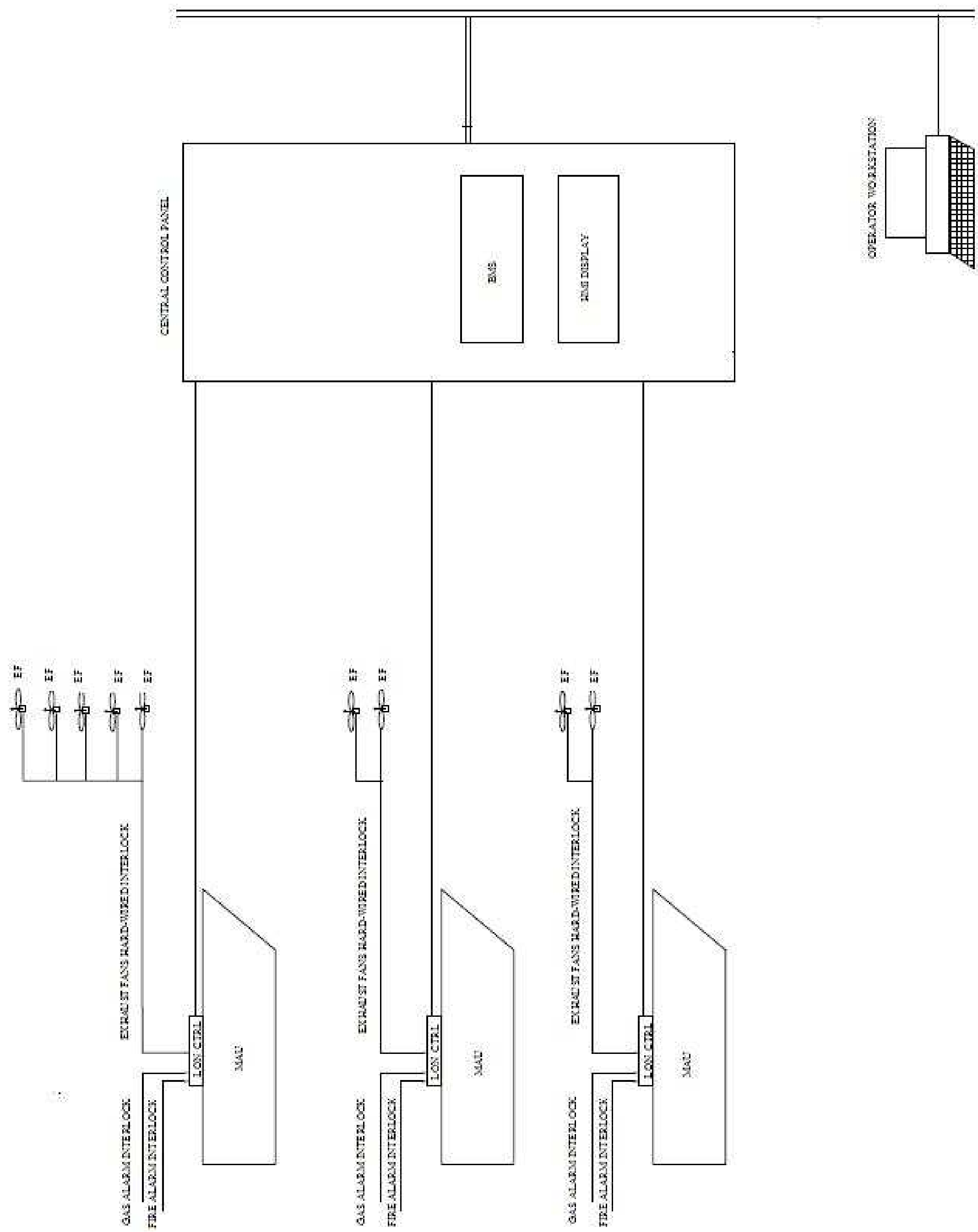
Appendix

Appendix 1. Existing HVAC Control Block Diagram [16]



Appendix 2. Controller Distech ECP-300 Technical Specifications [16]

DISTECH CONTROLS™

BUILDING OPEN CONTROL PRODUCTS

ECP–300

easyCONTROLS™ LONMARK® v3.4 Certified
18-Point Free Programmable Controller

- 10 Universal Inputs
- 8 Universal Outputs

LONMARK

Applications

- Control of equipment such as: roof top units, fan coils, heat pumps, ventilator units, terminal units, multistage air handling units, chillers, boilers, lighting systems, refrigeration systems, etc.
- Control of many other types of HVAC and lighting equipment, as well as power measurement applications

Features

Interoperability

- Based on LONWORKS® technology for peer-to-peer communication between controllers
- LONMARK® certified according to the Interoperability Guidelines Version 3.4

Hardware

- Fire retardant plastic enclosure
- Separable base plate allows base with connectors to be shipped to site for installation while engineering is done at the office
- Light weight and compact enclosure saves on shipping costs
- 10 universal inputs (jumper-less selection)
- 8 fuse-protected universal outputs
- Status indicator on each output
- 128K Flash memory for the configuration and trending of up to 12,000 events
- Battery backed-up clock with a fifteen year lifespan
- Transmit, receive and power LED indicators
- Din-rail mounting integrated into the enclosure

Software

More than 60 network variables including:

- 18 NVIs, changeable type and length
- 18 NVOs, changeable type and length
- Support of fan-in binding for zoning applications
- Each object is configurable and programmable through their own LNS® plug-in

Free Programmable Object

- Configuration, code and label stored in the controller itself for advanced backup purposes
- Many programming features available such as PID loops, timers, optimum start
- View all internal points (e.g. constants, variables, …) using 10 UNVTs of 15 values each

4 Scheduler Objects

- All schedules are stored in Flash memory
- Schedule network variables are of changeable type and length
- Seven weekday templates per scheduler
- Six configurable events per day, per scheduler
- Four holiday templates per scheduler
- Schedules can be edited locally on device

Real-Time Clock Object

- Allows configuration of daylight savings time
- Accurate timekeeping for controller applications

The easyCONTROLS ECP-300 is a microprocessor-based free programmable controller designed to control various HVAC applications. Designed to control equipment such as rooftop units, fan coils, heat pumps, ventilator units and terminal units, the ECP-300 can also be used for any lighting control and power measurement applications. The ECP-300 uses the LonTalk® communication protocol and is LONMARK certified using the Sensor profile (#1) for its input objects and the Actuator profile (#3) for its output objects.

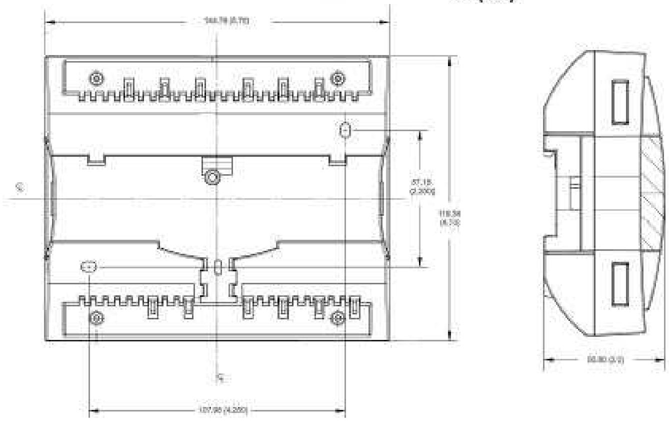
It is important for system integrators and installers to be able to easily understand and use Distech Controls' products and this is why ease-of-use has been made their primary feature. The ECP-300 can be programmed by using the EC-Program plug-in through either any LNS-based software such as Distech Controls Lonwatcher, or by using a multi-protocol platform software supporting LONWORKS devices such as the EC-Net^{AX} software powered by the Niagara^{AX} Framework™. The EC-Program plug-in is unique in the controls industry because it combines a user-friendly Graphical User Interface (GUI) with the power and flexibility of a code editor and compiler. Distech Controls' EC-Program plug-in uses a unique and simplified version of BASIC that has been developed in-house and that is custom made to suit controls requirements. Also available for use with the EC-Net software powered by the Niagara Framework™, the Distech Controls Shadow Objects and Modules allow one to configure and monitor the ECP-300 free programmable controller.

The easyCONTROLS product line is built to meet rigorous quality standards and carries a two-year warranty. The complete line of easyCONTROLS controllers is designed for use with any LONWORKS-based and/or any other open and interoperable system – such as EC-Net^{AX}. This provides both the contractor and the end user with the flexibility of using "best of breed" products in system design.

Distech Controls' quality management system is ISO 9001:2000 certified.

Product Specifications

mm (inch)



Power	
Voltage	24VAC/DC; ±15%, 50/60HZ, Class 2
Protection	1.85A auto-reset fuse
Typical Consumption	5VA
Maximum Consumption	18VA

Environmental	
Operating Temperature	0°C to 70°C; 32°F to 158°F
Storage Temperature	-20°C to 70°C; -4°F to 158°F
Relative Humidity	0 to 90% Non-condensing

General	
Processor	Neuron® 3150®; 8 bits; 10MHZ
Memory	Non-volatile Flash 64K (APB application) Non-volatile Flash 128K (Storage)
Communication	LonTalk protocol
Channel	TP/FT-10; 78Kbps
Clock	Real-time clock chip
Battery (for clock only)	CR2032 lithium battery
Status Indicator	Green LED: power status & LON TX Orange LED: service & LON RX
Communication Jack	LON audio jack mono 1/8" (3.5mm)

Enclosure	
Material	ABS type PA-765A
Color	Blue casing & grey connectors
Dimensions overall	5.7x4.7x2.0" (144.8x119.4x50.8mm)
Shipping Weight	0.86lbs (0.39kg)
Installation	Direct din-rail mounting or wall mounting through mounting holes (see figure above for hole positions)

Electromagnetic Compatibility	
CE -Emission	EN55022 : 1998 class B (conducted & radiated)
-Immunity	EN61000-4-2: 1995, level 3 in air EN61000-4-2: 1995, level 2 by contact EN61000-4-3: 1996, level 2 EN61000-4-4: 1995, level 2 EN61000-4-6: 1996, level 2 ENV 50204 : 1995, level 2
FCC	This device complies with FCC rules part 15, subpart B, class B

Inputs	
Quantity	10
Input Types:	Universal (software configurable)
-Voltage	0-10VDC, Accuracy ±0.5%
-Current	4-20mA with 249Ω external resistor (wired in parallel), Accuracy ±0.5%
-Digital	Dry contact
-Pulse	Dry contact 500ms minimum ON/OFF
-Resistor:	
Thermistor	Type 2.3 10KΩ Range: -40°C to 150°C; -40°F to 302°F Accuracy: ±0.5°C; ±0.9°F
Platinum	RTD 1KΩ Range: -40°C to 150°C; -40°F to 302°F Accuracy: ±1.0°C; ±1.8°F PT100 100Ω Range: -40°C to 135°C; -40°F to 275°F Accuracy: ±1.0°C; ±1.8°F
Potentiometer	Translation table configurable on several points, Accuracy ±0.5%
Input Resolution	16-bit analog / digital converter

Outputs	
Quantity	10 universal (software configurable) - 0-10VDC, digital 0-12VDC (on/off) or PWM - PWM output: adjustable period from 2 seconds to 15 minutes - 60mA max. @ 12VDC (60°C; 140°F) - Maximum load 200Ω - Auto-reset fuse - 60mA @ 60°C; 140°F - 100mA @ 20°C; 68°F
Output Resolution	10-bit digital / analog converter

Agency Approvals	
UL Listed (CDN & US)	UL916 Energy management equipment
Material[1]	UL94-5VA

1. All materials and manufacturing processes comply with the directive on Waste Electrical and Electronic Equipment (WEEE).

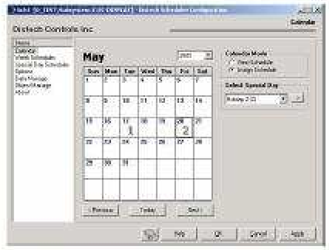
Distech Controls Software Plug-ins and Wizards

Software Preview

LNS Programming Plug-in*

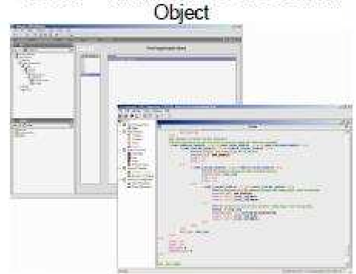
The EC-Program plug-in is unique in the controls industry because it combines a user-friendly Graphical User Interface (GUI) with the power and flexibility of a code editor and compiler. Distech Controls' EC-Program plug-in uses a unique and simplified version of BASIC that has been developed in-house and that is custom made to suit controls requirements.

LNS Scheduler Plug-in*



This plug-in allows you to easily configure a weekly-based schedule and a special day schedule for holidays. Easily add and remove the special day event into the calendar by a simple click of the mouse!

EC-Net^{AX} Wizard and EC-Net Shadow Object



Launch the free programmable wizard through EC-Net^{AX} to fully configure and program a controller. The wizard is unique in the controls industry because it combines a user-friendly Graphical User Interface (GUI) with the power and flexibility of a code editor and compiler.

Can also be used with the Niagara Framework, where the EC-Net Free Programmable Shadow Object allows you to add a free programmable device on your network for control and monitoring purposes.

* LNS Plug-ins can be used with any LONWORKS-based network management and GUI tools, such as Distech Controls' Lonwatcher or Londisplay.

Recommended Peripherals

Temperature Sensors

EC-SENSOR	Room sensor
EC-SENSOR-LO	Room sensor with LED and override push button
EC-SENSOR-SLO-CW	Room sensor with LED, override push button and setpoint adjustment (cool/warm)
EC-SENSOR-SLO-C	Room sensor with LED, override push button and setpoint adjustment (°C)
EC-SENSOR-SLO-F	Room sensor with LED, override push button and setpoint adjustment (°F)
EC-SENSOR-AVG	Averaging room sensor, no setpoint (Up to 3 in parallel)
EC-SENSOR-AVG-LO	Averaging room sensor with LED and override push button

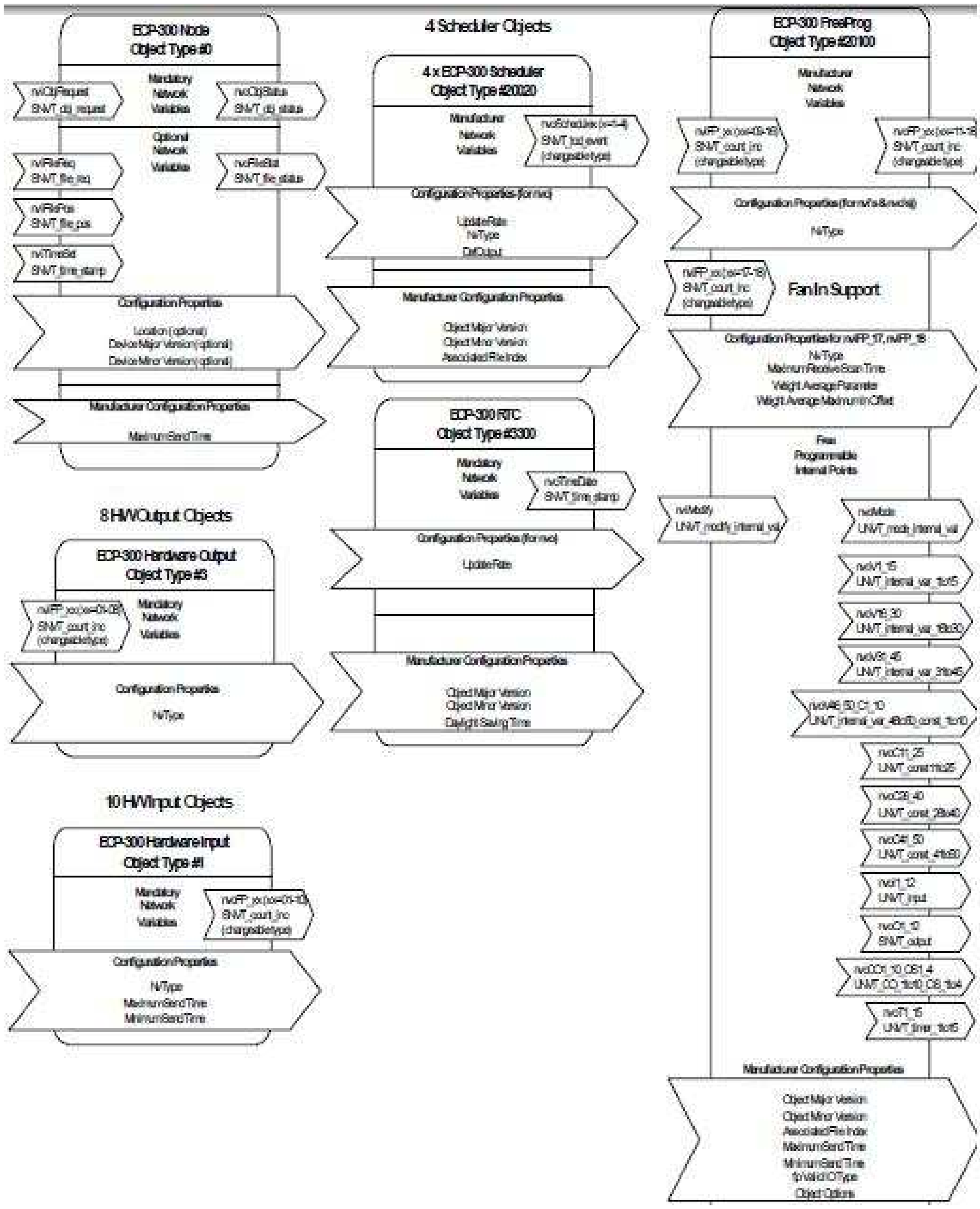
Other Peripherals

07KIT-RELAYUNDI	12VDC coil relay (Dry contact NO/NC 8A – 250VA single-pole coil. Consumption < 20mA) with din-rail mountable socket base

Please contact sales@distech-controls.com for a complete list of available products and peripherals.

Product Warranty and Total Quality Commitment

The easyCONTROLS product line is built to meet rigorous quality standards and carries a two-year warranty. Distech Controls is an ISO 9001 registered company. Distech Controls' products provide both the contractor and the end user with the flexibility of using "best-of-breed" products in system design.


ECP-300 Node
Object Type #0
4 Scheduler Objects
4 x ECP-300 Scheduler
Object Type #20020
ECP-300 FreeProg
Object Type #20100
Fan In Support
8 HW Output Objects
ECP-300 Hardware Output
Object Type #3
ECP-300 RTC
Object Type #3300
10 HW Input Objects
ECP-300 Hardware Input
Object Type #1
Configuration Properties
Manufacturer Configuration Properties

Appendix 3. Comparative overview of air-to-air energy recovery technologies [9]

	Supply Air Exhaust Air Relationship	Type of Energy Recovered	Effectiveness Range	Core Pressure Drop w/o filters	Cross Leakage	Economizer Cycle	Maintenance Issues
Coil Loop	Flexible	Sensible	50 to 60%	.4 – 2.0	0 %	Stop pump	Cleaning, valves, pumps, corrosion, filters, glycol replacement, controls.
Fixed Plate	Close	Sensible/Latent	50 to 80%	.1 – 1.8	0 to 8 %	None	Damper. Cleaning core, filters.
Rotary Wheel	Close	Latent/Sensible	55 to 85%	.25 – 1.0	1 to 10 %	Stop motor	Cleaning, motors, belts, seals, filters, controls.
Reverse Flow	Close	Latent/Sensible	75 to 95%	.25 – 1.02	1 to 3 %	Stop Damper	Damper, actuator.
Heat Pipe	Close	Sensible	45 to 65 %	.4 – 2.0	0 %	Tilt Angle	Cleaning, filters, tilt control.

Appendix 4. Fuji Easy Logic Controller Specifications [9]

FUJI ELECTRIC

Fuji Easy Logic Controller

ELC

The ELC incorporates a weekly time-setting function that allows you to configure several control logic sequences based on time. Ideal for replacing control relays, timers and counters. The ELC is programmed in Relay Ladder Logic using a Windows programming software or directly on the front panel. These are just a few of the many ELC applications:

- Opening/closing control of doors, gates and shutters
- Pump control for supplying and draining water
- Garbage/waste disposer control
- Illumination control of streetlights, show windows and signboards
- Temperature control in greenhouses and plant watering control
- Boiler control
- Parking area monitoring
- Air ventilation system control
- Escalator control
- Mixing and stirring control for various solvents
- Transfer conveyor and sorter control, etc.

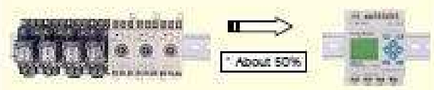
COMPACT

SAVE SPACE

Drastically reduce the size of your control panel!

The ELC has an extremely compact size. The 10-point type is only 72 × 90 × 57mm and the 20-point type is only 126 × 90 × 57mm in size. This compact size contributes to the drastic reduction of control panel dimensions

* For example, **if a control circuit including 3 timers and 4 power relays are replaced with the ELC (10 points type), the mounting space may be reduced by about 50%!**



* (Compared to Relays, Timers, Counters combined)

COST DOWN

REDUCE COST

Reduce hardware cost!

The ELC has an attractive price to help your bottom line.
Please contact Fuji Electric for more detail.

* For example,
if a control circuit including 3 timers and 4 power relays are replaced with the ELC (10 points type), the cost will be reduced by about 20%!

WIRING

REDUCE WIRING

Reduce wiring time

When individual Relays, Timers and Counter are used the wiring of each component becomes tedious. The ELC can drastically reduce the wiring the because only 1 component is involved. Further more, if changes to the logic need to be made these can be done in software or via the front panel.

SAVE ENERGY

LOWER ENERGY CONSUMPTION

Energy-saving operation.

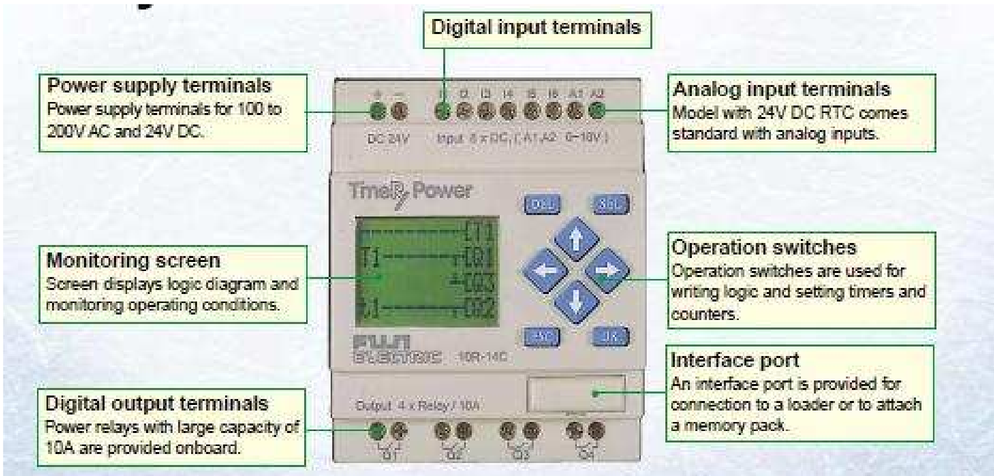
The ELC can be programmed to save electricity. A time management function can be programmed to shutdown Fans, Lights, etc. to save energy.

TIME

SAVE TIME

Improve Productivity

The ELC comes standard with Relay Ladder logic schemes for control applications.
The ELC can easily copy logic schemes by using the optional memory pack.
The control logic connections take considerably less time to implement than traditional hard-wiring.



Monitoring screen displays all operating conditions

The monitoring screen on the front of the ELC indicates to the user the total status of the ELC at a glance.

This screen displays the status of I/Os, internal relays, timers, counters, the analog current values and the clock time, as well as a monitoring screen of the control logic operation.

Control logic is easily configured in ladder diagram format with software

Control logic wiring in the ELC is implemented with software in a ladder diagram format that is developed from a traditional relay schematic diagram. The user only needs to program the ELC in Relay Ladder Logic.

Large power output relays with switching capacity of 10A are provided

The ELC includes large power output relays with a per point switching capacity of 10A at 250V AC, or 8A at 30V DC. These output relays can be directly connected to illumination lamps and valves for control.

Schedule management is achieved by using clock function

The ELC's equipped with RTC allow the user to program a daily or weekly control schedule without expensive time management system. Also, the ELC incorporates day light savings time.

2 channel analog inputs are standard (DC 24 V, with RTC)

The ELC comes equipped with 2 channel analog inputs standard. Simple control of analog applications, such as temperature, speed, and voltage can be achieved without any optional analog device.

Password feature is provided for security

The ELC contains a password feature for preventing unexpected modification of software with switch operation.

Special mounting hardware is not required

The ELC can be mounted with screws on sliding type mounting holes as well as DIN rails without using any special mounting clamps.

Maintenance-free EEPROM is used

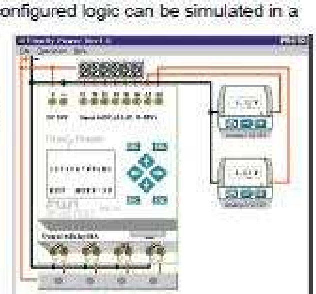
Since software information is stored into an EEPROM that does not require battery backup, the ELC is maintenance free.

Complies with CE marking and UL/cUL standards

The ELC is widely applicable throughout the world, with various global standards such as CE marking and UL.

Software data saving with loader and simulation via personal computer can be done

Software data can be saved by using the loader software program. The data will help the user to standardize wiring diagrams. Also, the configured logic can be simulated in a personal computer, and therefore performance of the logic scheme in the ELC can be verified prior to installation.



Specifications

●General specifications

	NQ2P10R-14□	NQ2P20R-14□	NQ2P10R-52□	NQ2P20R-52□
Power supply voltage	20.4 to 28.8V DC		85 to 264V AC	
Power consumption	2W	3W	3VA	7VA
Output current	Max. 10A			
Electrostatic discharge	IEC801-2 Severity3 Contact discharge ±4kV, aerial discharge ±8kV			
Radioelectromagnetic field	IEC801-3 10V/m			
Operating ambient	IEC801-4 Severity3 2kV			
temperature	0 to 55°C			
Relative humidity	20 to 90%RH no condensation			
Vibration	IEC68-2-6 $9.8m/s^2$			
Shock	IEC68-2-27 $147m/s^2$			
Construction	IP20			

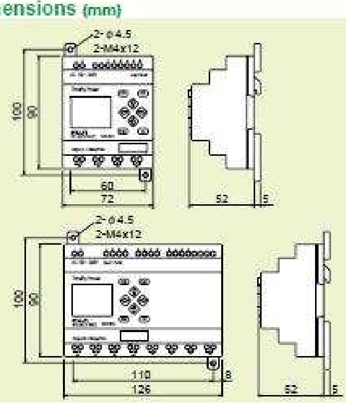
	NQ2P□R-□	NQ2P□R-□C
Programming language	Ladder, function brock	
Program memory capacity	240steps (4elements x 60lines)	
Backup	Built-in EEPROM, memory pack option	
Input relay	12points (I1 to C)	
Output relay	8points (Q1 to Q8)	
Auxiliary relay	15points (M1 to MF)	
RTC relay	8points (R1 to R8)	
Counter	15points (C1 to C8)	
Timer	4points (T1 to TF)	
Analog comparison	4points (G1 to G4)	
Analog input	×	2channel (A1 to A2) only for DC
RTC	×	○

●I/O specifications

		NQ2P10R-14□	NQ2P20R-14□	NQ2P10R-52□	NQ2P20R-52□
Input	No. of input points	6points	12points(10points**)	6points	12points
Input	Rated voltage	0 to 28.8V DC		0 to 265V AC	
Input	Rated current	3mA/24V		0.5mA/110V 1mA/230V	1mA/110V 2mA/230V
Input	Operating voltage	ON:15 to 28.8V OFF:0 to 5V		ON:79 to 265V OFF:0 to 40V	
Input	Delay time	OFF→ON:3ms ON→OFF:5ms		OFF→ON:50ms ON→OFF:50ms	
Input	Analog voltage*	0 to 10V DC Resolution:8bits		—	
Output	No. of output points	4points	8points	4points	8points
Output	Load current	10A/250V AC or 8A/30V DC			

*Analog input: only for NQ2P10R-14C, NQ2P20R-14C
**NQ2P20R-14C

Dimensions (mm)



Products

Item	Ordering code (Product code)	Specification
TimeRy Power	NQ2P10R-14	24V DC power supply, input 6points, output 4points Ry10A, no clock function
	NQ2P10R-14C	24V DC power supply, input 6points, output 4points Ry10A, clock function, analog 2channel
	NQ2P10R-52	100 to 240V AC power supply, input 6points, output 4points Ry10A, no clock function
	NQ2P10R-52C	100 to 240V AC power supply, input 6points, output 4points Ry10A, clock function
	NQ2P20R-14	24V DC power supply, input 12points, output 8points Ry10A, no clock function
	NQ2P20R-14C	24V DC power supply, input 10points, output 8points Ry10A, clock function, analog 2channel
	NQ2P20R-52	100 to 240V AC power supply, input 12points, output 8points Ry10A, no clock function
	NQ2P20R-52C	100 to 240V AC power supply, input 12points, output 8points Ry10A, clock function
Loader software	NQ4H-SE	Personal computer loader software (with connection cable)
Memory pack	NQ8P-MP	For program saving and transferring

⚠ Safety Considerations

●For safe operation, before using the product read the instruction manual or user manual that comes withthe product carefully or consult the Fuji sales representative from which you purchased the product.
●Some of the products listed in this catalog may have limits on their use or location or may require periodic inspections. Call Fuji's sales representative for further information.
●For safe operation, wiring should be conducted only by qualified engineers who have sufficient technical knowledge about electrical work or wiring.

●Appearance and specifications are subject to change without prior notice for the purpose of product improvement.

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Fax: (201) 368-8258
URL: http://www.fujielectric.com

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ED & C・Drive Systems Company
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11-2, Osaki 1-chome, Shinagawa-ku, Tokyo, 141-0032, Japan
Phone: +81-3-5435-7135~8
Fax: +81-3-5435-7456~9
URL: http://www.fujielectric.co.jp/edc/

Appendix 5. Climate Design Conditions - Bogotá, Colombia [12]

Meaning of acronyms:
DB: Dry bulb temperature, °C *WB: Wet bulb temperature, °C*
MCWB: Mean coincident wet bulb temperature, °C
Lat: Latitude, °
DP: Dew point temperature, °C
MCDB: Mean coincident dry bulb temperature, °C
Long: Longitude, °
HR: Humidity ratio, g of moisture per kg of dry air
HDD and CDD 18.3: Annual heating and cooling degree-days, base 18.3°C, °C-day
Elev: Elevation, m
WS: Wind speed, m/s

Station	Lat	Long	Elev	Heating DB		Cooling DB/MCWB						Evaporation WB/MCDB				Dehumidification DP/HR/MCDB						Extreme Annual WS			Heat./Cool. Degree-Days	
						0.4%		1%		2%		0.4%		1%		0.4%			1%							
				99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		WB / MCDB		WB / MCDB		DP / HR / MCDB			DP / HR / MCDB			1%	2.5%	5%	HDD / CDD 18.3	
Colombia																									*5 sites, 0 more on CD-ROM*	
BARRANQUILLA/ERNEST	10.88N	74.78W	30	22.8	23.0	34.1	27.1	33.2	26.9	32.9	26.8	28.6	31.3	28.1	30.9	28.0	24.3	29.9	27.2	23.1	29.3	13.2	10.9	9.9	0	3609
BOGOTA/ELDORADO	4.70N	74.13W	2546	2.8	4.1	21.2	13.6	20.8	13.5	20.1	13.4	15.4	19.0	15.0	18.5	14.2	13.8	17.0	13.8	13.5	16.7	8.4	7.0	6.1	1752	0
CALI/ALFONSO BONILL	3.55N	76.38W	969	17.7	18.0	32.1	22.1	31.2	22.0	30.8	22.0	23.5	29.5	22.9	29.4	21.8	18.5	26.8	21.1	17.7	26.0	8.4	6.5	5.5	0	2139
CARTAGENA/RAFAEL NU	10.45N	75.52W	12	23.0	23.8	32.3	27.1	32.1	27.0	31.8	26.9	28.1	31.0	27.7	30.6	27.2	23.0	30.2	26.9	22.7	30.1	9.2	7.9	6.5	0	3533
RIONEGRO/J.M.CORDOV	6.13N	75.43W	2142	10.0	10.9	23.9	15.8	23.2	15.7	23.0	15.6	17.6	21.3	17.1	21.0	16.2	15.1	18.5	16.1	14.9	18.2	9.1	7.6	5.9	412	23