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Ben Costelloe
Technological University Dublin, ben.costelloe@tudublin.ie

Donal Finn
University College Dublin, donal.finn@ucd.ie

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Evaporative Cooling Availability in Water Based Sensible Cooling Systems

Ben Costelloe, *Lecturer, Faculty of Engineering, Dublin Institute of Technology, Bolton Street, Dublin 1, Ireland.*
Donal Finn, *Lecturer, Department of Mechanical Engineering, University College Dublin, Belfield, Dublin 4, Ireland.*

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ABSTRACT

Recent developments have prompted a review of evaporative cooling technology as an effective means of cooling modern deep plan buildings. Prominent among these developments is the success of high temperature sensible cooling systems, such as chilled ceilings, which require a supply of cooling water at 14 to 18°C. Crucial to the success of evaporative cooling technology, as a significant means of cooling in modern applications, is the ability to generate cooling water, in an indirect circuit, at a temperature which closely approaches the ambient adiabatic saturation temperature or wet bulb temperature. Recent research in this area has shown that it is feasible to generate such cooling water at a temperature of 3 K above the ambient adiabatic saturation temperature.

While the frequency of ambient adiabatic saturation temperature occurrence can be obtained from meteorological sources, there is little published data and analysis on the potential for this form of cooling water generation, based on the approach temperatures which are now known to be feasible. This paper quantifies cooling availability for two European cities, Dublin and Milan and suggests a method of analysing such data for any world wide location for which suitable meteorological records are available. The paper, which is part of an ongoing research programme devoted to evaporative cooling, incorporates recent experimental research findings and bases the availability analysis on meteorological test reference weather year data, which has been published for 29 European locations.

The results of this research confirm a major potential for the generation of cooling water by evaporative means, which can be used to provide effective cooling of modern deep plan buildings by means of contemporary water based sensible cooling systems, such as chilled ceiling panels and beams. While the technique offers most potential in locations with a Northern European temperate climate, it seems to have a significant potential to contribute to cooling in Southern European cities, during the non-Summer months and also at other times, particularly where load shaving and night time cooling and pre-cooling techniques are incorporated.

1. INTRODUCTION

Air conditioning systems which combine the latent and sensible cooling functions in a single system require chilled water at low temperatures typically 5 to 8°C to produce dehumidification on the cooling coils. These systems generally rely on vapour compression refrigeration to generate the required chilled water temperatures. Many air conditioning systems, however, separate the sensible and latent cooling requirements into a central primary air system, which typically caters for ventilation and dehumidification, and a local secondary cooling system which deals with room sensible loads. Such systems typically include the perimeter induction system, the dry mode fan coil system and the modern chilled ceiling panel and beam system. These systems require two supplies of chilled water; one at the conventional temperatures of 5 to 8°C for primary air cooling and a second supply at a higher temperature, close to the room air dew point, for local sensible cooling. At present these systems generally use conventional vapour compression refrigeration to generate all cooling water at temperatures suitable for primary air dehumidification and subsequently raise the water temperature to the required secondary temperature by means of a mixing arrangement or heat exchanger. The possibility of generating the primary air cooling medium in a separate, possibly direct expansion, refrigeration system with a larger alternative, high temperature, cooling system for the secondary circuit is generally not considered in practice (ASHRAE 1996).

The temperatures required for the secondary cooling water circuit depend on the system employed. For example, dry mode fan coil units require a supply at 10 to 14°C while chilled ceiling panels and beams require water at 14 to 18°C (CIBSE 1998). The sensible cooling output of these systems is reduced as the cooling water temperature rises, however this reduction can be compensated for by increasing the area of the heat transfer surface. The radiant cooling provided by the chilled ceiling, however, allows higher room temperatures to be used, while still maintaining comfort conditions. This, in turn, allows higher cooling water temperatures to be used. A recent CIBSE research report (CIBSE 1998) concluded that office buildings with relatively high internal heat gains of $60W/m^2$ and served by chilled ceiling panels and beams could maintain reasonable thermal comfort conditions (a dry resultant temperature of 25.2°C and a predicted mean vote of 0.8) with a cooling water supply temperature of 18°C. A newly developed induction chilled beam can operate successfully with a water supply of 18°C provided sufficient active cooling surface can be incorporated in the ceiling. A temperature of 18°C seems to be the maximum cooling water temperature which can be used, although this largely depends on the comfort criteria considered acceptable in each project. A recent research paper states that chilled ceiling panels can operate with a supply water temperature as high as 18 to 20°C (Gan et al. 2000).

These elevated secondary chilled water temperatures raise the possibility of generating the required cooling in cooling towers. Hence the view has developed that tower based evaporative cooling ought now to be the subject of major review as a practical and low energy means of cooling modern buildings (De Saulles,1996). The changing nature of the cooling load in many modern deep plan office buildings has also helped to reinforce this view. As a result of the deep plan layout, better fabric insulation, lower glazing levels and more successful use of solar shading the cooling load in the modern office building is now often dominated by the internally generated sensible load (De Saulles,1996). The internally generated sensible load is derived from high occupancy levels, lighting, IT equipment, other small power loads and is present throughout the year. Hence, the cooling season in such buildings is not confined to the Summer months, but extends into periods of the year with good evaporative cooling availability due to the lower ambient wet bulb temperatures experienced.

At present, however there is little in depth research and analysis of the performance, energy efficiency and year round availability of this alternative form of cooling especially in temperate climates. To address these issues an experimental research programme has been established with a view to demonstrating the potential and optimising the design of this form of cooling in modern deep plan buildings. This programme is based on a prototype evaporative cooling rig, optimised for close approach conditions and incorporating an indirect heat rejection circuit. This research programme has been described previously (Costelloe, Finn 2000). A key issue in this research is the detailed evaluation of the extent of cooling availability which can be expected for various locations, types of cooling system, and for a range of cooling water supply temperatures. This paper quantifies cooling availability for two European sites, Dublin and Milan, and suggests a method of analysing such data for any world wide location for which suitable meteorological records are available.

2. EXPERIMENTAL PROGRAMME

Crucial to the success of evaporative cooling technology as a significant means of cooling in modern deep plan buildings is the ability to generate cooling water in an indirect secondary circuit at a temperature which closely approaches the ambient adiabatic saturation temperature (AST) or wet bulb temperature (WBT). Recent research in this area (Costelloe, Finn 2000) has shown that it is possible to design an indirect heat rejection system, based on close approach principles and utilising high contact area plate heat exchangers in conjunction with enhanced evaporative heat transfer in open, counter flow, cooling towers, which is capable of generating secondary cooling water at a temperature of 3 K above the ambient adiabatic saturation temperature. This is considerably less than the 4.5 K minimum secondary approach temperature (SAT) previously considered feasible (CIBSE 1998). A summary of some typical experimental test results is shown in Table 1. Figure 1 shows the results of a recent typical daily test. Table 1 confirms a primary approach temperature of approximately 1.5 K and a secondary approach temperature of approximately 3 K for a 20 kW heat rejection load. Figure 1 and Table 1 show how the secondary flow temperature tracks the ambient adiabatic saturation temperature, rather than the more widely fluctuating ambient dry bulb temperature. This research confirms that open cooling towers, incorporating modern packing designs, in conjunction with an enhanced surface area and operating under close approach conditions perform, in this respect, in a manner similar to conventional wide approach towers, for which the dependence of the exiting water temperature on the ambient adiabatic saturation temperature or wet bulb temperature is well established (ASHRAE 1996).

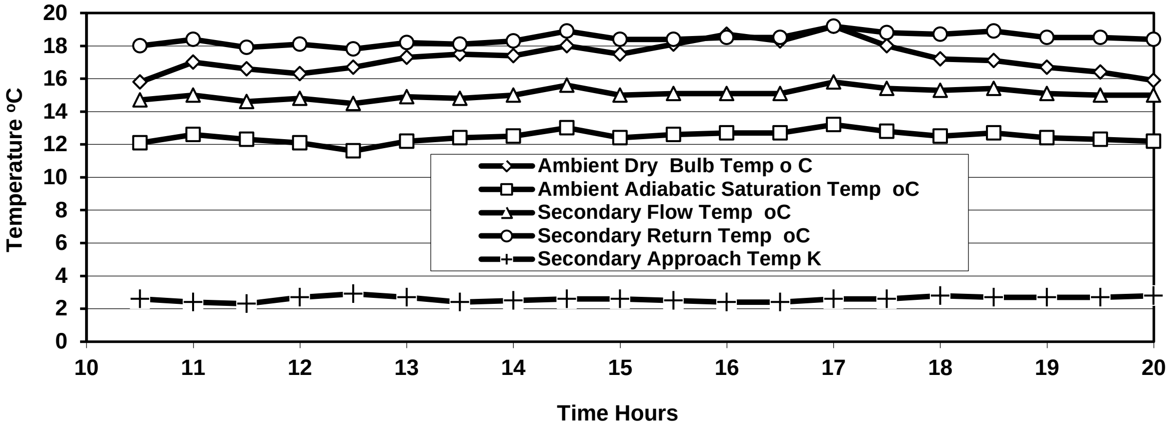

Figure 1. Results of Experimental Test on Prototype Cooling Tower Test Rig, for 6th September 2000 (Dublin).

Table 1. Summary of Experimental Test Results from Prototype Cooling Tower Test Rig (Dublin).

Load	AST	Primary Flow Temp. From Tower	Secondary Flow Temp. From Heat Exchanger	Primary Approach to AST	Secondary Approach to AST
kW	°C	°C	°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	**12.5**	**13.5**	**15.1**	**1.0**	**2.6**
20	**16.5**	**17.4**	**19.0**	**0.9**	**2.5**
19	**8.4**	**9.8**	**11.3**	**1.4**	**2.9**
19	**9.2**	**10.6**	**12.1**	**1.4**	**2.9**
19	**10.2**	**11.3**	**12.9**	**1.1**	**2.7**
15	8.7	9.7	10.9	1	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	2.2

In order to quantify the evaporative cooling availability which can be expected for any given location it is therefore necessary to establish the typical yearly record pattern of the ambient adiabatic saturation temperature. This can be achieved by using, either a meteorological test reference weather year or alternatively, where such is available, an hourly record of ambient wet bulb temperatures over a standard 30 year period. The test reference year (TRY) method has been used in this analysis as it is now readily available in software format for a wide range of world wide locations.

A test reference year consists of a data base record of hourly weather data for 12 typical months forming a composite year. Each month is chosen on the basis of its statistical typicality. The data is intended for use in computer programmes concerned with energy load and local climate analysis. A total of 29 European TRYs have been developed for the locations shown in Appendix 1. The data is applicable to these locations and for a limited area around these locations. The hourly weather records include data on dry bulb temperature, relative humidity, wind speed and solar radiation. A sample of data from a TRY is shown in Appendix 1. By using the dry bulb temperature and relative humidity listed in the original TRY a new TRY has been developed which lists a range of standard psychrometric properties. These have been determined from the fundamental psychrometric equations involved (ASHRAE 1997) and include the atmospheric pressure corrected for height above mean sea level (67m for Dublin and 122m for Milan). The determination of the AST required an iteration of the fundamental equations in a separate software routine. A sample of data from the new TRY developed is also shown in Appendix 1. The difference between the AST and WBT is generally less than 0.25 K for dry bulb temperatures above 0°C and where the wet bulb depression is less than 11 K (Mc Quiston, Parker 1982). Hence for the purpose of this analysis the WBT can be considered equal to the AST without significant error. The AST is used in this analysis as it is a fundamental property of the air which, unlike the WBT, can be determined without recourse to empirical constants.

3. AVAILABILITY ANALYSIS

3.1 Evaporative cooling potential

Having established the new psychrometric test reference year for the site the data can now be analysed to determine the evaporative cooling potential. In the first instance the availability of the ambient adiabatic saturation temperature is calculated and then, using a 3 K secondary approach temperature the potential for cooling water generation is determined. This potential can then be analysed in detail in terms of cooling water availability, average monthly cooling water temperatures, variation in potential with length and time of the working day, and assessment of the penalty imposed by the indirect system in terms of the diminished cooling availability which results.

Figure 2 shows the % occurrence of the adiabatic saturation temperature for Dublin and Milan based on the hourly measurement of the ambient condition as contained in the test reference year data. Also shown is the % occurrence of the hourly wet bulb temperature for Dublin based on a thirty year period (1966-1995). The results show that the adiabatic saturation temperature of 13°C (required to supply cooling water at 16°C to chilled ceiling panels) is statistically available for 57.3% of the year in Milan, 88% of the year in Dublin on an AST test reference year basis and 87.7% of the year in Dublin on a 30 year wet bulb occurrence basis. There is a very close correlation between the AST and WBT occurrence results for Dublin. The percentage annual occurrence is calculated on a 24 hour day basis and is defined as the percentage of the total annual hours (8760 hours) during which, a temperature at and below a particular temperature, occurs.

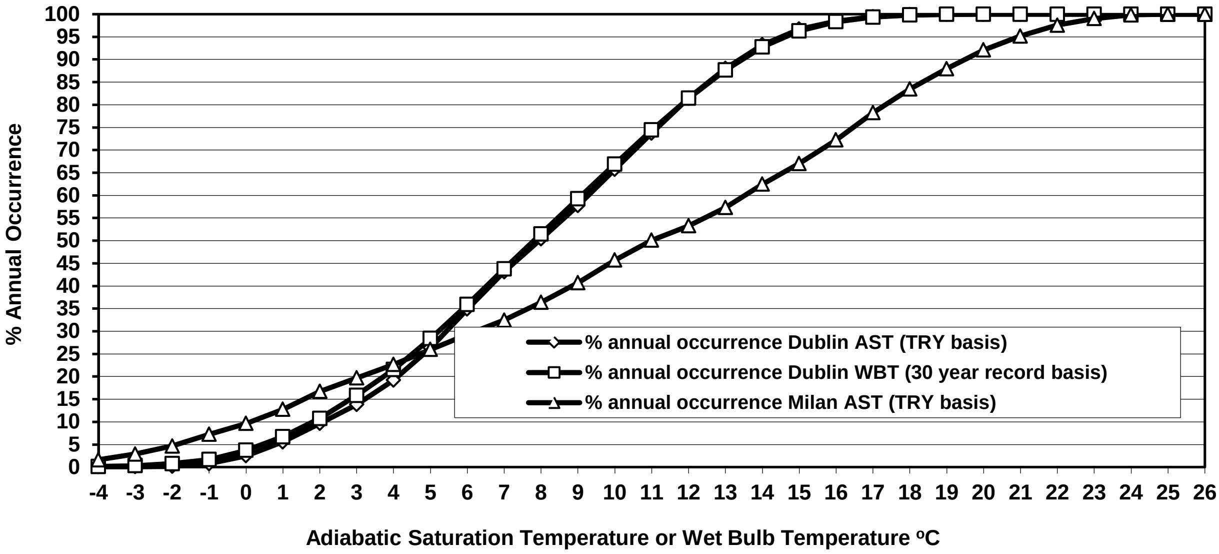

Figure 2 Percentage Annual Occurrence of AST in Milan and AST with WBT in Dublin

Availability of chilled water at any given temperature is significantly increased by reducing the secondary approach temperature. Figures 3 and 4 show the impact on availability of reducing the secondary approach temperature from a more conventional 8K to 3K. Availability of chilled water at 16°C increases from 36.4 % in Milan at 8K secondary approach temperature to 57.3% at 3K, while in Dublin at the same conditions availability increases from 50.4% to 88%. The benefits which can be obtained by reducing the secondary approach temperature are greatest at low cooling water temperatures, in Dublin, however, as the cooling water temperature rises the benefit diminishes, particularly at low secondary approach temperatures. The relationship between the secondary approach temperature and the % availability is approximately linear at all chilled water temperatures above 4°C for Milan, whereas such a relationship holds only between 11 and 15°C for Dublin.
The % annual availability is defined as:

$$A = [100\sum(H_{tas})]/8760 \qquad (1)$$

where

A = % annual availability

$\sum(H_{tas})$ = the statistically typical (on a test reference year basis) total number of annual hours, during which, the ambient adiabatic saturation temperature is less than or equal to (T_{sf} - T_{sa})

T_{sf} = the secondary flow temperature °C

T_{sa} = the secondary approach temperature K

8760 = number of hours in a year.

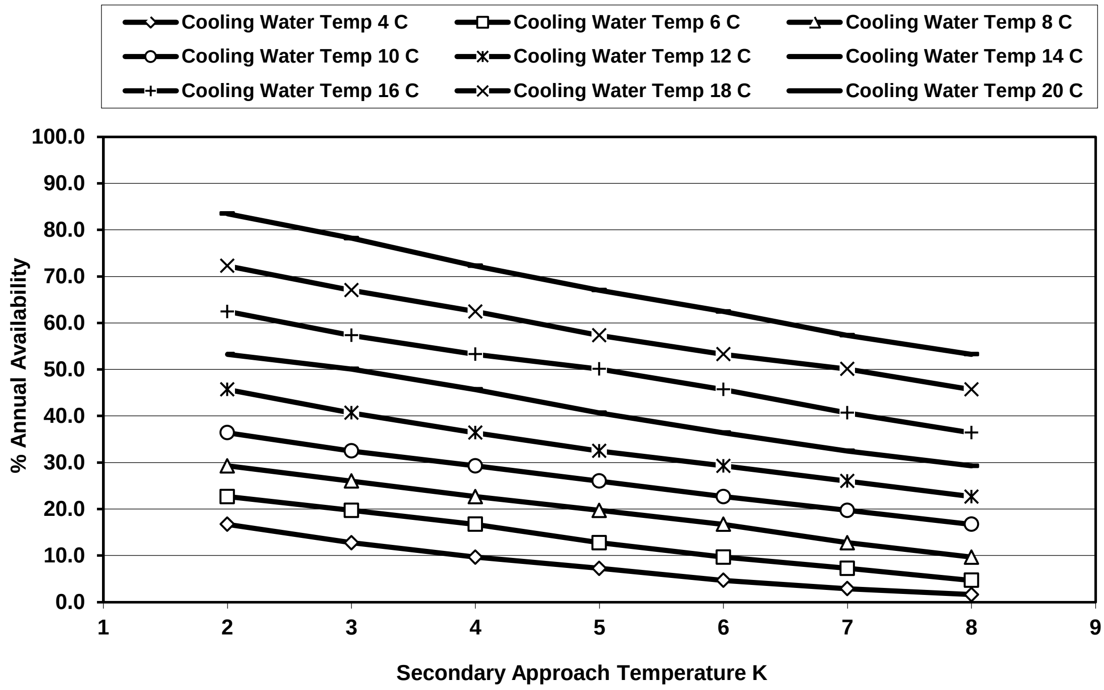

Figure 3. Impact of Secondary Approach Temperature on % Annual Availability of Cooling Water in Milan.

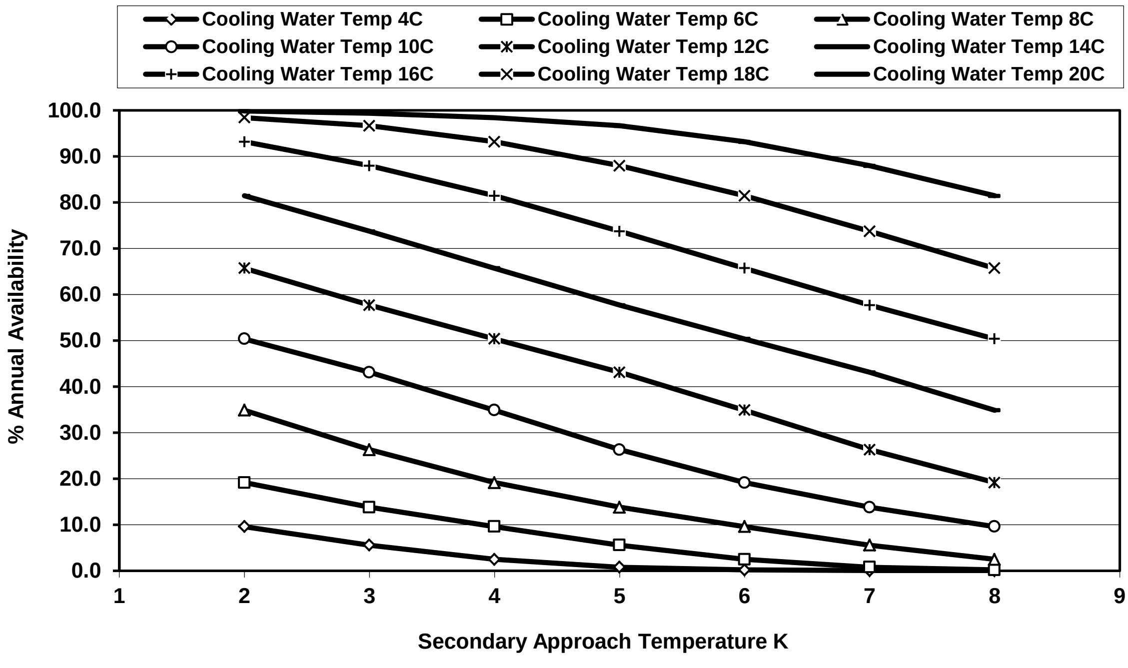

Figure 4. Impact of Secondary Approach Temperature on % Annual Availability of Cooling Water in Dublin.

3.2 Annual Distribution of Cooling Potential

Having established the overall yearly % availability the question now arises as to how this availability is distributed over a typical year. In order to quantify this aspect the average hourly cooling water temperature possible for each month has been calculated by applying a 3K secondary approach temperature to the hourly adiabatic saturation temperature and obtaining the monthly arithmetic average for each of the 24 hours. This results in a 24 hour pattern of cooling water availability for each of the 12 months. These graphs, which are shown for Dublin and Milan in Figures 5,6,7 and 8, show the typical diurnal swing in possible cooling water temperature, throughout the year. On the basis of this analysis the ranges of cooling water temperatures which can be achieved, through out the year, have been divided into 5 groups as shown in Table 2. The range shown is the approximate range which can be achieved with a secondary approach temperature of 3K over the 24 hour period, with, generally, the minimum of the range occurring at dawn and maximum in the afternoon.

Table 2. Ranges of Cooling Water Temperatures Achievable Throughout the Year

Cooling Water Temperature Range Achievable °C	Dublin	Milan
2 to 8	December	December, January, February
7 to 11	January, February, March April, November	March, November
11 to 15	May, June, September, October	April
14 to 18	July, August	May, October
18 to 23		June, July, August, September

Given the typical range of 2 to 4K in the cooling water temperature which it is possible to generate over the 24 hour day it is useful to examine the variation in the average temperature which can be achieved with days of different length and range period. This is also of interest in view of the current trend to enhance the cooling storage capacity of buildings by extracting heat from the building fabric and contents during unoccupied periods. Figures 9 and 10 show the variation in the average monthly cooling water temperature, which it is possible to generate with four different periods of building occupation. In the case of Dublin and Milan there is no significant difference between the average cooling water temperature of the 8 am to 6 pm day and the 8 am to 12 pm day throughout the year. In the Winter months of December January and February the average temperatures of all 4 day types do not differ by much more than 1 K for both locations. In Dublin the maximum average variation in the year is 2 K and occurs in September. In Milan the maximum average variation is 2.8 K and occurs in April and May.

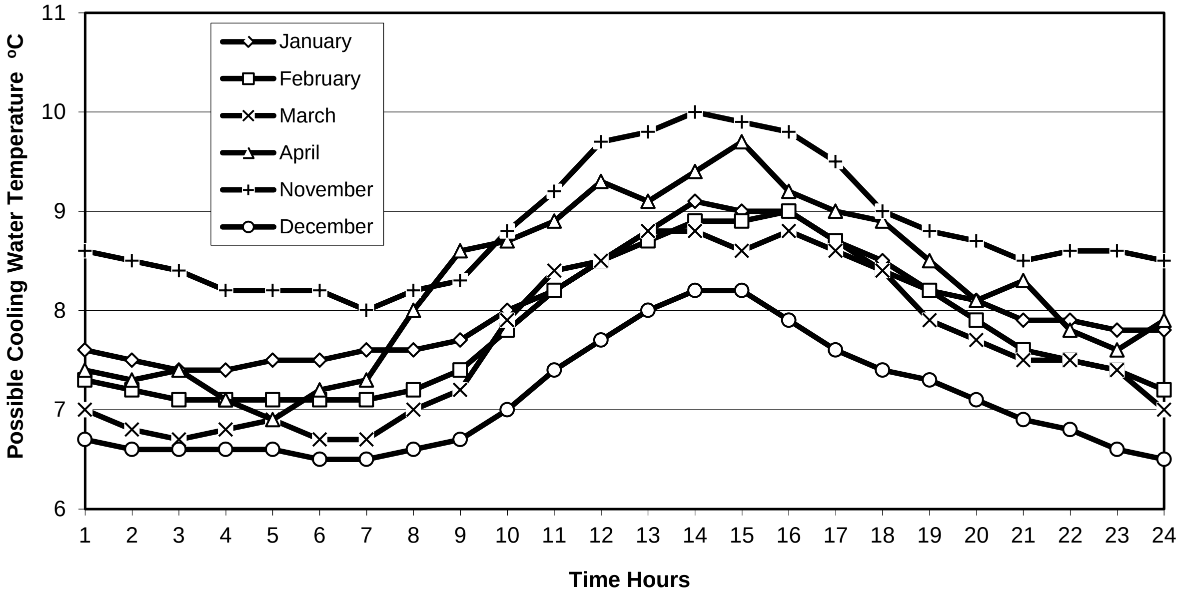

Figure 5. Cooling Water Temperature Possible from November to April at 3 K SAT in Dublin (based on the hourly average AST derived from the TRY data)

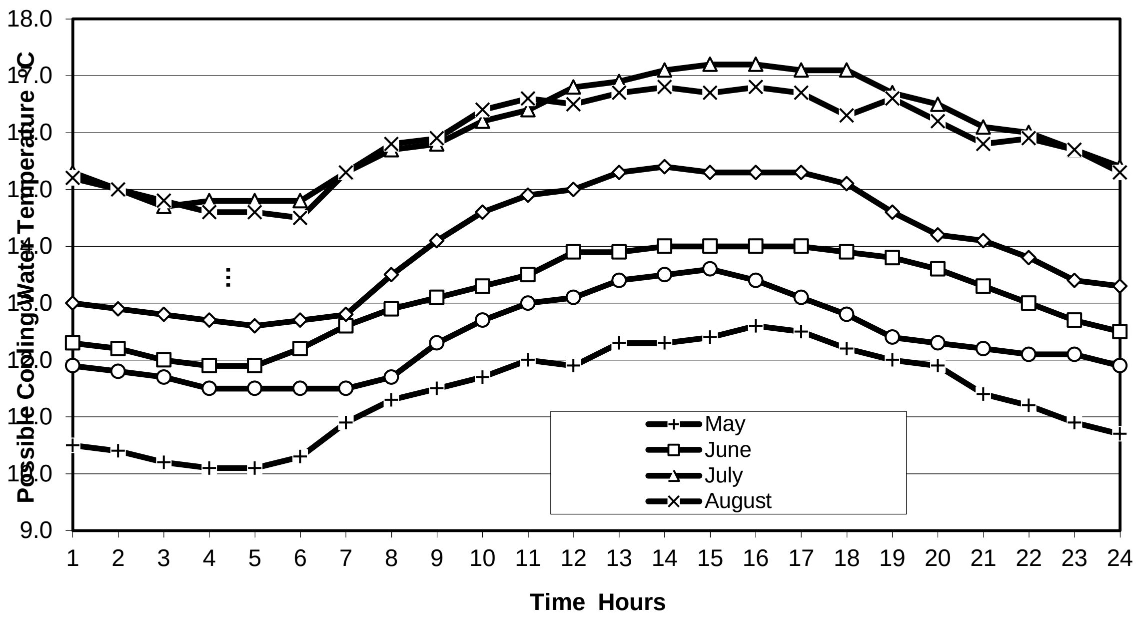

Figure 6 Cooling Water Temperature Possible from May to October at 3K SAT in Dublin (based on the hourly average AST derived from the TRY data).

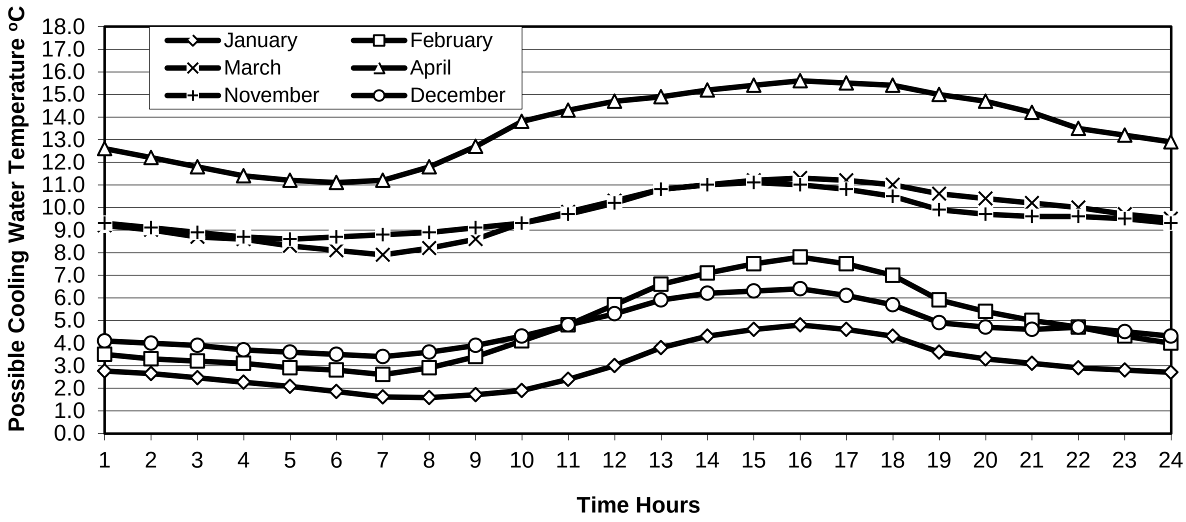

Figure 7. Cooling Water Temperature Possible from November to April at 3 K SAT in Milan (based on the hourly average AST derived from the TRY data).

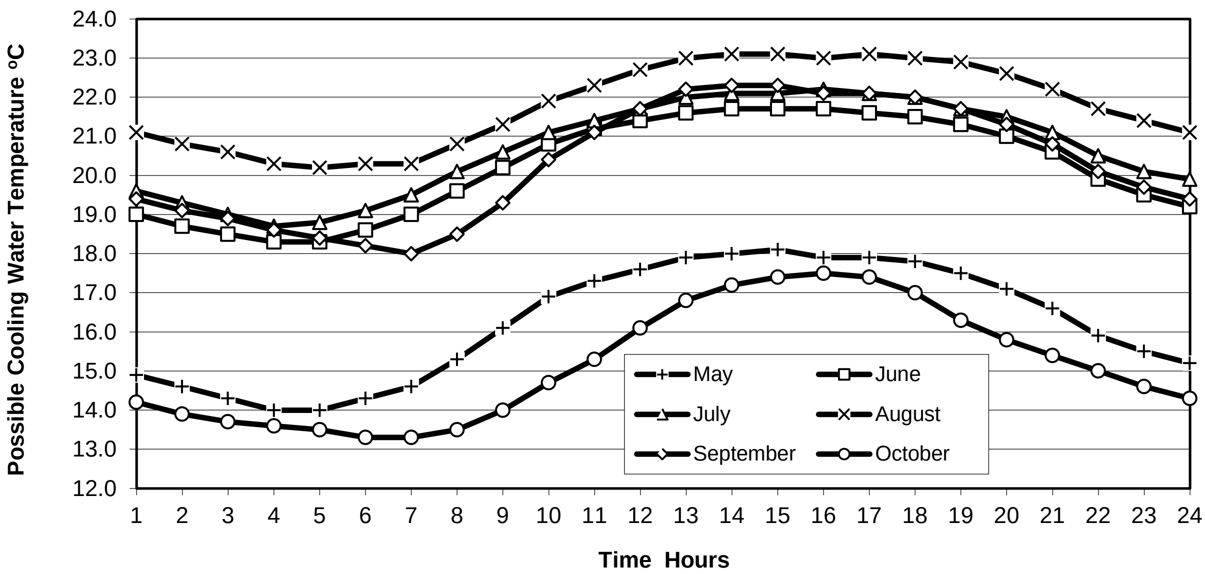

Figure 8. Cooling Water Temperature Possible from May to October at 3 K SAT in Milan (based on the hourly average AST derived from the TRY data).

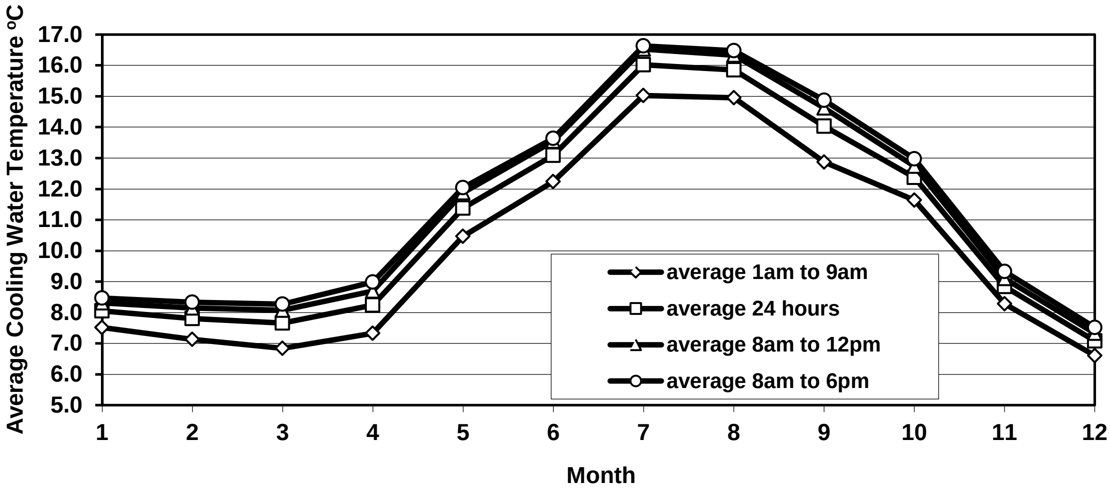

Figure 9. Variation in Average Monthly Cooling Water Temperature with Length and Time of Cooling Day for Dublin.

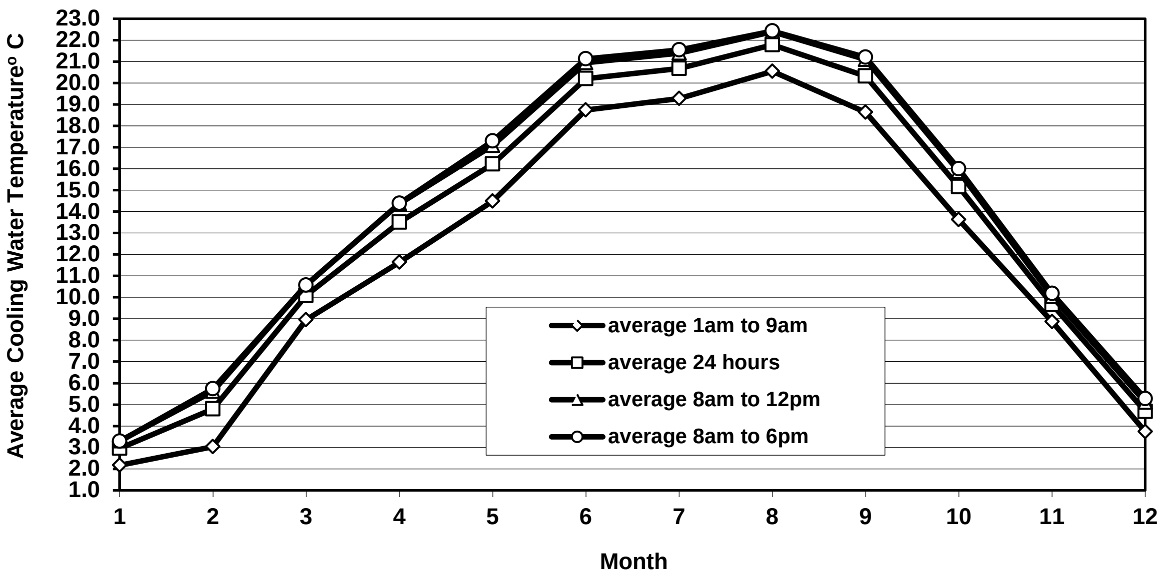

Figure 10. Variation in Average Monthly Cooling Water Temperature with Length and Time of Cooling Day for Milan

4. DISCUSSION OF RESULTS

In general the results show an extensive potential for cooling water generation by evaporative means, in the case of Dublin and a less extensive but significant potential in the case of Milan. The assessment of this potential for individual projects clearly depends on the yearly and daily pattern of the cooling load and on the maximum secondary cooling water temperature for which the cooling system has been designed. Table 3 shows the percentage cooling availability on a 24 hour day basis for two types of sensible cooling system.

Table 3. Percentage Cooling Availability for Two Types of Sensible Cooling System (24hour basis)

Sensible Cooling System	Design Secondary Cooling Water Temperature °C	Dublin % Cooling Availability at 3K SAT	Milan % Cooling Availability at 3K SAT
Dry Mode Fan Coil Units	10	43.1	32.5
	12	57.7	40.7
	14	73.8	50.1
Chilled Ceiling Panels and Beams	14	73.8	50.1
	15	81.5	53.3
	16	88.0	57.3
	17	93.2	62,5
	18	96.7	67.0
	19	98.4	72.2
	20	99.4	78.2
	21	99.9	83.5
	22	100	88.0

On the basis of the CIBSE finding (CIBSE 1998) that 18°C chilled water can, if cooling loads are suitable, be successfully used in panels and beams, the maximum annual availability is at least 96% in Dublin and 67% in Milan. As chilled ceiling panels and beams usually operate with a 2 to 3 K temperature difference between flow and return, the cooling tower can contribute to return water cooling on those occasions when it is unable to produce a supply water temperature of 18°C , a technique known as load shaving (De Saulles 1996). If, for example, a cooling water temperature of 16°C is sought at a time when the ambient adiabatic saturation temperature is 14°C this is not possible with a design based on a 3 K secondary approach temperature. However, it is possible to cool the return water from 19°C to 17°C in the tower and subsequently to 16°C by means of the refrigeration system. This increases the availability of the tower for partial cooling of the load from 88% to 93.2% for Dublin and from 57.3% to 62.5% for Milan. In fact for Dublin, the load shaving technique can always (99.4% of the year) contribute to the production of cooling water at 18°C, when the return water temperature is 21°C or less. For Milan the technique can contribute to 18°C cooling up to an ambient adiabatic saturation temperature of 17°C which implies approximately 80% availability for full or partial cooling. This is significant as it implies, with reference to Figure

8, that the tower can contribute to cooling at night from 10 pm to 8 am during the months of June, July and September.

The diurnal variation in the Summer ambient adiabatic saturation temperature is 2 to 3 K for Dublin and 3 to 4 K for Milan. Hence on occasions considerably lower chilled water temperature can be produced at night than at midday, which will enable night time cooling of the building fabric and contents to be achieved. Cooling water temperatures are however limited by the necessity to avoid condensation on the panels or beams by limiting the temperature difference between room air dew point and cooling water flow temperature to 2 K at most (CIBSE 1998). The fall in cooling system capacity during the day by the inability of the tower to maintain the chilled water set point is offset by the increased cooling storage provided by night time cooling. Hence the day time rise in room thermal conditions is damped. Further research is, however, required on this aspect in order to determine the room comfort index which results from such conditions. However, the radiant cooling produced by the chilled ceiling panel, is particularly suited to this arrangement as it is inherently a slow response system having a high degree of self regulation.

5. CONCLUSIONS

The results of a detailed meteorological analysis of evaporative cooling availability for two European cities, Dublin and Milan, have been presented and discussed. The results confirm a major potential for the generation of cooling water by evaporative means, which can be used to provide effective cooling of modern deep plan buildings by means of contemporary water based sensible cooling systems, such as chilled ceiling panels and beams. While the technique offers most potential in locations with a Northern European temperate climate it has a significant potential to contribute to cooling in Southern European cities during the non-Summer months and also at other times by means of load shaving and night cooling. In order to take maximum advantage of the technique the building needs to be designed to minimise solar gain and to separate the latent and sensible cooling functions. The technique is particularly suited to large deep plan buildings with stable load patterns and long cooling seasons.

The following specific conclusions can be drawn:

1. The AST determined from the meteorological TRY is a suitable means of assessing evaporative cooling availability and gives similar results to an analysis based on a record of wet bulb occurrence.
2. The SAT has a major impact on the percentage availability at all cooling water temperatures in both locations but particularly between 10 and 16°C in Dublin.
3. The potential for this form of evaporative cooling is greatest in buildings which have been designed to operate at the high cooling water temperatures of 16 to 18°C, which incorporate load shaving and, or, night time pre-cooling arrangements. Cooling water can be generated at 18°C, for chilled ceiling panels and beams, for 97% of the year in Dublin. A similar temperature can be generated in Milan for 67% of the year during the months of October through May. During the months of June, July and September in Milan there is also some potential for night time load shaving.
4. Dry mode fan coil units designed to operate with 14°C cooling water can be supplied from October through June in Dublin and from November through March in Milan. In Dublin this implies that buildings, such as educational institutes which are lightly

occupied during July, August and September may be successfully sensibly cooled throughout the year, without the use of refrigeration cooling, if they are designed to operate with 14°C cooling water.

5. The penalty of diminished cooling availability associated with the indirect system depends on the slope of the % occurrence curve for each location. As the introduction of the heat exchanger adds approximately 1.5°C to the flow temperature the resulting reduction in availability is less in Milan than in Dublin.
6. As the maximum secondary chilled water temperature is 18°C cooling tower primary water will not exceed 20 °C when operating. Hence the possibilities for the growth of legionella are minimal compared with conventional condenser water cooling towers in which water temperatures are normally in the higher growth range of 27 to 33°C. 37°C is the optimum temperature for growth of the bacterium (CIBSE 1991).
7. This paper presents an analysis of two European test reference years. Another 27 data bases are available for European locations (see Appendix 1) for which a similar analysis is required to develop the knowledge of the potential of this alternative form of cooling in the European context.

6. ACKNOWLEDGEMENTS

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REFERENCES

ASHRAE, 1996. *HVAC Systems and equipment handbook.* ASHRAE, Atlanta, GA.

ASHRAE, 1997. *Fundamentals handbook.* ASHRAE, Atlanta, GA.

CIBSE, 1998. *Chilled ceilings and beams, research report RR5.* CIBSE, London.

CIBSE,1991. *Minimising the risk of Legionaires' disease TM13*. CIBSE, London.

Costelloe, B. Finn, D. 2000. The design and performance of an evaporative cooling test rig for a maritime climate. *Proceedings of joint CIBSE/ASHRAE conference, Dublin* September 2000. pp. 830-845.

De Saulles, T. 1996. *Free cooling systems.* p37. BSRIA, Bracknell, UK.

Gan, G. Riffat, S.B. Shao, L. 2000. Performance prediction of a prototype closed wet cooling tower. *Journal of the Institute of Energy*. Vol. 73, No 495 (June), pp. 106-113.

Mc Quiston, F.C. Parker, J.D. 1982. *Heating, ventilating and air conditioning.* p18. Wiley, New York.

APPENDIX 1

Table 1. Locations for which European Test Reference Years have been completed.

Country	Location	Country	Location	Country	Location
U.K.	Aberporth	Belgium	Ooostende	Italy	Bolzano
	Eskdalemuir		Saint-Hubert		Cagliari
	London Kew		Uccle		Crotone
	Lerwick	Netherlands	De Bilt		Amandola-Foggia
France	Carpentras		Eelde		Genova
	Limoges		Vlissingen		**Milano**
	Macon	Denmark	Copenhagen		Monte Terminillo
	Nancy	Ireland	**Dublin**		Roma Ciampino
	Nice		Valentia		Trapani
	Trappes				Venezia

Table 2. Extract from Meteorological Test Reference Year for Dublin.

A	B	C	D	E	F	G	H	I	K	L	M	N
Station	Time	DBT x 10	Global	Diffuse	Direct	Sunshine	Relative	Wind	Year	Month	Day	Hour
Dub Airprt	GMT	Celsius	Radiation	Radiation	Radiation	duration	Humidity	Speed	based			
			J/cm^2	J/cm^2	J/cm^2	minutes	%	x10 m/s	on			
DUB	T	178	128	105	31	48	73	36	79	7	4	10
DUB	T	188	172	139	41	48	66	31	79	7	4	11
DUB	T	192	205	135	82	36	64	21	79	7	4	12
DUB	T	198	191	121	82	6	66	10	79	7	4	13
DUB	T	192	259	106	187	24	67	21	79	7	4	14

Table 3. Extracts from New Psychrometric Test Reference Year Developed for Dublin

Year	**Month**	**Day**	**Hour**	**DBT**	**Relative**	**Sat.**	**Vapour**	**Humidity**	**Specific**	**Density**	**Enthalpy**	**Adiabatic**
Based				**°C**	**Humidity**	**Vapour**	**Pressure**	**Ratio**	**Volume**			**Sat.**
on					**%**	**Pressure**						**Temp**
						Pa	**Pa**	**g/kg**	**m^3/kg**	**kg/m^3**	**kJ/kg**	**°C**
69	1	1	1	2.2	100	716	716	4.46	0.7867	1.28	13.26	2.2
69	1	1	2	2.7	98	742	727	4.53	0.7881	1.27	13.94	2.6
69	1	1	3	2.8	98	747	732	4.57	0.7884	1.27	14.12	2.7
69	1	1	4	2.6	98	736	722	4.50	0.7879	1.27	13.75	2.5
74	5	31	11	14.8	63	1682	1060	6.63	0.8227	1.22	31.44	11.0
74	5	31	12	12.9	71	1487	1056	6.61	0.8173	1.23	29.44	10.1
74	5	31	15	13.4	79	1536	1214	7.61	0.8187	1.23	32.45	11.4
74	5	31	16	14.8	81	1682	1363	8.55	0.8227	1.23	36.24	12.9
70	10	21	18	8.2	75	1087	815	5.09	0.8039	1.25	20.89	6.2
70	10	21	19	7.9	78	1065	831	5.19	0.8030	1.25	20.83	6.1
70	10	21	20	8.3	75	1094	821	5.12	0.8041	1.25	21.08	6.3
70	10	21	21	8.1	79	1079	853	5.33	0.8036	1.25	21.38	6.4