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Experimental Energy Performance of Open Cooling Towers Used Under Low and Variable Approach Conditions for Indirect Evaporative Cooling of Buildings

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approach conditions for indirect evaporative cooling in buildings Experimental energy performance of open cooling towers used under low and variable

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Experimental energy performance of open cooling Experimental energy performance of open cooling
towers used under low and variable approach Experimental energy performance of open coolin
towers used under low and variable approach
conditions for indirect evaporative cooling in
buildings buildings

B Costelloe^a BA MSc CEng MInstE MCIBSE and **D Finn^b** BE MEngSc PhD CEng MASHRAE **B Costelloe**® BA MSc CEng MInstE MCIBSE and **D Finn**^b BE MEngSc PhD CEng MASHRAE
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nt of Mechanical Engineering, University College Dublin, Ireland
The success of chilled ceilings and displacement ventilation systems as a means
of sensible seeling in buildings has aremated a raview of exenerative seeling The success of chilled ceilings and displacement ventilation systems as a means
of sensible cooling in buildings has prompted a review of evaporative cooling
technology of an offective means of generating the required soci The success of chilled ceilings and displacement ventilation systems as a means
of sensible cooling in buildings has prompted a review of evaporative cooling
technology as an effective means of generating the required coo of sensible cooling in buildings has prompted a review of evaporative cooling
technology as an effective means of generating the required cooling water. When
such cooling water is generated at low approach conditions (2–5 technology as an effective means of generating the required cooling water. When
such cooling water is generated at low approach conditions (2–5 K), at the higher
temperatures required in these systems (14–18°C), very high such cooling water is generated at low approach conditions $(2-5 K)$, at the higher
temperatures required in these systems $(14-18^{\circ}C)$, very high levels of availability
result. In many north western European locations t temperatures required in these systems (14–18°C), very high levels of availability
result. In many north western European locations the levels of availability are such
that the prospect of supplanting rather than simply su result. In many north western European locations the levels of availability are such
that the prospect of supplanting rather than simply supplementing the refriger-
ation system, for sensible cooling purposes, arises. The ation system, for sensible cooling purposes, arises. The viability of the technique, however, largely depends on achieving low approach conditions, at acceptable ation system, for sensible cooling purposes, arises. The viability of the technique,
however, largely depends on achieving low approach conditions, at acceptable
levels of energy performance. Hence the need to investigate however, largely depends on achieving low approach conditions, at acceptable
levels of energy performance. Hence the need to investigate the energy perform-
ance of the process. This paper presents the results of recent ex research into: i) the achievement of low approach conditions in an evaporative research into: i) the achievement of low approach conditions in an evaporative research into: i) the achievement of low approach conditions in ance of the process. This paper presents the results of recent experimental
research into: i) the achievement of low approach conditions in an evaporative
cooling test rig; and ii) the energy performance of this test rig w research into: i) the achievement of low approach conditions in an evaporative
cooling test rig; and ii) the energy performance of this test rig when generating
cooling water, indirectly, at the temperatures required for c cooling test rig; and ii) the energy performance of this test rig when generating
cooling water, indirectly, at the temperatures required for chilled ceilings. Energy
performance is presented for a range of specific condit cooling water, indirectly, at the temperatures required for chilled ceilings. Energy
performance is presented for a range of specific conditions and typical annual
efficiencies of cooling water generation are determined. R performance is presented for a range of specific conditions and typical annual efficiencies of cooling water generation are determined. Results are compared with typical energy efficiencies of conventional, vapour compress efficiencies of cooling water generation are determined. Results are compared
with typical energy efficiencies of conventional, vapour compression based,
refrigeration systems. A significant potential for improved annual e with typical ene
refrigeration syste
ance, is shown.

List of symbols

		$\mathcal{L}_{\mathcal{L}}$
$T_{\rm pf}$	primary loop flow temperature C	
$T_{\rm pr}$	primary loop return temperature °C	\boldsymbol{P}_f
$T_{\rm sf}$	secondary loop flow temperature °C	
$T_{\rm sr}$	secondary loop return temperature °C	$P_{\rm t}$
$T_{\rm wb}$	ambient wet bulb temperature (WBT)	
	$^{\circ}$ C	W
$T_{\rm pa}$	primary approach temperature (PAT)	С

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1 Introduction

Concern with environmental emissions and global energy consumption has lead to the develop-

164 *Experimental energy performance of open co*
ment of low energy cooling technologies, among rather the method of the method evaporative cooling technologies, among references
them evaporative cooling, as an alternative to the the ment of low energy cooling technologies, among
them evaporative cooling, as an alternative to the
use of refrigeration in buildings for general sens-
ible cooling ¹ Cooling of buildings by means of them evaporative cooling, as an alternative to the
use of refrigeration in buildings for general sens-
ible cooling.¹ Cooling of buildings by means of water of refrigeration in buildings for general sens-
ible cooling.¹ Cooling of buildings by means of
water evaporation has traditionally been seen as ible cooling.¹ Cooling of buildings by means of
water evaporation has traditionally been seen as
appropriate mainly in hot and arid climates.² The
technique has had very limited application in water evaporation has traditionally been seen as
appropriate mainly in hot and arid climates.² The in
technique has had very limited application in la
maritime and temperate climates where the t appropriate mainly in hot and arid climates.² The it technique has had very limited application in 1 maritime and temperate climates where the t technique has had very limited application in
maritime and temperate climates where the
ambient relative humidity is often high. How-
ever, the recent success of chilled ceilings, as an maritime and temperate climates where the temperatures. This work suggests that chilled ambient relative humidity is often high. How-
eiling panel cooling outputs may increase to ever, the recent success of chilled ceilin ambient relative humidity is often high. However, the recent success of chilled ceilings, as an 1
effective means of cooling buildings has to
prompted a review of the evaporative cooling in
technique as an effective supplement to or even effective means of cooling buildings, a has
prompted a review of the evaporative cooling in
technique as an effective supplement to, or even the
a substitute for refrigeration based sensible coo prompted a review of the evaporative cooling
technique as an effective supplement to, or even
a substitute for, refrigeration based sensible cooling. technique as an effective supplement to, or even tube, to the more integrated rectangular water-
a substitute for, refrigeration based sensible coo-
ing.
a more uniform panel surface temperature.
While the evaporative cool

ling.
While the evaporative cooling technique can
be exploited with any water based building coo-
ling system, such as the commonly used fan coil While the evaporative cooling technique can
be exploited with any water based building coo-
ling system, such as the commonly used fan coil
system, the technique is particularly advanbe exploited with any water based building cooling system, such as the commonly used fan coil
system, the technique is particularly advanthe commonly used fan coil
system, the technique is particularly advan-
tageous when a chilled ceiling system is used,
due to the higher cooling water temperatures system, the technique is particularly advan-
tageous when a chilled ceiling system is used,
due to the higher cooling water temperatures tageous when a chilled ceiling system is used, approach temperature (PAT) which is equal to due to the higher cooling water temperatures $T_{\text{pf}} - T_{\text{wb}}$. This aspect is complicated by the which are employed. Chilled cei due to the higher cooling water temperatures
which are employed. Chilled ceiling systems
generally require cooling water at 14–18°C. which are employed. Chilled ceiling systems
generally require cooling water at 14–18°C.
Conditions vary, but a typical design arrangegenerally require cooling water at $14-18^{\circ}$ C. sep
Conditions vary, but a typical design arrange-
ment would be a supply temperature of 15° C. He Conditions vary, but a typical design arrange-
ment would be a supply temperature of 15° C. H
with a 3° C rise, returning at 18° C. A research b ment would be a supply temperature of 15° C
with a 3° C rise, returning at 18° C. A research
project³ which investigated thermal comfort con-
ditions menteined in a test room, with internal with a 3° C rise, returning at 18° C. A research project³ which investigated thermal comfort conditions maintained in a test room, with internal project³ which investigated thermal comfort conditions maintained in a test room, with internal
heat gains of 60 W/m² and served by a chilled colling established that cooling water supplied ditions maintained in a test room, with internal
heat gains of 60 W/m² and served by a chilled c
ceiling, established that cooling water, supplied to the ceiling at a temperature as high as $18\degree C$ th the ceiling, established that cooling water, supplied coording, established that cooling water, supplied where the ceiling, at a temperature as high as 18°C the ceiling, at a temperature as high as 18°C th colling, established that cooling water, supplied
to the ceiling, at a temperature as high as 18°C to
could maintain a satisfactory comfort index (a) to the ceiling, at a temperature as high as 18° C the
could maintain a satisfactory comfort index (a lin
maximum dry resultant temperature of 25.2°C was could maintain a satisfactory comfort index (a limaximum dry resultant temperature of 25.2°C w
and a maximum predicted mean vote of +0.8) in I maximum dry resultant temperature of 25.2° C
and a maximum predicted mean vote of $+0.8$) in
the space. This maximum condition was meas-
ured between 16:00 and 17:00 hours with lower and a maximum predicted mean vote of +0.8) in Dublin.⁸ Examining this figure it can be seen, the space. This maximum condition was meas-
tor example, that at a secondary flow $(T_{\rm sf.})$ see ured between 16:00 and 17:00 h the space. This maximum condition was measured between 16:00 and 17:00 hours with lower conditions at other times. This was considered acceptable, as it implies a predicted percentage conditions at other times. This was considered total annual availability increases from 50% at acceptable, as it implies a predicted percentage 8 K SAT to 88% at 3 K SAT. While the relation-
dissatisfied of no greater than dissatisfied of no greater than 20% for short per-Exercise acceptable, as it implies a predicted percentage acceptable, as it implies a predicted percentage $\frac{8}{18}$ dissatisfied of no greater than 20% for short periods. A temperature of 18° C would seem to be a th dissatisfied of no greater than 20% for short per-
iods. A temperature of 18°C would seem to be
the maximum cooling water temperature which
can be used with sensible cooling systems, of call the used with sensible cooling systems, of
the maximum cooling water temperature which
can be used with sensible cooling systems, of the maximum cooling water temperature which
can be used with sensible cooling systems, of
this type, although this largely depends on the complement with sensible cooling systems, of
this type, although this largely depends on the
comfort criteria considered acceptable for each
project and whether an edentive approach to project this type, although this largely depends on the
comfort criteria considered acceptable for each
project and whether an adaptive approach to
comfort conditions could be employed. Two comfort criteria considered acceptable for each
project and whether an adaptive approach to p
comfort conditions could be employed. Two 3 project and whether an adaptive approach to perature, will increase total availability from comfort conditions could be employed. Two 37% to 57%.⁸ Similar charts can be produced recent research papers state that chilled

radiant panels can operate with a supply water temperature as high as $18-20^{\circ}$ C.^{4,5} diant panels can operate with a supply water
nperature as high as $18-20^{\circ}C^{4,5}$
Some recent work^{6,7} on raising the cooling
tput of chilled cailing panels, above the cur-

temperature as high as $18-20^{\circ}$ C.^{4,5}
Some recent work^{6,7} on raising the cooling
output of chilled ceiling panels, above the cur-
rent level of 70 W/m² is also relevant. An Some recent work^{6,7} on raising the cooling
output of chilled ceiling panels, above the cur-
rent level of 70 W/m², is also relevant. An output of chilled ceiling panels, above the current level of 70 W/m², is also relevant. An increase in panel cooling output will allow simirent level of 70 W/m², is also relevant. An increase in panel cooling output will allow simi-
lar loads to be cooled by higher cooling water
temperatures. This work suggests that chilled increase in panel cooling output will allow simi-
lar loads to be cooled by higher cooling water
temperatures. This work suggests that chilled
ceiling panel cooling outputs may increase to lar loads to be cooled by higher cooling water
temperatures. This work suggests that chilled
ceiling panel cooling outputs may increase to
 100 W/m^2 (at 10 K panel surface to room air temperatures. This work suggests that chilled
ceiling panel cooling outputs may increase to
 100 W/m^2 (at 10 K panel surface to room air
temperature difference) as a result of a change ceiling panel cooling outputs may increase to 100 W/m^2 (at 10 K panel surface to room air temperature difference) as a result of a change in panel design from the rear mounted coiled 100 W/m^2 (at 10 K panel surface to room air
temperature difference) as a result of a change
in panel design, from the rear mounted coiled
tube to the more integrated rectangular watertemperature difference) as a result of a change in panel design, from the rear mounted coiled Figure 1 unique, to the more integrated rectangular wat
way, which increases heat transfer and leads
a more uniform panel surface temperature. Figure 1, which increases heat transfer and leads to
more uniform panel surface temperature.
Figure 1, which shows a simplified schematic
a tunical indirect evenogative cooling system

a more uniform panel surface temperature.
Figure 1, which shows a simplified schematic
of a typical indirect evaporative cooling system,
indicates, the relevant design parameters. An Figure 1, which shows a simplified schematic
of a typical indirect evaporative cooling system,
indicates the relevant design parameters. An
important performance parameter is the primary of a typical indirect evaporative cooling system,
indicates the relevant design parameters. An
important performance parameter is the primary
annoach temperature (PAT) which is equal to indicates the relevant design parameters. An
important performance parameter is the primary
approach temperature (PAT) which is equal to
 T , T , This appect is complicated by the *Theorem is the primary*
 *T*_{pf}– T_{wb} . This aspect is complicated by the
 *T*_{pf}– T_{wb} . This aspect is complicated by the
 *T*_{pf}– T_{wb} . This aspect is complicated by the approach temperature (PAT) which is equal to $T_{\text{pf}} - T_{\text{wb}}$. This aspect is complicated by the requirement, in contemporary applications, to separate the tower water circuit from the build $T_{\text{pf}} - T_{\text{wb}}$. This aspect is complicated by the requirement, in contemporary applications, to separate the tower water circuit from the buildrequirement, in contemporary applications, to separate the tower water circuit from the building cooling circuit by means of a heat exchanger.
Hence the significant performance parameter
becomes the secondary approach temperature ing cooling circuit by means of a heat exchanger.
Hence the significant performance parameter
becomes the secondary approach temperature
(SAT) which is equal to $T_{\text{sf}}-T_{\text{wh}}$. Hence the significant performance parameter
becomes the secondary approach temperature
(SAT) which is equal to $T_{\text{sf}}-T_{\text{wb}}$.
The importance of the SAT, for evaporative

cooling systems, is demonstrated in Figure 2, The importance of the SAT, for evaporative
cooling systems, is demonstrated in Figure 2,
which shows the impact of reducing the SAT on
the percentage total annual availability of \cos the percentage total annual availability of coo-
the percentage total annual availability of coo-
ting water for the perceible renge of cooling which shows the impact of reducing the SAT on
the percentage total annual availability of cooling water, for the possible range of cooling the percentage total annual availability of cooling water, for the possible range of cooling
water temperatures, generated by evaporation, in
Dublin⁸ Examining this figure it can be seen ling water, for the possible range of cooling
water temperatures, generated by evaporation, in
Dublin.⁸ Examining this figure it can be seen,
for example, that at a secondary flow (T_{eff} see water temperatures, generated by evaporation, in Figure 1) cooling this figure it can be seen,
for example, that at a secondary flow $(T_{\rm sf.}$ see
Figure 1) cooling water temperature of 16°C, the
total annual availability increases from 50% at For example, that at a secondary flow $(T_{\rm sf,}$ see
Figure 1) cooling water temperature of 16°C, the
total annual availability increases from 50% at
8 K SAT to 88% at 3 K SAT. While the relation Figure 1) cooling water temperature of 16° C, the
total annual availability increases from 50% at
8 K SAT to 88% at 3 K SAT. While the relation-
thin between SAT and perceptage annual avail 8 K SAT to 88% at 3 K SAT. While the relation- $8 K SAT$ to 88% at $3 K SAT$. While the relation-
ship between SAT and percentage annual availability differs for each location, the impact of ship between SAT and percentage annual availability differs for each location, the impact of reducing the SAT on availability is generally considerable in European locations. In Milan, for ability differs for each location, the impact of
reducing the SAT on availability is generally
considerable in European locations. In Milan, for
example as shown in Figure 3, a similar reducing the SAT on availability is generally
considerable in European locations. In Milan, for
example, as shown in Figure 3, a similar reducting the STT on availability is considerable in European locations. In Milan, for example, as shown in Figure 3, a similar reduction in SAT, at 16°C cooling water temexample, as shown in Figure 3, a similar
reduction in SAT, at 16° C cooling water tem-
perature, will increase total availability from
 27% to 57% ⁸ Similar charts can be produced Example, in SAT, at 16^oC cooling water tem-
perature, will increase total availability from
37% to 57%.⁸ Similar charts can be produced
for other locations 37% to 57% .⁸ Similar charts can be produced

Figure 1 Simplified schematic of indirect evaporative cooling system with an open tower

و سیاست کردی دیا یہ Figure 2 Impact of secondary approach temperature
Iin, for a range of cooling water temperatures (°C)⁸

In, for a range of cooling water temperatures $({}^{\circ}C)^{8}$
As shown in Figure 2 cooling water at 18°C is used.² Supply air at 20°C can be used in dishas statistically a total availability level of 96.3% placement venti As shown in Figure 2 cooling water at 18° C is u
has statistically a total availability level of 96.3% place As shown in Figure 2 cooling water at 18° C is
has statistically a total availability level of 96.3% p
in Dublin, provided a low SAT of 3 K can be has statistically a total availability level of 96.3% p
in Dublin, provided a low SAT of 3 K can be c
achieved. While cooling water at 18°C used in V in Dublin, provided a low SAT of 3 K can be
achieved. While cooling water at 18° C used in
chilled ceilings can successfully cool buildings achieved. While cooling water at 18^oC used in V
chilled ceilings can successfully cool buildings of
with internal loads of up to 60 W/m², it can also chilled ceilings can successfully cool buildings
with internal loads of up to 60 W/m², it can also d
be used to cool the supply air to buildings to c
20°C provided a suitable design of cooling coil with internal loads of up to 60 W/m², it can also
be used to cool the supply air to buildings to
20°C, provided a suitable design of cooling coil

is used.² Supply air at 20° C can be used in dis-
placement vertilation systems to supplement the is used.² Supply air at 20° C can be used in dis-
placement ventilation systems to supplement the
cooling provided by the chilled cailing system is used.² Supply air at 20^oC can be used in dis-
placement ventilation systems to supplement the
cooling provided by the chilled ceiling system. placement ventilation systems to supplement the
cooling provided by the chilled ceiling system.
With such a combination, cooling loads of the
order of 80 $\frac{W}{m^2}$ can be trouted. However, when provided by the chilled ceiling system.
With such a combination, cooling loads of the
order of 80 W/m² can be treated. However, when
displeasement ventilation, is combined, with With such a combination, cooling loads of the order of 80 W/m² can be treated. However, when displacement ventilation is combined with chilled ceilings the cooling contribution of the order of 80 W/m² can be treated. However, when ventilation system needs to be limited to

¹⁶⁶ *Experimental energy performance of open cooling towers*

Figure 3 Impact of secondary approach temperatures
for a range of cooling water temperatures (°C)⁸ for a range of cooling water temperatures (°C)⁸
approximately 25% of the sensible load if high

levels of ventilation efficiency are to be mainrepresentation officiency are to be main-
levels of ventilation efficiency are to be main-
tained.⁹ Sensible cooling loads of this magnitude for
are common in many commercial buildings, with the tained.⁹ Sensible cooling loads of this magnitude
are common in many commercial buildings, with
standard internal loads and constructed using
high performance building envelopes in temper hainted building performance building envelopes, with
standard internal loads and constructed using
high performance building envelopes, in temperstandard internal loads and constructed using
high performance building envelopes, in temper-
ate European regions. Example internal bails and constructed using
the performance building envelopes, in temper-
European regions.
Cooling water at 18°C and 3K SAT is statisti-

European regions.
Cooling water at 18°C and 3K SAT is statistically unavailable for just 320 h out of a possible
8760 h per ennum in Dublin ¹⁰ The extent of this Cooling water at 18 $^{\circ}$ C and 3K SAT is statistically unavailable for just 320 h out of a possible 8760 h per annum in Dublin.¹⁰ The extent of this availability is so wide that it comes very close cally unavailable for just 320 h out of a possible $SATs$.
8760 h per annum in Dublin.¹⁰ The extent of this This raises the prospect that the evaporative availability is so wide that it comes very close cooling technique 8760 h per annum in Dublin.¹⁰ The extent of this availability is so wide that it comes very close component cooling. Table 1 (in ju

tained.⁹ Sensible cooling loads of this magnitude for some cities in north western Europe with ascending order of the wet bulb temperature ascending order of the wet bulb temperature
(WBT) shows the 1% external design conditions
for some sities in porth western Europe with ascending order of the wet bulb temperature
(WBT) shows the 1% external design conditions
for some cities in north western Europe with
temperate and maritime elimates $\frac{11}{2}$ All these eit (WBT) shows the 1% external design conditions
for some cities in north western Europe with
temperate and maritime climates.¹¹ All these cit-
iss have similar external design WBTs, but diffor some cities in north western Europe with
temperate and maritime climates.¹¹ All these cit-
ies have similar external design WBTs, but dif-
ferent dry bulb temperatures (DBTs) and would For some cross in norm women.¹¹ All these cit-
temperate and maritime climates.¹¹ All these cit-
ies have similar external design WBTs, but dif-
ferent dry bulb temperatures (DBTs) and would, therefore, have similar external design WBTs, but different dry bulb temperatures (DBTs) and would, therefore, have approximately similar levels of cooling water evailability in summer at similar For the community of the cooling term of the temperatures (DBTs) and would,
therefore, have approximately similar levels of
cooling water availability in summer at similar SATs. This raises the prospect that the evaporative
This raises the prospect that the evaporative

SATs.
This raises the prospect that the evaporative
cooling technique, either acting alone or in con-
innction with other low energy cooling strategies This raises the prospect that the evaporative
cooling technique, either acting alone or in con-
junction with other low energy cooling strategies

(such as night ventilation or fabric thermal storage), can supplant rather than simply sup-(such as night ventilation or fabric thermal c
storage), can supplant rather than simply sup-
plement the requirement for refrigeration based to
sensible cooling For this to occur the evenocet storage), can supplant rather than simply sup-
plement the requirement for refrigeration based
sensible cooling. For this to occur the evaporat-
ive cooling system must be used in conjunction plement the requirement for refrigeration based
sensible cooling. For this to occur the evaporative
ive cooling system must be used in conjunction
with a 'high temperature' building cooling sys sensible cooling. For this to occur the evaporat-
ive cooling system must be used in conjunction
with a 'high temperature' building cooling systhe cooling system must be used in conjunction
with a 'high temperature' building cooling system and a low approach condition must be achi-
aved in the cooling tower and heat exchanger with a 'high temperature' building cooling sys-
tem and a low approach condition must be achieved in the cooling tower and heat exchanger,
particularly during the warmer months. This in tem and a low approach condition must be achieved in the cooling tower and heat exchanger,
particularly during the warmer months. This in eved in the cooling tower and heat exchanger,
particularly during the warmer months. This in
turn requires a high air and water mass flow rate
in the cooling tower per unit of load which itself particularly during the warmer months. This in
turn requires a high air and water mass flow rate
in the cooling tower per unit of load which itself
has the potential to raise the energy consumption turn requires a high air and water mass flow rate
in the cooling tower per unit of load which itself
has the potential to raise the energy consumption
of the process. The success of this strategy in the cooling tower per unit of load which itself
has the potential to raise the energy consumption
of the process. The success of this strategy, therefore, largely depends on achieving low
therefore, largely depends on achieving low
annroach conditions in the heat rejection system For the process. The success of this strategy,
therefore, largely depends on achieving low
approach conditions in the heat rejection system, therefore, largely depends on achieving low
approach conditions in the heat rejection system,
at viable levels of primary energy consumption.
An important issue, that merits mention in the proach conditions in the heat rejection system,
viable levels of primary energy consumption.
An important issue, that merits mention in the
ntext of current health and sofety concerns is

at viable levels of primary energy consumption.
An important issue, that merits mention in the
context of current health and safety concerns is
the considerably lower cooling tower water tem-An important issue, that merits mention in the
context of current health and safety concerns is
the considerably lower cooling tower water tempermit of current health and safety concerns is
the considerably lower cooling tower water tem-
peratures required in this application, in com-
perison with cooling towers used to reject heat the considerably lower cooling tower water temperatures required in this application, in comparison with cooling towers used to reject heat peratures required in this application, in com-
parison with cooling towers used to reject heat
from refrigeration condensers. The cooling
tower primary water temperature will generally parison with cooling towers used to reject heat
from refrigeration condensers. The cooling
tower primary water temperature will generally France refrigeration condensers. The cooling
tower primary water temperature will generally
not exceed 20°C when operating in summer.
Hence the possibilities for the growth of the beg tower primary water temperature will generally
not exceed 20° C when operating in summer.
Hence the possibilities for the growth of the bacthe proceed 20°C when operating in summer.

Hence the possibilities for the growth of the bac-

terium *Legionella pneumophila* are minimal,

compared with conventional refrigeration con-Exercise the possibilities for the growth of the bac-
terium *Legionella pneumophila* are minimal,
compared with conventional refrigeration condensity the *Legionella pneumophila* are minimal,
compared with conventional refrigeration con-
denser water cooling towers, in which water compared with conventional refrigeration con-
denser water cooling towers, in which water
temperatures are normally in the high growth
time climate of north western Europe. range of 27–33°C. The optimum temperature for temperatures are normally in the high growth
range of $27-33$ °C. The optimum temperature for
growth of the bacterium being 37 °C. At tem-
paratures shows 37 °C the rate of multiplication range of 27–33°C. The optimum temperature for
growth of the bacterium being 37° C. At temperatures above 37° C, the rate of multiplication
of the organism decreases and casese at 46°C growth of the bacterium being 37° C. At temperatures above 37° C, the rate of multiplication
of the organism decreases and ceases at 46° C. beratures above 37° C, the rate of multiplication
of the organism decreases and ceases at 46° C.
Below 37° C the multiplication rate decreases of the organism decreases and ceases at 46° C.
Below 37° C the multiplication rate decreases
and it can be considered insignificant below Below 37°C the multiplication rate decreases
and it can be considered insignificant below
 $20^{\circ}C^{-12}$ Nevertheless water treatment is advisand it can be considered insignificant below 20° C.¹² Nevertheless water treatment is advisable, and is required in any event to limit scale and corrosion. This fact is important in promotable, and is required in any event to limit scale able, and is required in any event to limit scale
and corrosion. This fact is important in promot-
ing greater confidence in the use of cooling towers for evaporation. This fact is important in promoting greater confidence in the use of cooling tow-
ers for evaporative cooling, particularly in commercial buildings.
The greater confident ers for evaporative
mercial buildings. ers for evaporative cooling, particularly in commercial buildings.
2 Background

The use of indirect evaporative cooling systems, using cooling towers, was rst reported in Ari-The use of indirect evaporative cooling systems,
using cooling towers, was first reported in Ari-
zona in the 1920s.² While water side evaporative

cooling arrangements are occasionally used cooling arrangements are occasionally used
today with air–water systems, the use of the
technique is well short of its potential 13 The lack cooling arrangements are occasionally used
today with air-water systems, the use of the
technique is well short of its potential.¹³The lack today with air-water systems, the use of the
technique is well short of its potential.¹³ The lack
of in-depth knowledge of the energy performtechnique is well short of its potential.¹³ The lack
of in-depth knowledge of the energy perform-
ance of water side free cooling systems has been of in-depth knowledge of the energy perform-
ance of water side free cooling systems has been
identified by Field¹⁴ as a barrier to the wider use ance of water side is
identified by Field¹
of the technique.
The traditional as entified by Field¹⁴ as a barrier to the wider use
the technique.
The traditional approach to indirect water side
approaching is to apply the technology in

of the technique.
The traditional approach to indirect water side
evaporative cooling is to apply the technology in The traditional approach to indirect water side
evaporative cooling is to apply the technology in
the context of a changeover system,¹³ at standard
ecoling, water temperatures, typically, 7% By evaporative cooling is to apply the technology in
the context of a changeover system,¹³ at standard
cooling water temperatures, typically 7° C. By the context of a changeover system,¹³ at standard
cooling water temperatures, typically 7° C. By
routing the cooling tower water and the cooling
load water through a plate heat exchanger the cooling water temperatures, typically 7° C. By
routing the cooling tower water and the cooling
load water through a plate heat exchanger the
condenser and evenerator circuits are hypessed routing the cooling tower water and the cooling
load water through a plate heat exchanger the
condenser and evaporator circuits are bypassed, load water through a plate heat exchanger the condenser and evaporator circuits are bypassed, providing cooling without operating the refrigercondenser and evaporator circuits are bypassed,
providing cooling without operating the refriger-
ation compressor. The extent of the annual
anargy savings yery greatly with each preject providing cooling without operating the refriger-
ation compressor. The extent of the annual
energy savings vary greatly with each project,
but are typically of the order of 30% loss than ation compressor. The extent of the annual
energy savings vary greatly with each project,
but are typically of the order of 30% less than energy savings vary greatly with each project,
but are typically of the order of 30% less than
a non changeover system. With such systems,
building equipments largely by refrigeration. In but are typically of the order of 30% less than
a non changeover system. With such systems,
building cooling is largely by refrigeration. In a non changeover system. With such systems,
building cooling is largely by refrigeration. In
recent years some measures have been taken to building cooling is largely by refrigeration. In recent years some measures have been taken to extend the period for which evaporative cooling recent years some measures have been taken to
extend the period for which evaporative cooling
is effective.¹⁵ However, traditional low temperaextend the period for which evalues
is effective.¹⁵ However, tradition
ture cooling systems are used.
The following factors have been effective.¹⁵ However, traditional low tempera-
re cooling systems are used.
The following factors have been identified as

ture cooling systems are used.
The following factors have been identified as
limiting the widespread application of this tech-The following factors have been identified as
limiting the widespread application of this tech-
nology, particularly in the temperate and mari-
time climate of porth western Europe limiting the widespread application of th
nology, particularly in the temperate an
time climate of north western Europe.

- time climate of north western Europe.

1) Availability levels, for conventional cooling

weter temperatures, concreted by evenor Availability levels, for conventional cooling
water temperatures, generated by evapor-
ation are canorally low For evapore Availability levels, for conventional cooling
water temperatures, generated by evapor-
ation, are generally low. For example, even
on the hosis of a $3 \times 5 \text{ AT}$ sooling water at water temperatures, generated by evaporation, are generally low. For example, even
on the basis of a 3 K SAT, cooling water at ation, are generally low. For example, even
on the basis of a 3 K SAT, cooling water at
 7° C can statistically be generated in Dublin
for only 22% of the year. However, cooling on the basis of a 3 K SAT, cooling water at
7°C can statistically be generated in Dublin
for only 22% of the year. However, cooling
water at 15% can be produced for 81% and 7° C can statistically be generated in Dublin
for only 22% of the year. However, cooling
water at 15° C can be produced for 81% and
at 18° C for 96% of the year. With agricon for only 22% of the year. However, cooling
water at 15° C can be produced for 81% and
at 18° C for 96% of the year. With conven-
tional cooling water, temperatures, conital water at 15° C can be produced for 81% and
at 18° C for 96% of the year. With conven-
tional cooling water temperatures capital
investment is required in both refrigeration at 18°C for 96% of the year. With conventional cooling water temperatures capital
investment is required in both refrigeration
and abangeouse plant and controls for a year. tional cooling water temperatures capital
investment is required in both refrigeration
and changeover plant and controls, for a very
limited return in evoluability. investment is required in both refrigeration
and changeover plant and controls, for a very
limited return in availability.
- 2) The seasonal stability associated with large limited return in availability.
The seasonal stability associated with large
continental land mass climates, which is
sheart in maritime elimates, and the experi-The seasonal stability associated with large
continental land mass climates, which is
absent in maritime climates, and the experi-
ange of other large abangaouse systems, in continental land mass climates, which is
absent in maritime climates, and the experi-
ence of other large changeover systems, in
maritime climates, hes not aposure and conabsent in maritime climates, and the experience of other large changeover systems, in maritime climates, has not encouraged con-

Experimental energy performance of open co
fidence in changeover arrangements, from an a fidence in changeover arrangements, from an operational point of view. fidence in changeover arrangements, from an
operational point of view.
3) The increase in the use of air-cooled chilling to
plants, at the expanse of water cooled con

perational point of view.
The increase in the use of air-cooled chilling
plants, at the expense of water cooled con-The increase in the use of air-cooled chilling
plants, at the expense of water cooled con-
densers, particularly for smaller loads, subdensers, particularly for smaller loads, sub-
sequent to the first recognized outbreak of
Legionnaires' disease in July 1976, has favsequent to the first recognized outbreak of
Legionnaires' disease in July 1976, has fav-
oured the use of dry cooling as a means of
improving the energy efficiency of refriger Legionnaires' disease in July 1976, has fav-
oured the use of dry cooling as a means of
improving the energy efficiency of refrigeroured the use of dry cooling as a means of
improving the energy efficiency of refriger-
ation plants.

3 Experimental test rig
The application of evaporative cooling to water based, high temperature, sensible cooling The test rig includes a prototype cooling tower, systems, in general, and to chilled ceilings in with three packing sections and a laboratory test The application of evaporative cooling to
water based, high temperature, sensible cooling T
systems, in general, and to chilled ceilings in water based, high temperature, sensible cooling
systems, in general, and to chilled ceilings in
particular, offers the prospect of eliminating the
changeover requirement and therefore of over systems, in general, and to chilled ceilings in
particular, offers the prospect of eliminating the
changeover requirement and therefore of over-
coming these limitations. The objective is to particular, offers the prospect of eliminating the
changeover requirement and therefore of over-
coming these limitations. The objective is to
maximize evaporative cooling and to look to $\overline{1}$ changeover requirement and therefore of over-
coming these limitations. The objective is to the
maximize evaporative cooling and to look to T
other low energy cooling strategies during those coming these limitations. The objective is to
maximize evaporative cooling and to look to
other low energy cooling strategies during those maximize evaporative cooling and to look to
other low energy cooling strategies during those
periods when the cooling water temperature genother low energy cooling strategies
periods when the cooling water ten
erated is above the design level.

Form of indirect evaporative cooling—closed
form of indirect evaporative cooling—closed
wet cooling towers and onen towers with senare Two approaches have been developed to this
form of indirect evaporative cooling—closed
wet cooling towers and open towers with separ-
ate plate hast exchanges. Each arrangement has Form of indirect evaporative cooling—closed
wet cooling towers and open towers with separ-
ate plate heat exchangers. Each arrangement has wet cooling towers and open towers with separate plate heat exchangers. Each arrangement has ate plate heat exchangers. Each arrangement has
advantages in particular circumstances. The ther-
mal performance of closed towers in this appli-
extinct has been investigated experimentally, advantages in particular circumstances. The thermal performance of closed towers in this appli-
cation has been investigated experimentally⁵ and a mal performance of closed towers in this application has been investigated experimentally⁵ and using CFD.⁴ This work does not include, how-
ever, an assessment of energy performance. extra Free-
cation has been investigated experimentally⁵ and
using CFD.⁴ This work does not include, how-
ever, an assessment of energy performance. This work does not include, how-
ever, an assessment of energy performance.
Computational modelling work has been comever, an assessment of energy performance.
Computational modelling work has been completed recently on the energy performance of alogod wet cooling towers, in this emplication 16 Computational modelling work has been com-
pleted recently on the energy performance of
closed wet cooling towers, in this application.¹⁶
In this work COB lovels renging from 3 to 20 pleted recently on the energy performance of
closed wet cooling towers, in this application.¹⁶ T
In this work COP levels ranging from 3 to 20 to closed wet cooling towers, in this application.¹⁶
In this work COP levels ranging from 3 to 20
were indicated, depending on the level of heat In this work COP levels ranging from 3 to 20 to
were indicated, depending on the level of heat a
rejected and tower air velocity, with a predicted e were indicated, depending on the level of heat
rejected and tower air velocity, with a predicted
COP of 4.6 for the nominal tower design data. rejected and tower air velocity, with a predicted COP of 4.6 for the nominal tower design data. In this study, also, it is shown that the COP level **4.1 Feasibility of low approach conditions** could be optimized to 11.4 by increasing the heat A series of tests was conducted to investigate transfer area (quantity of c could be optimized to 11.4 by increasing the heat
transfer area (quantity of coil rows and tubes)
and reducing the air velocity. A subsequent
simulation study, based on the optimized heat transfer area (quantity of coil rows and tubes) and reducing the air velocity. A subsequent a
simulation study, based on the optimized heat of
transfer area, and applied to an office building less and applied to an office building in The Texture and American control of the simulation study, based on the optimized heat of transfer area, and applied to an office building low and applied to an office building benefited a COP of 8.4, for the cooling ben Fransfer area, and applied to an office building
in Zurich indicated a COP of 8.4, for the cooling
period April to October. There is, however, a in Zurich indicated a COP of 8.4, for the cooling
period April to October. There is, however, a T
need for experimental research on the energy d period April to October. There is, however, a
need for experimental research on the energy
performance of open and closed towers, in this

plants, at the expense of water cooled con-
conditions; and ii) can such cooling water be
densers, particularly for smaller loads, sub-
generated at viable levels of annual energy con-
sequent to the first recognized outbr application. Two experimental research issues arise in this context: i) is it technically feasible application. Two experimental research issues
arise in this context: i) is it technically feasible
to generate cooling water at such low approach
conditions: and ii) can such cooling water be arise in this context: i) is it technically feasible
to generate cooling water at such low approach
conditions; and ii) can such cooling water be to generate cooling water at such low approach
conditions; and ii) can such cooling water be
generated at viable levels of annual energy con-
sumption? To investigate these issues an auto conditions; and ii) can such cooling water be generated at viable levels of annual energy consumption? To investigate these issues an automated experimental research facility has been
designed and constructed at the Dublin Institute sumption? To investigate these issues an auto-
mated experimental research facility has been
designed and constructed at the Dublin Institute
of Technology, as shown in Figure 4 mated experimental research facility h
designed and constructed at the Dublin
of Technology, as shown in Figure 4. designed and constructed at the Dublin Institute
of Technology, as shown in Figure 4.

periods when the cooling water temperature gen-
erated is above the design level.
Two approaches have been developed to this individually measured. Modulated speed control **3 Experimental test rig**
The test rig includes a prototype cooling tower,
with three packing sections and a laboratory test The test rig includes a prototype cooling tower,
with three packing sections and a laboratory test
rig with automatic data logging of key variables The test rig includes a prototype cooling tower,
with three packing sections and a laboratory test
rig with automatic data logging of key variables. with three packing sections and a laboratory test
rig with automatic data logging of key variables.
A schematic diagram of the rig, which includes
the magained conditions is shown in Figure 4. the measured conditions is shown in Figure 4.
A schematic diagram of the rig, which includes
the measured conditions is shown in Figure 4. A schematic diagram of the rig, which includes
the measured conditions is shown in Figure 4.
The open counter-flow cooling tower and the
plate heat exchanger are optimized for close plate measured conditions is shown in Figure 4.
The open counter-flow cooling tower and the
plate heat exchanger are optimized for close The open counter-flow cooling tower and the
plate heat exchanger are optimized for close
approach conditions. The electrical energy con-
sumption of all power consuming equipment is plate heat exchanger are optimized for close
approach conditions. The electrical energy con-
sumption of all power consuming equipment is
individually magained. Modulated speed control individually measured. Modulated speed control sumption of all power consuming equipment is
individually measured. Modulated speed control
of the cooling tower fan is achieved by inverter
control of the fan motor. The cooling load is pro individually measured. Modulated speed control
of the cooling tower fan is achieved by inverter
control of the fan motor. The cooling load is pro-Figure 2.1 and the cooling tower fan is achieved by inverter
control of the fan motor. The cooling load is pro-
vided by an in-line electric immersion heater, control of the fan motor. The cooling load is provided by an in-line electric immersion heater. vided by an in-line electric immersion heater,
with modulated thyristor control. This enables
the imposed cooling load on the tower to be
accurately massured and controlled. The design with modulated thyristor control. This enables
the imposed cooling load on the tower to be
accurately measured and controlled. The design
of the rig is described elections 17 the imposed cooling load on the tower to be accurately measured and controlled. The design of the rig is described elsewhere.¹⁷ **4 Experimental test programme results**

4 Experimental test programme results
The measured results are first presented for the
tests on the technical fossibility of very low. The measured results are first presented for the tests on the technical feasibility of very low The measured results are first presented for the
tests on the technical feasibility of very low
approach conditions. Secondly the results of the
aparay performance tests are presented Figures in the technical feasibility of ver
approach conditions. Secondly the results
energy performance tests are presented. **4.1 Feasibility of low approach conditions**

A series of tests was conducted to investigate **4.1 Feasibility of low approach conditions**
A series of tests was conducted to investigate
the technical feasibility of achieving low
approach temperatures in the primery and see A series of tests was conducted to investigate
the technical feasibility of achieving low
approach temperatures in the primary and secthe technical feasibility of achieving low
approach temperatures in the primary and sec-
ondary circuits. Three imposed constant cooling
loads of 24 kW 20 kW and 15 kW were used ondary circuits. Three imposed constant cooling
loads of 24 kW, 20 kW and 15 kW were used, by setting the thyristor at the appropriate value.
by setting the thyristor at the appropriate value.
The embiont WBT ranged from 6.4% to 16.5% boads of 24 kW, 20 kW and 15 kW were used,
by setting the thyristor at the appropriate value.
The ambient WBT ranged from 6.4°C to 16.5°C
during the source of the tests. As the objective by setting the thyristor at the appropriate value.
The ambient WBT ranged from 6.4° C to 16.5° C during the course of the tests. As the objective was to minimize the approach condition at the The ambient WBT ranged from 6.4° C to 16.5° C during the course of the tests. As the objective was to minimize the approach condition at the

Figure 4 Schematic diagram of evaporative cooling experimental test rig with open tower

tower, the tower air volume flow rate was set to maximum and all three packing sections were tower, the tower air volume flow rate was set to
maximum and all three packing sections were
used. The cooling tower range temperature (see
Figure 1) effects the approach condition sobies Figure 1) and all three packing sections were
used. The cooling tower range temperature (see
Figure 1) affects the approach condition achi-
aved hance the primary circuit water volume eved. The cooling tower range temperature (see
Figure 1) affects the approach condition achieved, hence the primary circuit water volume
flow rate was set to maximum to minimize the Figure 1) affects the approach condition achieved, hence the primary circuit water volume
flow rate was set to maximum to minimize the
range temperature. The secondary circuit volume
flow rate was also set to maximum to minimize flow rate was set to maximum to minimize the duced, per unit of electrical energy input to the range temperature. The secondary circuit volume cooling tower fan and primary circuit pump. The flow rate was also set to maxim range temperature. The secondary circuit volume cooling tower fan and primary circuit pump. The flow rate was also set to maximum to minimize primary circuit pump energy has been included the heat exchanger approach condit the was also set to maximum to minimize
the heat exchanger approach condition and ithereby minimize the SATs for the rig as a
whole. The test results are summerized in Table the heat exchanger approach condition and if
thereby minimize the SATs for the rig as a t
whole. The test results are summarized in Table
2. Primery approach temperatures (PAT) renging thereby minimize the SATs for the rig as a whole. The test results are summarized in Table 2. Primary approach temperatures (PAT) ranging from 0.9 to 2.3 K were measured depending on whole. The test results are summarized in Table flow rate p
2. Primary approach temperatures (PAT) ranging achieve love
from 0.9 to 2.3 K were measured depending on pose of the
imposed load and ambient condition SATs rang-2. Primary approach temperatures (PAT) ranging
from 0.9 to 2.3 K were measured depending on
imposed load and ambient condition. SATs rang-
ing from 2.2 to 4.3 K, were measured. These From 0.9 to 2.3 K were measured depending on
imposed load and ambient condition. SATs rang-
ing from 2.2 to 4.3 K were measured. These imposed load and ambient condition. SATs rang-
ing from 2.2 to 4.3 K were measured. These
results indicate that a SAT of 3 K is clearly feas-
ible with an imposed cooling load of 20 kW. In ing from 2.2 to 4.3 K were measured. These
results indicate that a SAT of 3 K is clearly feas-
ible with an imposed cooling load of 20 kW. In general, therefore, this implies a heat rejection rate with an imposed cooling load of 20 kW. In
general, therefore, this implies a heat rejection rate of 1 kW per 0.05 m³ or a load/volume ratio
of 20 kW/m³ of positing based on the positing to general, therefore, this implies a heat rejection
rate of 1 kW per 0.05 m³ or a load/volume ratio
of 20 kW/m³ of packing, based on the packing the
surface area of 200 m²/m³ or 10 m² par kW of rate of 1 kW per 0.05 m³ or a load/volume ratio
of 20 kW/m³ of packing, based on the packing
surface area of 200 m²/m³, or 10 m² per kW of surface area of 200 m²/m³, or 10 m² per kW of of 20 kW/m³ of packing, based on the packing
surface area of 200 m²/m³, or 10 m² per kW of
heat rejected, which is technically quite feasible.

4.2 Energy viability of low approach conditions

The energy performance of the process can be assessed in terms of the energy coefficient of The energy performance of the process can
be assessed in terms of the energy coefficient of
performance (COP) or the cooling energy probe assessed in terms of the energy coefficient of
performance (COP) or the cooling energy pro-
duced, per unit of electrical energy input to the
cooling tower for and primary circuit nume. The performance (COP) or the cooling energy pro-
duced, per unit of electrical energy input to the
cooling tower fan and primary circuit pump. The duced, per unit of electrical energy input to the cooling tower fan and primary circuit pump. The primary circuit pump energy has been included of the person rate per unit of load is high) in order to
the low rate per unit of load is high) in order to
schious low approach conditions. For the purachieve low (and hence the primary circuit mass
flow rate per unit of load is high) in order to
achieve low approach conditions. For the pur-
nose of the research tests this persmeter can be flow rate per unit of load is high) in order to
achieve low approach conditions. For the pur-
pose of the research tests this parameter can be
defined sy. achieve low approach conditions. For the purpose of the research tests this parameter can be

$$
COP = Q/(P_f + P_p) \tag{1}
$$

In general, building secondary cooling systems, $COP = Q/(P_f + P_p)$ (1)
In general, building secondary cooling systems,
require cooling water at a constant design tem-
parature throughout the year. The cooling water In general, building secondary cooling systems,
require cooling water at a constant design tem-
perature throughout the year. The cooling water
temperature cannot be allowed to fall, if condan the general colling accounting to complete the person of the peak of the peak of the search of the allowed to fall, if condensation is to be avoided on chilled collings or dry perature throughout the year. The cooling water
temperature cannot be allowed to fall, if conden-
sation is to be avoided on chilled ceilings or dry secondary coils. Furthermore, chilled ceilings

	Table 2 Summary of low approach experimental test results from the evaporative cooling test rig (Dublin) Ambient Primary flow Secondary flow Secondary						
Nominal load	WBT	temperature from tower	temperature from heat exchanger	Primary approach to WBT (PAT)	approach to WBT (SAT)		
(kW)	$(^{\circ}C)$	$(^{\circ}C)$	$(^{\circ}C)$	(K)	(K)		
24	6.4	8.7	10.7	2.3	4.3		
24	8.9	10.8	12.5	1.9	3.6		
24	9.2	11.1	12.8	1.9	3.6		
24	11.1	12.8	14.6	1.7	3.5		
20	8.4	9.8	11.3	1.4	2.9		
20	9.2	10.6	12.1	1.4	2.9		
20	10.2	11.3	12.9	1.1	2.7		
20	12.5	13.5	15.1	1.0	2.6		
20	16.5	17.4	19.0	0.9	2.5		
15	8.7	9.7	10.9	1.0	2.2		
15	9.3	10.6	11.7	1.3	2.4		
15	9.7	11.1	12.3	1.4	2.6		
15	10.6	11.6	12.8	1.0	$2.2\,$		

Table 2 Summary of low approach experimental test results from the evaporative cooling test rig (Dublin)

have also been shown to have a significant have also been shown to have a significant g
degree of self-regulation,¹⁸ with an increased face have also been shown to have a significant
degree of self-regulation,¹⁸ with an increased
cooling output as room conditions rise at a con-
stant degian cooling water flow temperature degree of self-regulation,¹⁸ with an increased
cooling output as room conditions rise at a con-
stant design cooling water flow temperature.
This feature enables the energy performance of cooling output as room conditions rise at a constant design cooling water flow temperature.
This feature enables the energy performance of the evaporative cooling process to be improved Example and design cooling water flow temperature.
This feature enables the energy performance of let be evaporative cooling process to be improved contracted to be explained to the scaling tower air. This feature enables the energy performance of
the evaporative cooling process to be improved
at lower ambient WBT, as the cooling tower air
welling. flow, retaining to reduced, which the evaporative cooling process to be improved cooling tower fan, primary pump and immersion
at lower ambient WBT, as the cooling tower air heater was automatically measured and accumu-
volume flow rate can be reduced, whi In the approach we have a material at lower ambient WBT, as the cooling tower air
volume flow rate can be reduced, which
increases the approach condition, but maintains
the required degree evolups were temperature. where the reduced, which
increases the approach condition, but maintains
the required design cooling water temperature.
The objective of the tests therefore wes to mea. increases the approach condition, but maintains
the required design cooling water temperature.
The objective of the tests, therefore, was to measure the required design cooling water temperature.
The objective of the tests, therefore, was to measure the energy performance of the heat rejection (sprocess, not only at minimum or design c The objective of the tests, therefore, was to mea-
sure the energy performance of the heat rejection (sprocess, not only at minimum or design compress) sure the energy performance of the heat rejection
process, not only at minimum or design
approach conditions but also across a typical
range of $3, 10$ K SAT. The energy performance sure the energy performance of the heat rejection (see Equation 1) on the basis that a secondary process, not only at minimum or design circuit pump is required whether cooling is pro-
approach conditions but also across approach conditions but also across a typical
range of $3-10$ K SAT. The energy performance
needs to be assessed, in the first instance, at a
constant full cooling load (24 kW) at various range of $3-10$ K SAT. The energy performance refrigeration.
needs to be assessed, in the first instance, at a A series of 11 test runs were completed. The constant full cooling load (24 kW) at various test results are approach conditions. Secondly, in order to simulate the situations. Secondly, in order to simulate the situation in which a partial cooling load Latern in the situation in which a partial cooling load
approach conditions. Secondly, in order to simulate the situation in which a partial cooling load
west imposed on the tower, the same series of approach conditions. Secondly, in order to simulate the situation in which a partial cooling load was imposed on the tower, the same series of late the situation in which a partial cooling load 24 kW (tests $1-5$) and with a fan power conwas imposed on the tower, the same series of sumption of 100% , 75% , 60% , 32% , and 20% tests were repeated a was imposed on the tower, the same series of
tests were repeated at a constant partial load of
70% of the full load (17 kW). This would represent the situation in a building in which the situation was reduced due to a reduced internal load 170% of the full load (17 kW) . This would rep-
resent the situation in a building in which the
load was reduced due to a reduced internal load, resent the situation in a building in which the
load was reduced due to a reduced internal load,
or the absence of an external load.
The test method used was to select a particular

Four the absence of an external load.
The test method used was to select a particular
cooling load by setting the thyristor at a parti-
where output. This load remained constant during cular output. This load remained constant during fan power consumption level. Ambient WBT a series of tests in which the fan power was pro- ranged from 8 to 14° C during the course of the cooling load by setting the thyristor at a particular output. This load remained constant during a series of tests in which the fan power was pro-

gressively reduced by altering the cooling tower
fan motor, inverter set point, for each test. The gressively reduced by altering the cooling tower
fan motor, inverter set point, for each test. The
cooling load was then altered and a further series gressively reduced by altering the cooling tower
fan motor, inverter set point, for each test. The
cooling load was then altered and a further series
of tests repeated at the same series of fan power fan motor, inverter set point, for each test. The
cooling load was then altered and a further series
of tests repeated at the same series of fan power cooling load was then altered and a further series
of tests repeated at the same series of fan power
levels. The electrical energy consumption of the
cooling tower fan primary pump and immersion of tests repeated at the same series of fan power
levels. The electrical energy consumption of the
cooling tower fan, primary pump and immersion
heater wes sutematically measured and accumu levels. The electrical energy consumption of the recoling tower fan, primary pump and immersion
heater was automatically measured and accumu-
lated. During all tests the primary and secondary water was automatically measured and accumulated. During all tests the primary and secondary
water volume flow rates remained constant. The power input to the secondary
and secondary
water volume flow rates remained constant. The
power input to the secondary pump was not con-
sidered in the energy performance assessment water volume flow rates remained constant. The
power input to the secondary pump was not con-
sidered in the energy performance assessment power input to the secondary pump was not considered in the energy performance assessment
(see Equation 1) on the basis that a secondary
circuit pump is required whether cooling is prosidered in the energy performance assessment
(see Equation 1) on the basis that a secondary
circuit pump is required whether cooling is provided by evaporation or vapour compression
vided by evaporation or vapour compression
refrigention refrigeration. vided by evaporation or vapour compression
refrigeration.
A series of 11 test runs were completed. The

resent the situation in a building in which the ditions but with a nominal load of 17 kW, repload was reduced due to a reduced internal load, resenting a 70% partial load condition. One or the absence of an external lo terrigeration.

A series of 11 test runs were completed. The

test results are summarized in Table 3. Five tests A series of 11 test runs were completed. The
test results are summarized in Table 3. Five tests
were run at a constant nominal cooling load of
 24 kW (tests 1.5) and with a fan nower con test results are summarized in Table 3. Five tests
were run at a constant nominal cooling load of
24 kW (tests 1–5) and with a fan power con-
sumption of 100% , 75% , 60%, 32%, and 20% were run at a constant nominal cooling load of
24 kW (tests 1–5) and with a fan power con-
sumption of 100%, 75%, 60%, 32%, and 20%
of the movimum value A further five tests (tests) 24 kW (tests 1–5) and with a fan power consumption of 100%, 75%, 60%, 32%, and 20% of the maximum value. A further five tests (tests (6.10) were repeated at similar fan power consider sumption of 100%, 75%, 60%, 32%, and 20%
of the maximum value. A further five tests (tests 6–10) were repeated at similar fan power con-
ditions but with a nominal load of 17 kW ronof the maximum value. A further five tests (tests 6–10) were repeated at similar fan power conditions but with a nominal load of 17 kW, rep- $6-10$) were repeated at similar fan power conditions but with a nominal load of 17 kW, representing a 70% partial load condition. One
further test (test 11) was carried out at a nominal ditions but with a nominal load of 17 kW, rep-
resenting a 70% partial load condition. One
further test (test 11) was carried out at a nominal
load of 17 kW but with a far nower consumption resenting a 70% partial load condition. One
further test (test 11) was carried out at a nominal
load of 17 kW but with a fan power consumption
of 16% , which represents the minimum precticel further test (test 11) was carried out at a nominal
load of 17 kW but with a fan power consumption
of 16%, which represents the minimum practical
fan power, consumption, lovel, Ambient WPT of 16% , which represents the minimum practical ranged from 8 to 14°C during the course of the

	Table 3 Summary of results of energy performance tests on evaporative cooling test rig							
Test no.	Cooling tower fan power $(\%)$	Accumulated cooling energy effect (load rejected) (kWh)	Accumulated energy input to tower fan (kWh)	Accumulated energy input to primary pump (kWh)	Average PAT achieved (K)	Average SAT achieved (K)	Test COP	
	100	48.2	5.0	1.4	1.2	4.4	7.5	
2	75	45.3	3.8	1.3	1.3	4.4	8.9	
3	60	47.9	2.9	1.3	1.7	4.8	11.4	
4	32	47.0	1.6	1.3	4.4	7.4	16.2	
5	20	47.0	1.0	1.3	6.2	9.4	20.4	
6	100	34.4	5.1	1.3	1.0	3.0	5.4	
	75	35.0	3.8	1.2	1.0	2.9	7.0	
8	60	35.0	3.0	1.3	1.5	3.8	8.1	
9	32	33.9	1.6	1.3	2.5	4.7	11.7	
10	20	34.1	1.1	1.3	4.1	6.5	14.2	
11	16	34.1	0.8	1.3	5.5	7.8	16.2	

B C*ostello*
T<mark>able 3</mark> Summary of results of energy performance tests on evaporative cooling test rig

tests. At a full load of 24 kW and with a SAT tests. At a full load of 24 kW and with a SAT ind
ranging from 4.4 to 4.8 K, a COP ranging from and
 7.5 to 11.4 was achieved. At a partial load of 17 yol tests. At a full load of 24 kW and with a SAT in
ranging from 4.4 to 4.8 K, a COP ranging from a
7.5 to 11.4 was achieved. At a partial load of 17 v
kW and with a SAT ranging from 2.9 to 4.7 K ranging from 4.4 to 4.8 K, a COP ranging from
7.5 to 11.4 was achieved. At a partial load of 17
kW and with a SAT ranging from 2.9 to 4.7 K,
a COP ranging from 5.4 to 11.7 was achieved 7.5 to 11.4 was achieved. At a partial load of 17 kW and with a SAT ranging from 2.9 to 4.7 K, a COP ranging from 5.4 to 11.7 was achieved. kW and with a SAT ranging from 2.9 to 4.7 K,
a COP ranging from 5.4 to 11.7 was achieved. a
These energy performance levels demonstrate
that the technique is clearly viable at the low a COP ranging from 5.4 to 11.7 was achieved.
These energy performance levels demonstrate
that the technique is clearly viable at the low 5 These energy performance levels demonstrate
that the technique is clearly viable at the low
approach conditions, which have been shown to
be technically fossible that the technique is clearly viable at the low
approach conditions, which have been shown to
be technically feasible. proach conditions, which have been shown to
technically feasible.
Over the course of the tests very small

be technically feasible.

Over the course of the tests very small T

changes occurred in water and air density, due to

small changes in the embient dry bulb condition Over the course of the tests very small
changes occurred in water and air density, due to
small changes in the ambient dry bulb condition.
These are not significant as the range of ambient changes occurred in water and air density, due to
small changes in the ambient dry bulb condition.
These are not significant, as the range of ambient
DBT was small, from 10 to 20 \degree C over the course small changes in the ambient dry bulb condition.
These are not significant, as the range of ambient
DBT was small, from 10 to 20 $^{\circ}$ C over the course small changes in the ambient dry bulb condition. ation in the measured conditions over the course
These are not significant, as the range of ambient of a full day. For this purpose test 4 and test 7
DBT was small, from 10 DBT was small, from 10 to 20° C over the course
of the tests, with a maximum variation in air
density of 4.3% for this temperature range.
There is also some evidence that the engregate of the tests, with a maximum variation in air
density of 4.3% for this temperature range. sl
There is also some evidence that the approach recondition has a small dependence on the sheel density of 4.3% for this temperature range.
There is also some evidence that the approach
condition has a small dependence on the absol-
we value of the embient WPT ⁵ The approach There is also some evidence that the approach results for a full 24 kW cooling load at 32% fan condition has a small dependence on the absol-
ute value of the ambient WBT.⁵ The approach results for a 17 kW cooling load condition has a small dependence on the absol-The value of the ambient WBT.⁵ The approach recondition seems to fall marginally as the absolute value of the ambient WBT rises. The vectors of the ambient WBT rises. condition seems to fall marginally as the absolute value of the ambient WBT rises. The v
decrease in the approach condition is linear and F
is reported as approximately 8% as the ambient is reported as approach condition is linear and
is reported as approximately 8% as the ambient
 WBT rises from 10 to 20%. In the case of these decrease in the approach condition is linear and
is reported as approximately 8% as the ambient b
WBT rises from 10 to 20 \degree C. In the case of these is reported as approximately 8% as the ambient
WBT rises from 10 to 20 $^{\circ}$ C. In the case of these
tests the ambient WBT varied from 8 to 14 $^{\circ}$ C. WBT rises from 10 to 20 $^{\circ}$ C. In the case of these
tests the ambient WBT varied from 8 to 14 $^{\circ}$ C.
Hence the variation in the approach condition,
due to this effect, ever this test range is in the WBT rises from 10 to 20 $^{\circ}$ C. In the case of these out the day, demonstrating the suitability of the tests the ambient WBT varied from 8 to 14 $^{\circ}$ C. process for radiant cooling applications and Hence the variation in Frace the variation in the approach condition,
due to this effect, over this test range is in the
order of 5% and will not materially affect the
calculated aparaxy performance. The results due to this effect, over this test range is in the
order of 5% and will not materially affect the
calculated energy performance. The results Shown in Table 2 (for the 24 and 20 kW load)
shown in Table 2 (for the 24 and 20 kW load)

indicate a similar trend to that reported by Facao indicate a similar trend to that reported by Facao
and Oliveira.⁵ A small variation in the supply
voltage of up to 4% can also have slight effects indicate a similar trend to that reported by Facao
and Oliveira.⁵ A small variation in the supply
voltage of up to 4% can also have slight effects
on the output of the electric heater, which are and Oliveira.⁵ A small variation in the supply
voltage of up to 4% can also have slight effects
on the output of the electric heater, which are
also not significant voltage of up to 4% can also have slight effects
on the output of the electric heater, which are
also not significant.

5 Discussion of results

While a summary of each test result is given in While a summary of each test result is given in
Table 3, it is useful to investigate some of the
test results in more detail and examine the very While a summary of each test result is given in
Table 3, it is useful to investigate some of the
test results in more detail and examine the vari-
ation in the measured conditions over the course Table 3, it is useful to investigate some of the
test results in more detail and examine the vari-
ation in the measured conditions over the course
of a full day. For this purpose test 4 and test 7 First results in more detail and examine the vari-
ation in the measured conditions over the course
of a full day. For this purpose test 4 and test 7
have been selected as being representative of the have been selected as being representative of the course
of a full day. For this purpose test 4 and test 7
have been selected as being representative of the
range of conditions tested. These results are of a full day. For this purpose test 4 and test 7
have been selected as being representative of the
range of conditions tested. These results are
shown in Figures 5 and 6. Figure 5 shows the have been selected as being representative of the range of conditions tested. These results are
shown in Figures 5 and 6. Figure 5 shows the
results for a full 24 kW cooling load at 32% fan
nower and 7.4 K SAT, while Figure 6 shows the shown in Figures 5 and 6. Figure 5 shows the
results for a full 24 kW cooling load at 32% fan
power and 7.4 K SAT, while Figure 6 shows the
results for a 17 kW cooling load at 75% for results for a full 24 kW cooling load at 32% fan power and 7.4 K SAT, while Figure 6 shows the
results for a 17 kW cooling load at 75% fan
power and 2.9 K SAT. Both figures show the
variation in conditions over a 9 h period. In both results for a 17 kW cooling load at 75% fan Figures and 2.9 K SAT. Both figures show the
variation in conditions over a 9 h period. In both
Figures 5 and 6 a secondary flow temperature
between 15 and 17⁹C wes maintained through variation in conditions over a 9 h period. In both
Figures 5 and 6 a secondary flow temperature
between 15 and 17°C was maintained through-
out the day demonstrating the suitability of the Figures 5 and 6 a secondary flow temperature
between 15 and 17^oC was maintained through-
out the day, demonstrating the suitability of the
process for radiant cooling applications and between 15 and 17 \degree C was maintained through-
out the day, demonstrating the suitability of the
process for radiant cooling applications and
chilled coilings concrelly out the day, demonstrating
process for radiant coolinchilled ceilings generally. Figures 5 and 6 also show how the secondary,
Figures 5 and 6 also show how the secondary,
we temperature tracks the embiont WPT rather

on the cellings generally.

Figures 5 and 6 also show how the secondary,

flow temperature tracks the ambient WBT, rather

than the more widely fluctuating embient DBT. Figures 5 and 6 also show how the secondary,
flow temperature tracks the ambient WBT, rather
than the more widely fluctuating ambient DBT.
This close tracking, which is evident in both The tracking, the most offer the tracking, the ambient WBT, rather
than the more widely fluctuating ambient DBT.
This close tracking, which is evident in both

Figure 5 Measured diui
(results of test no. 4)

Figure 6 Measured diu
(results of test no.7) (results of test no.7)
cases, is displayed in the consistent linearity of

cases, is displayed in the consistent linearity of or the SAT and seems to be little affected by load up or for now set point. In this regnect the close d cases, is displayed in the consistent linearity of
the SAT and seems to be little affected by load
or fan power set point. In this respect the close the SAT and seems to be little affected by load
or fan power set point. In this respect the close
approach tower performs in a manner similar to
the conventional wide approach tower for which the dependence of the exiting water temperature

or fan power set point. In this respect the close described by Facao and Oliveira⁵ whereby approach tower performs in a manner similar to increases in the wet bulb temperature give rise the conventional wide approach tow on the ambient WBT, is well established. Figon the ambient WBT, is well established. Figures 5 and 6 also demonstrate the effect described by Escape and Oliveira⁵ whereby on the ambient WBT, is well established. Figures 5 and 6 also demonstrate the effect described by Facao and Oliveira⁵ whereby Figures 5 and 6 also demonstrate the effect
described by Facao and Oliveira⁵ whereby
increases in the wet bulb temperature give rise
to small degreeses in the approach temperature. described by Facao and Oliveira⁵ whereby
increases in the wet bulb temperature give rise
to small decreases in the approach temperature.
It can also be seen, that the effect of increasincreases in the wet bulb temperature give rise

ing the fan power to 75%, as shown in Figure ing the fan power to 75%, as shown in Figure to 6, is to bring the secondary flow temperature $\frac{1}{5}$ ing the fan power to 75%, as shown in Figure
6, is to bring the secondary flow temperature
between the ambient DBT and the ambient
WBT Whereas at 32% fan power the secondary 6, is to bring the secondary flow temperature g
between the ambient DBT and the ambient p
WBT. Whereas at 32% fan power the secondary local between the ambient DBT and the ambient
WBT. Whereas at 32% fan power the secondary
flow temperature achieved is above the ambient
dry bulb temperature (as shown in Figure 5) WBT. Whereas at 32% fan power the secondary loads, the initial 40% reduction in fan power
flow temperature achieved is above the ambient input results in a small 1 K rise in SAT. Hence
dry bulb temperature (as shown in Fig flow temperature achieved is above the ambient
dry bulb temperature (as shown in Figure 5)
which implies that similar conditions could poss-
ibly be achieved with enhanced dry coolers dry bulb temperature (as shown in Figure 5)
which implies that similar conditions could poss-
ibly be achieved with enhanced dry coolers. which implies that similar conditions could poss-
ibly be achieved with enhanced dry coolers.
However, as the ambient WBT is generally far
more stable than the ambient DBT (as shown ibly be achieved with enhanced dry coolers. tial. However, subsequent reductions in power However, as the ambient WBT is generally far input result in a steep rise in the approach con-
more stable than the ambient DBT (as However, as the ambient WBT is generally far in
more stable than the ambient DBT (as shown d
in the diurnal variation in both temperatures in a
Eigures 5 and 6) wet cooling will produce a more more stable than the ambient DBT (as shown
in the diurnal variation in both temperatures in
Figures 5 and 6) wet cooling will produce a more
stable cooling water temperature and bence is in the diurnal variation in both temperatures in
Figures 5 and 6) wet cooling will produce a more
stable cooling water temperature and hence is
the preferred method of cooling aven when it is Figures 5 and 6) wet cooling will produce a more
stable cooling water temperature and hence is
the preferred method of cooling even when it is stable cooling water temperature and hence is
the preferred method of cooling even when it is
feasible to produce the required cooling water the preferred method of cooling even wh
feasible to produce the required cooling
temperatures by means of dry coolers. **5.1 Analysis of energy performance**
5.1 Analysis of energy performance

Frame of the dependence
I Analysis of energy performance
Figure 7 shows the dependence of the SAT also 5.1 Analysis of energy performance
Figure 7 shows the dependence of the SAT
on the cooling tower fan power for the series
of 11 tests. The measured data points and the Figure 7 shows the dependence of the SAT
on the cooling tower fan power for the series
of 11 tests. The measured data points and the of 11 tests. The measured data points and the associated power law regression lines are shown
in Figures 7 and 8. SAT ranged from approxi-
mately 3 to 10 K. The rising SAT (and bence associated power law regression lines are shown
in Figures 7 and 8. SAT ranged from approxi-
mately 3 to 10 K. The rising SAT (and hence f

the reduction in the potential for cooling water the reduction in the potential for cooling water
generation) which results from reducing the fan
power input is clearly demonstrated. For both the reduction in the potential for cooling water
generation) which results from reducing the fan
power input, is clearly demonstrated. For both
loads, the initial 40% reduction in fan power generation) which results from reducing the fan
power input, is clearly demonstrated. For both
loads, the initial 40% reduction in fan power
input results in a small 1 K rise in SAT. Hence power input, is clearly demonstrated. For both input results in a small 1 K rise in SAT. Hence input results in a small 1 K rise in SAT. Hence
significant energy benefits can be gained,
initially, for small reductions in cooling poten-
tial. However, subsequent reductions in power significant energy benefits can be gained,
initially, for small reductions in cooling poten-
tial. However, subsequent reductions in power
input result in a steep rise in the approach coninitially, for small reductions in cooling potential. However, subsequent reductions in power
input result in a steep rise in the approach con-
dition and hance a significant decline in cooling tial. However, subsequent reductions in power input result in a steep rise in the approach con-Figure 8 expresses the relationship between
Figure 8 expresses the relationship between
a measured fan nower input and the test COP

Figure 7 shows the dependence of the SAT also comparable with the COP value of 11.4, on the cooling tower fan power for the series reported by the same author, for the optimized of 11 tests. The measured data points and th A availability in summer.

Tigure 8 expresses the relationship between

the measured fan power input and the test COP.

As shown in Table 3 the possible COP ranged Figure 8 expresses the relationship between
the measured fan power input and the test COP.
As shown in Table 3 the possible COP ranged
from 5.4 to 20.4. This range of values is compathe measured fan power input and the test COP.
As shown in Table 3 the possible COP ranged
from 5.4 to 20.4. This range of values is compa-As shown in Table 3 the possible COP ranged
from 5.4 to 20.4. This range of values is comparable with those reported by Hasan and Siren¹⁶
for closed wet towers for which a possible range from 5.4 to 20.4. This range of values is comparable with those reported by Hasan and Siren¹⁶ for closed wet towers for which a possible range of $3, 20$ was indicated. The results achieved are rable with those reported by Hasan and Siren¹⁶
for closed wet towers for which a possible range
of 3–20 was indicated. The results achieved are
also comparable with the COP value of 11.4 for closed wet towers for which a possible range
of 3–20 was indicated. The results achieved are of 3–20 was indicated. The results achieved are
also comparable with the COP value of 11.4,
reported by the same author, for the optimized
closed wet tower. For the 24 kW full load the also comparable with the COP value of 11.4,
reported by the same author, for the optimized
closed wet tower. For the 24 kW full load the
COP rises from a minimum of 7.5 at a SAT of reported by the same author, for the optimized
closed wet tower. For the 24 kW full load the
COP rises from a minimum of 7.5 at a SAT of
 $4.4 K$ to 20.4 at an approach of 9.4 K. This par closed wet tower. For the 24 kW full load the
COP rises from a minimum of 7.5 at a SAT of
4.4 K to 20.4 at an approach of 9.4 K. This per-
formance can be compared with the COP layels COP rises from a minimum of 7.5 at a SAT of 4.4 K to 20.4 at an approach of 9.4 K. This performance can be compared with the COP levels

power law regression of the secondary approach temperature on fan pow
power law regression lines and regression line equations are shown

Figure 8 Relationship between fan power input and COP for the law regression lines and regression line equations are shown

Expansion lines and regression line equations are show
which can be achieved with standard vapour
compression systems, which range from 2.8 for which can be achieved with standard vapour
compression systems, which range from 2.8 for
small air cooled screw machines to the very best which can be achieved with standard vapour
compression systems, which range from 2.8 for
small air cooled screw machines to the very best
values of 7.0 which are reported for large water compression systems, which range from 2.8 for
small air cooled screw machines to the very best
values of 7.0 which are reported for large water
cooled centrifugal machines, operating at full example are a small air cooled screw machines to the very best
values of 7.0 which are reported for large water
cooled centrifugal machines, operating at full
lood and producing chilled water at conventional values of 7.0 which are reported for large water
cooled centrifugal machines, operating at full
load and producing chilled water at conventional
temperatures of 5,8%C, as quoted in a review by cooled centrifugal machines, operating at full COP assessment, high levels of COP can still load and producing chilled water at conventional be achieved, particularly in the off-peak cooling temperatures of $5-8^{\circ}$ C, as Ioad and producing chilled water at conventional
temperatures of 5–8°C, as quoted in a review by
Davis *et al.*¹⁹ The COP figures quoted in this temperatures of $5-8^{\circ}$ C, as quoted in a review by
Davis *et al.*¹⁹ The COP figures quoted in this
review exclude power consumption outside of Davis *et al.*¹⁹ The COP figures quoted in this
review exclude power consumption outside of
the machine, such as in condenser water pumps Figure exclude power compared the machine, such as in c
and cooling tower fans. Example to the machine, such as in condenser water pumps
d cooling tower fans.
While some modern vapour compression to

and cooling tower fans.

While some modern vapour compression to

machines (particularly water cooled screw and contrifused) on display a significant improve While some modern vapour compression
machines (particularly water cooled screw and
centrifugal) can display a significant improvemachines (particularly water cooled screw and
centrifugal) can display a significant improve-
ment in energy efficiency, at part load, the 17
kW part load maximum COB of the avenerative entrifugal) can display a significant improve-
ment in energy efficiency, at part load, the 17
kW, part load, maximum COP of the evaporative
cooling process, at 16.2 is three times the initial ment in energy efficiency, at part load, the 17
kW, part load, maximum COP of the evaporative
cooling process, at 16.2 is three times the initial
 COP at 5.4 and is at loast twice the hest part EW, part load, maximum COP of the evaporative
cooling process, at 16.2 is three times the initial
COP at 5.4 and is at least twice the best part
load COP which can be schieved with current cooling process, at 16.2 is three times the initial
COP at 5.4 and is at least twice the best part
load COP, which can be achieved, with current COP at 5.4 and is at least twice the best part
load COP, which can be achieved, with current ta
vapour compression systems. The significantly complex for power inputs required under bigher. load COP, which can be achieved, with current
vapour compression systems. The significantly
smaller fan power inputs required under higher
annoach period load conditions makes possible vapour compression systems. The significantly
smaller fan power inputs required under higher
approach partial load conditions makes possible
the achievement of high levels of COP at lower the achievement of high levels of COP, at lower
the achievement of high levels of COP, at lower
loads in the nonsummar months, when invertor approach partial load conditions makes possible inverter to reduce the air volume flow rate and
the achievement of high levels of COP, at lower increase the approach temperature. In this way
loads in the nonsummer months, represent parameters in the fan is employed.
The achievement of high levels of COP, at lower
loads in the nonsummer months, when inverter
control of the fan is employed. The results measured are also comparable with the maximum such as this, COP levels will remain at their COP of $16.6¹$ achieved with wet bulb tempera- minimum value, all year and the cooling water control of the fan is employed. The results measured are also comparable with the maximum
COP of $16.6¹$ achieved with wet bulb temperatures below 19°C for supply air cooling using a temperature will rise and fall as it tracks the

wh
wh
combination of indirect air cooling followed by
direct adiabatic cooling in an air stream combination of indirect air cooling follows
direct adiabatic cooling in an air stream.
This analysis demonstrates even with mbination of indirect air cooling followed by
rect adiabatic cooling in an air stream.
This analysis demonstrates, even with the
clusion of the tower water nump power in the

direct adiabatic cooling in an air stream.
This analysis demonstrates, even with the
inclusion of the tower water pump power in the
COP assessment, high layels of COP can still This analysis demonstrates, even with the
inclusion of the tower water pump power in the
COP assessment, high levels of COP can still
be schieded perticularly in the off posk cooling inclusion of the tower water pump power in the
COP assessment, high levels of COP can still
be achieved, particularly in the off-peak cooling
sesson. This, is, significant, as low, approach COP assessment, high levels of COP can still be achieved, particularly in the off-peak cooling Frame Frame and Frame Frame Frame Frame Season. This is significant, as low approach
evaporative cooling requires a range temperature
approximately half that required for waterevaporative cooling requires a range temperature
approximately half that required for water-
cooled refrigeration condensers. Hence for simiapproximately half that required for water-
cooled refrigeration condensers. Hence for simi-
lar rates of heat rejection and system design,
tower water pumps in low approach evaporative cooled refrigeration condensers. Hence for similar rates of heat rejection and system design,
tower water pumps in low approach evaporative
cooling can be up to twice as large as those used
in condenser water cooling circuits tower water pumps in low approach e
cooling can be up to twice as large as
in condenser water cooling circuits. **5.2 Assessment of range of annual energy**

performance

In chilled ceilings normal practice is to maintain the supply water temperature approximately In chilled ceilings normal practice is to main-
tain the supply water temperature approximately
constant throughout the year. Hence, as ambient
WPT folls, the control strategy is to use the tain the supply water temperature approximately
constant throughout the year. Hence, as ambient
WBT falls, the control strategy is to use the
invertor to reduce the six volume flow rate and From the peak of probability constant throughout the year. Hence, as ambient
WBT falls, the control strategy is to use the
inverter to reduce the air volume flow rate and
increase the approach temperature. In this way WBT falls, the control strategy is to use the mere the contract strategy is to the the
inverter to reduce the air volume flow rate and
increase the approach temperature. In this way
a constant cooling water temperature is mainthe optimum COP and the optimum COP.

The optimum COP. Without a strategy,

a constant cooling water temperature is main-

tained at the optimum COP. Without a strategy, a constant cooling water temperature is main-
tained at the optimum COP. Without a strategy,
such as this, COP levels will remain at their tained at the optimum COP. Without a strategy, such as this. COP levels will remain at their

ambient condition. In this situation the space could be over-cooled and condensation could ambient condition. In this situation the space
could be over-cooled and condensation could
occur on the chilled ceiling. Knowing the annual
statistical frequency of occurrance of each WBT statistical frequency of occurrence of each WBT,
statistical frequency of occurrence of each WBT,
for each location⁸ it is possible to determine an occur on the chilled ceiling. Knowing the annual T
statistical frequency of occurrence of each WBT, b
for each location⁸ it is possible to determine an sample statistical frequency of occurrence of each WBT,
for each location⁸ it is possible to determine an
annualized COP, for a specific cooling water for each location⁸ it is possible to determine an
annualized COP, for a specific cooling water
temperature, and hence the range of the annual annualized COP, for a specific cooling water
temperature, and hence the range of the annual fe
energy performance can be assessed. Table 4 li temperature, and hence the range of the annual
energy performance can be assessed. Table 4
shows such an analysis for a 15° C supply water
temperature at a constant 17 kW cooling load energy performance can be assessed. Table 4 lin, a primary energy consumption of 9130 kWh shows such an analysis for a 15^oC supply water is required to reject a total of 121329 kWh. This temperature at a constant 17 kW over that portion of the year for which it is feastemperature at a constant 17 kW cooling load
over that portion of the year for which it is feas-
ible to generate this water temperature in Dublin.
The relationship between the fan power input Exercise that portion of the year for which it is feas-
a to generate this water temperature in Dublin.
The relationship between the fan power input
d the SAT can be established from the experi

Figure 1. The state of the SAT can be established from the experi-
and the SAT can be established from the experi-
mantal work, and bance the fan power required and the SAT can be established from the experimental work, and hence the fan power required C
at each SAT can be predicted. The primary pump w mental work, and hence the fan power required
at each SAT can be predicted. The primary pump
power input is constant at 0.65 kW. For example,
for the 17 kW load, the correlation between the at each SAT can be predicted. The primary pump
power input is constant at 0.65 kW. For example, s
for the 17 kW load, the correlation between the r power input is constant at 0.65 kW. For example, such as occurs in data processing centres. In
for the 17 kW load, the correlation between the most buildings, subject to seasonal and diurnal
SAT and the fan power input is power law regression equation (see Figure 7) as:

$$
T_{\rm sa} = 4.5131 \ W_{\rm f}^{-0.5352} \tag{2}
$$

known T_{sa} , the equation can be rearranged as:

$$
W_{\rm f} = 10^{-[(\log (T_{\rm sa}/4.5131))/0.5352]}
$$
 (3)

The relationship between the fan power input to reject 190776 kWh over 7949 hours; an effecand the SAT can be established from the experitive annual COP of 18.8. These effective annual mental work, and hence the fan power $T_{sa} = 4.5131 W_f^{-0.5352}$ (2) ment, therefore, is to define the range and limits
Alternatively, where W_f is required from a design cooling water temperature, when a vari-
known T_{sa} , the equation can be rearranged as: These correlations define the relationship These correlations define the relationship
between columns 5 and 6 of Table 4. The analy-
sis in Table 4 shows that in that portion of a These correlations define the relationship
between columns 5 and 6 of Table 4. The analy-
sis in Table 4 shows that, in that portion of a
full vear (7137 hours) for which it is statistically between columns 5 and 6 of Table 4. The analy-
sis in Table 4 shows that, in that portion of a
full year (7137 hours), for which it is statistically
feasible to generate 15% cooling water in Dub sis in Table 4 shows that, in that portion of a
full year (7137 hours), for which it is statistically
feasible to generate 15°C cooling water in Dub-
lin a primary energy consumption of 0130 kWh full year (7137 hours), for which it is statistically
feasible to generate 15° C cooling water in Dub-
lin, a primary energy consumption of 9130 kWh
is required to reject a total of 121320 kWh. This feasible to generate 15° C cooling water in Dublin, a primary energy consumption of 9130 kWh
is required to reject a total of 121329 kWh. This
results in an effective annual COP of 13.3. On \lim , a primary energy consumption of 9130 kWh results in an effective annual COP of 13.3. On results in an effective annual COP of 13.3. On
the same basis, cooling water generated at 18° C,
at a constant load of 24 kW requires 10138 kWh
to reject 190776 kWh over 7949 bours: an effecthe same basis, cooling water generated at 18° C,
at a constant load of 24 kW requires 10138 kWh
to reject 190776 kWh over 7949 hours; an effec-
tive annual COP of 18.8. These effective annual at a constant load of 24 kW requires 10138 kWh
to reject 190776 kWh over 7949 hours; an effec-
tive annual COP of 18.8. These effective annual
COPs would apply however only in a building COPs would apply, however, only in a building tive annual COP of 18.8. These effective annual
COPs would apply, however, only in a building
with a constant steady year round cooling load,
such as occurs in data processing centres. In COPs would apply, however, only in a building
with a constant steady year round cooling load,
such as occurs in data processing centres. In
most buildings, subject to seesonal and diurnal with a constant steady year round cooling load,
such as occurs in data processing centres. In
most buildings, subject to seasonal and diurnal
variations in load the annualized COB would be variations in data processing centres. In
most buildings, subject to seasonal and diurnal
variations in load the annualized COP would be
less than these values. The use of this assess most buildings, subject to seasonal and diurnal
variations in load the annualized COP would be
less than these values. The use of this assessvariations in load the annualized COP would be less than these values. The use of this assessment, therefore, is to define the range and limits
of the annual energy performance, at a particular
design cooling water temperature, when a veriment, therefore, is to define the range and limits
of the annual energy performance, at a particular
design cooling water temperature, when a vari-
able approach control strategy is employed able approach control strategy is employed.
design cooling water temperature, when a variable approach control strategy is employed.

Table 4 Computation of annual energy performance with variable SAT for a constant 15°C cooling water generation **Table 4** Computatio
and 17 kW load

and 17 kW load									
1	2	3	4	5	6	7	8	9	10
Ambient WBT (Dublin)	Number of annual hours \leq WBT	Number of annual hours at WBT range of WBT-0.5C	% annual hours \leq WBT	SAT required for 15° C cooling water	Tower fan power required at this SAT	Primary pump power required at this SAT	Total primary energy fan and pump	Cooling energy effect in this number hours	Effective COP in this number cooling hours
$(^{\circ}C)$	(hours)	(hours)	(%)	(K)	(kW)	(kW)	(kWh)	(kWh)	
≤ 7	3778	3778	43.1	8.0	0.34	0.65	3752	64226	17.1
7.5	4103	325	46.8	7.5	0.39	0.65	337	5525	16.4
8.0	4414	311	50.4	7.0	0.44	0.65	339	5287	15.6
8.5	4710	296	53.8	6.5	0.51	0.65	342	5032	14.7
9.0	5058	348	57.7	6.0	0.59	0.65	431	5916	13.7
9.5	5446	388	62.2	5.5	0.69	0.65	520	6596	12.7
10.0	5760	314	65.8	5.0	0.83	0.65	463	5338	11.5
10.5	6115	355	69.8	4.5	1.01	0.65	588	6035	10.3
11.0	6461	346	73.8	4.0	1.25	0.65	658	5882	8.9
11.5	6816	355	77.8	3.5	1.61	0.65	802	6035	7.5
12.0	7137	321	81.5	3.0	2.14	0.65 Total	897 9130	5457 121329	6.1
						Effective annual COP			

6 Conclusions
The results of experimental research into the **EXECUTE SERVIES CONCLUSIONS**
The results of experimental research into the
energy performance of cooling water generation
(at temperatures suitable for chilled cailing The results of experimental research into the
energy performance of cooling water generation
(at temperatures suitable for chilled ceiling
applications) in an indirect open cooling tower energy performance of cooling water generation
(at temperatures suitable for chilled ceiling
applications) in an indirect open cooling tower
test rig have been presented and discussed. The (at temperatures suitable for chilled ceiling
applications) in an indirect open cooling tower
test rig, have been presented and discussed. The applications) in an indirect open cooling tower
test rig, have been presented and discussed. The
research indicates that the energy performance
is significantly superior to that of modern vapour Fig. have been presented and discussed. The
research indicates that the energy performance
is significantly superior to that of modern vapour
compression plants in general and to air cooled research indicates that the energy performance
is significantly superior to that of modern vapour
compression plants in general and to air cooled
reciprocating plants in particular. The following is significantly superior to that of modern vapour
compression plants in general and to air cooled
reciprocating plants in particular. The following
specific conclusions can be drawn: compression plants in general and to air cooled reciprocating plants in particular. The following
specific conclusions can be drawn:
1) At a full load of 24 kW, as shown in Table
3 and with a SAT ranging from 4.4 to 4.8 K

- cific conclusions can be drawn:

At a full load of 24 kW, as shown in Table

3 and with a SAT ranging from 4.4 to 4.8 K,

3 COP ranging from 7.5 to 11.4 was achi At a full load of 24 kW, as shown in Table
3 and with a SAT ranging from 4.4 to 4.8 K,
a COP ranging from 7.5 to 11.4 was achi-3 and with a SAT ranging from 4.4 to 4.8 K,
a COP ranging from 7.5 to 11.4 was achieved, with primary circuit pump energy
included in the COP calculation. These COP a COP ranging from 7.5 to 11.4 was achi-
eved, with primary circuit pump energy
included in the COP calculation. These COP
values are above the very best values of 7.0 eved, with primary circuit pump energy
included in the COP calculation. These COP
values are above the very best values of 7.0
which are reported for large, vapour comincluded in the COP calculation. These COP
values are above the very best values of 7.0
which are reported for large, vapour com-
pression water cooled, centrifused machines present a shove the very best values of 7.0
which are reported for large, vapour com-
pression, water cooled, centrifugal machines which are reported for large, vapour com-
pression, water cooled, centrifugal machines
and are considerably better than the standard pression, water cooled, centrifugal machines
and are considerably better than the standard
reciprocating air cooled machine for which 5
 COP values in the order of 4.0 are typical and are considerably better than the standard
reciprocating air cooled machine for which
COP values in the order of 4.0 are typical. reciprocating air cooled machine for which
COP values in the order of 4.0 are typical.
At these approach conditions the total annual
availability of sooling, water, at 18% is COP values in the order of 4.0 are typical.
At these approach conditions the total annual availability of cooling water at 18° C is At these approach conditions the total annual
availability of cooling water at 18° C is
approximately 90% in Dublin and 83% in London. approximately 90% in Dublin and 83% in
London.
2) At a partial load of 17 kW and with a SAT
renging from 2.0 to 3.8 K, a COB renging
- London.
At a partial load of 17 kW and with a SAT
ranging from 2.9 to 3.8 K, a COP ranging
from 5.4 to 8.1 was achieved with primary At a partial load of 17 kW and with a SAT
ranging from 2.9 to 3.8 K, a COP ranging
from 5.4 to 8.1 was achieved, with primary
circuit pump aparay included in the COP cal. Example from 2.9 to 3.8 K, a COP ranging
from 5.4 to 8.1 was achieved, with primary
circuit pump energy included in the COP cal-From 5.4 to 8.1 was achieved, with primary
circuit pump energy included in the COP cal-
culation. Hence at very low approach and circuit pump energy included in the COP cal-
culation. Hence at very low approach and
partial load conditions the COP levels culation. Hence at very low approach and
partial load conditions the COP levels
approach the values reported for modern partial load conditions the COP levels
approach the values reported for modern
large high efficiency water cooled vapour primal approach the values reported for modern
large high efficiency water cooled vapour
compression plants. At these approach con-
ditions the total appual availability of cooling directly have the total annual availability of cooling
ditions the total annual availability of cooling
weter at 15% is approximately 80% in Dub compression plants. At these approach conditions the total annual availability of cooling water at 15° C is approximately 80% in Dub-
lin and 72% in London. ditions the total annual availability of cooling. water at 15 $^{\circ}$ C is approximately 80% in Dub-
lin and 72% in London.
3) When advantage is taken of a falling ambient
 WPT while concepting a constant tempore
- From and 72% in London.
When advantage is taken of a falling ambient
WBT, while generating a constant tempera-When advantage is taken of a falling ambient
WBT, while generating a constant tempera-
ture cooling water, considerable reductions WBT, while generating a constant tempera-
ture cooling water, considerable reductions
can be achieved in the annual energy con-
sumption. For a constant 18% cooling water ture cooling water, considerable reductions
can be achieved in the annual energy con-
sumption. For a constant 18° C cooling water can be achieved in the annual energy consumption. For a constant 18° C cooling water generation, in Dublin, at a steady load of 24 kW, the annualized (over the 7949 hours sumption. For a constant 18° C cooling water available) COP is 18.8 and for a constant

¹⁵°C cooling water generation, at a steady 15 \degree C cooling water generation, at a steady
load of 17 kW, the annualized (over the 7137
hours available). COP is 13.3. These values 15 \degree C cooling water generation, at a steady load of 17 kW, the annualized (over the 7137 hours available) COP is 13.3. These values indicate the limits of the process rather than load of 17 kW, the annualized (over the 7137)
hours available) COP is 13.3. These values
indicate the limits of the process, rather than
typical values, which could be achieved. To hours available) COP is 13.3. These values
indicate the limits of the process, rather than
typical values, which could be achieved. To indicate the limits of the process, rather than
typical values, which could be achieved. To
achieve high levels of annual COP therefore,
it is necessary to incorporate stapless control typical values, which could be achieved. To
achieve high levels of annual COP therefore,
it is necessary to incorporate stepless control
of the cooling tower fan speed, in a manner of the cooling to the cooling to the cooling tower fan speed, in a manner,
which automatically tracks the ambient it is necessary to incorporate stepless control
of the cooling tower fan speed, in a manner,
which automatically tracks the ambient of the cooling tower fan speed, in a manner,
which automatically tracks the ambient
enthalpy condition. Similar and interlocked
control of the primary water pump is also which automatically tracks the ambient
enthalpy condition. Similar and interlocked
control of the primary water pump is also
desirable. Eurther research is required to enthalpy condition. Similar and interlocked
control of the primary water pump is also
desirable. Further research is required to
develop a control optimization analysis of the example of the primary water pump is also
desirable. Further research is required to
develop a control optimization analysis of the
fan and primary pump energy usage Fan and primary pump energy usage.
fan and primary pump energy usage.
The COP schieved in this work are comdevelop a control optimization analysis of the
fan and primary pump energy usage.
4) The COP achieved in this work are compara-
ble with those reported recently in a comput

- fan and primary pump energy usage.
The COP achieved in this work are compara-
ble with those reported recently in a compu-
tational modelling study on closed wet tow The COP achieved in this work are compara-
ble with those reported recently in a compu-
tational modelling study on closed wet towble with those reported recently in a computational modelling study on closed wet tow-
ers, in this application. In this work possible
COP levels ranging from 3 to 20 were indi-Extractional modelling study on closed wet tow-
ers, in this application. In this work possible
COP levels ranging from 3 to 20 were indi-
cated, with a value of 11.4 for a closed tower ers, in this application. In this work possible
COP levels ranging from 3 to 20 were indicated, with a value of 11.4 for a closed tower
design optimized for energy efficiency COP levels ranging from 3 to 20 were indicated, with a value of 11.4 for a closed tower design, optimized for energy efficiency. cated, with a value of 11.4 for a closed tower
design, optimized for energy efficiency.
5) The high COP levels which can be achieved
in the off park cooling season implies that
- design, optimized for energy efficiency.
The high COP levels which can be achieved
in the off-peak cooling season implies that
the chilled ceiling supplied by evaporatively The high COP levels which can be achieved
in the off-peak cooling season implies that
the chilled ceiling, supplied by evaporatively in the off-peak cooling season implies that
the chilled ceiling, supplied by evaporatively
generated cooling water, is particularly suited to applications with long cooling seasons and stead cooling water, is particularly suited
to applications with long cooling seasons and
steady, sensible, internal, cooling loads. Such
load profiles increasingly occur in the current to applications with long cooling seasons and
steady, sensible, internal, cooling loads. Such
load profiles increasingly occur in the current exady, sensible, internal, cooling loads. Such
load profiles increasingly occur in the current
generation of commercial buildings, con-
structed with a high performance envelope load profiles increasingly occur in the current
generation of commercial buildings, con-
structed with a high performance envelope. generation of commercial buildings, constructed with a high performance envelope.
6) As the diurnal variation in WBT (typically 29 C in Dublin) is less than similar variations
- structed with a high performance envelope.
As the diurnal variation in WBT (typically 3° C in Dublin) is less than similar variations
in the embient DBT (typically 7° C in As the diurnal variation in WBT (typically 3° C in Dublin) is less than similar variations
in the ambient DBT (typically 7° C in
Dublin) the avenerative process produces a 3° C in Dublin) is less than similar variations
in the ambient DBT (typically 7° C in
Dublin), the evaporative process produces a in the ambient DBT (typically 7° C in
Dublin), the evaporative process produces a
significantly more stable diurnal cooling
weter temperature and hance is the proferred water temperature process produces a
significantly more stable diurnal cooling
water temperature and hence is the preferred
means of concreting sooling water for chilled examples of generative present presenting
significantly more stable diurnal cooling
water temperature and hence is the preferred
means of generating cooling water for chilled water temperature and hence is the preferred
means of generating cooling water for chilled means of generating cooling water for chilled
ceiling applications, even during those per-
iods when it is feasible to use dry air coolers. Figure 2012 and the research results are based on
The while the research results are based on
The research results are based on
Nuncrimontal management the test rig base
- iods when it is feasible to use dry air coolers.
While the research results are based on
experimental measurement the test rig has
been constructed to a semi-industrial scale. 7) While the research results are based on Experimental measurement the test rig has
been constructed to a semi-industrial scale,
using currently available cooling tower, heat experimental inclustment and test right
been constructed to a semi-industrial scale,
using currently available cooling tower, heat
exchanger and energy efficient control technology. A building cooling tower, heat
exchanger and energy efficient control tech-
nology. A building cooling system, therefore, exchanger and energy efficient control technology. A building cooling system, therefore, constructed along similar lines and based on the design conditions incorporated in the rig,

could be expected to achieve similar could be expected to achieve similar
results—a minimum secondary approach
condition of $3K$ and COP layels ranging could be expected to achieve similar
results—a minimum secondary approach
condition of 3 K and COP levels ranging
from 6 to 12 depending on percentage load results—a minimum secondary approach
condition of 3 K and COP levels ranging
from 6 to 12, depending on percentage load
and ambient WBT condition of 3 K and COP levels ranging
from 6 to 12, depending on percentage load
and ambient WBT

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of the laboratory staff of the Department of also donated equipment and their generous sup-
port is gratefully acknowledged, as is the support
of the laboratory staff of the Department of
Building Services Engineering DIT From is gratefully acknowledged, as is the
of the laboratory staff of the Depar
Building Services Engineering, DIT.

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