Saving resources by going evaporative: how evaporative cooling technologies and water cooled chillers can significantly reduce energy demands

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SUMMARY

Evaporative (latent) heat transfer is used in cooling towers, closed circuit cooling towers and evaporative condensers for the removal of waste heat from the HVAC processes.

Compared to cooling with dry air (sensible heat transfer), evaporative cooling is more efficient; with 1 kilogram of water the heat removed is about 2200 kilojoule (heat of evaporation) while with 1 kilogram of air the heat removed is about 1 kilojoule per degree °C. In addition, with evaporative technologies it is possible to decrease the process temperature up to about the wet bulb temperature (lower than dry temperature).

These advantages have long been recognized by the market and, today, a great variety of evaporative cooling products exists in terms of size, concept and configuration.

The Eurovent association has recently released the recommendation 9/12. This is an industry recommendation that constitutes the first European thermal performance efficiency standard for evaporative cooling equipment. The scheme has been developed over the past 14 months in a joint effort by 10+ cooling tower manufacturers that account for a joint market share of more than 90% in the EU28.

In specific, it introduces:

- the different evaporative cooling technologies available on the market,
- background, scope and outline of the new performance and efficiency rating standard, - thermal energy efficiency definitions and targets,
- thermal testing and uncertainty calculations,
- efficiency target verification,
- tools for an effective efficiency verification.

When selecting a particular product, next to the thermal duty, there are often a number of other criteria to be met, such as sound radiation, layout, operating weight. Such criteria usually differ from project to project, but a common element in most purchase decisions is also the cost effectiveness of the evaporative cooling product.

Unfortunately, the most cost effective product is often not the one with the best energy efficiency. In fact, it can be experienced that the worst energy efficiency is usually linked to the cheapest product.

With today's concern about global warming and the growing recognition of the need to save energy, purchase decisions solely based on cost effectiveness are no longer acceptable.

In this direction, one of the measures taken by the EU Member States was the launch of the 'EU Fan Regulation' 327/2011, which is currently being revised.

This Regulation sets out the minimum energy efficiency requirements for fans (defined as the combination of rotor, stator and drive). Fans are being used in hundreds of thousands products and the logic behind the 'EU Fan Regulation' is that a product with an efficient fan is also an efficient product. For evaporative cooling products, this is unfortunately not the case.

Whilst in mechanically driven cooling towers the fan is undoubtedly the main energy consumer, the fan efficiency cannot be used as the sole measure of cooling tower efficiency. Unlike with air cooled heat exchangers using sensible heat transfer, the effectiveness of thermal heat transfer is not based on the aerodynamically performance of the product. Indeed, the thermal and energy efficiency of evaporative cooling equipment is based on the effective mixing of air and cooling water streams.

Knowing that a major part of the electricity usage in Italy comes from the HVACR systems, any power reductions on those systems will support energy savings in general.

This paper introduces the fundamentals of state-of-the-art of the evaporative cooling technologies. Amongst others, it highlights the advantages of evaporative cooling, and clarifies water consumption issues of this technology.

With reference to the new Eurovent recommendation, this paper also illustrates a case study about how water cooled chiller systems with cooling towers reduce the power consumption by up to 50% compared to other technological solutions.

Key words: cooling towers, evaporative technologies, water cooled chillers, energy saving,

1. INTRODUCTION

The demand for energy efficient buildings and more stringent environmental sustainability requirements in the process industry have increased in recent years. As a consequence, the comfort and industrial cooling industry needed to be extremely dynamic in replying to the changing market demand.

Evaporative cooling combines high thermal efficiency and cost effectiveness by achieving low cooling temperatures with minimum energy and water usage. Low cooling temperatures are essential for many processes to achieve high system efficiency. These processes consume less energy and in this regard evaporative cooling contributes to preserving natural resources and the environment.

Evaporative cooling is the most efficient way to remove the excess heat from modern air conditioning systems and industrial processes and, as such, most suited to address the increasing of ambient temperatures due to the warming up of the atmosphere as well as the restrictions in energy usage and efficiency constraints.

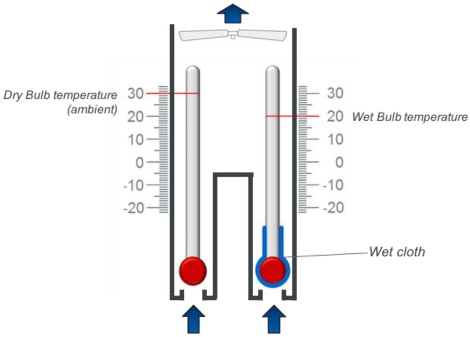

Figure 1 - Air wet bulb and air dry bulb temperature

Cooling towers are efficient and cost effective means of removing heat from air conditioning, refrigeration and industrial process cooling systems. They have been in use for more than half a century. They are compact, quiet, consume little energy and save more than 95% of the water in circulation. They are simple to operate and maintain and the system efficiency and safety are assured.

2. PRINCIPLE OF OPERATION

Evaporative cooling is based on a natural principle by the evaporation of water when cooling a fluid or condensing a gas the heat is rejected into the atmosphere. This is achieved by having close contact between the water circuit and an airstream, whereby the major part of the heat is transferred to the air by evaporation of a small amount of the water and the heat is then carried away in the warm, saturated discharge air.

With evaporative technologies it is possible to decrease the process temperature up to about the wet bulb temperature (lower than dry temperature). Compared to cooling with dry air (sensible heat transfer), evaporative cooling is more efficient; with 1 kilogram of water the heat removed is about 2200 kilojoule (heat of evaporation) while with 1 kilogram of air the heat removed is about 1 kilojoule per degree °C.

2.1. Open circuit cooling tower

Water from the heat source enters an inlet connection and is distributed over the fill pack through a spray distribution arrangement. Simultaneously, ambient air is induced or forced through the tower, causing a small portion of the water to evaporate. This evaporation removes heat from the remaining water. The cooled water falls into the tower sump from where it is returned to the heat source. It is open circuit as the water to be cooled is in contact with the atmosphere.

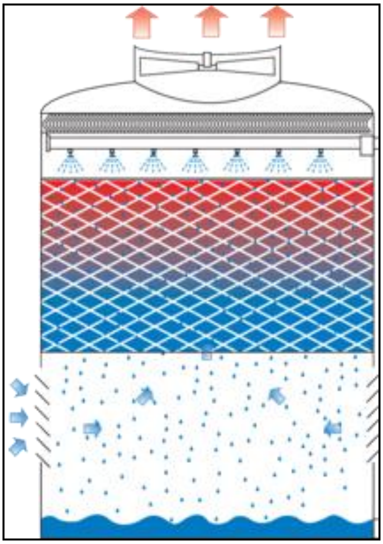

Figure 2 - Open circuit cooling tower.

2.2. Closed circuit cooling tower

The fluid to be cooled is circulated inside the tubes of the heat exchange coil. A secondary system distributes water over the tubes of the coil. Simultaneously air is forced or drawn through the coil causing a portion of the secondary water to evaporate. This evaporation removes heat from the fluid inside the coil. The secondary water falls to the sump from where it is pumped over the coil again. This is called closed circuit as the fluid to be cooled is in a sealed loop and does not come into contact with the atmosphere.

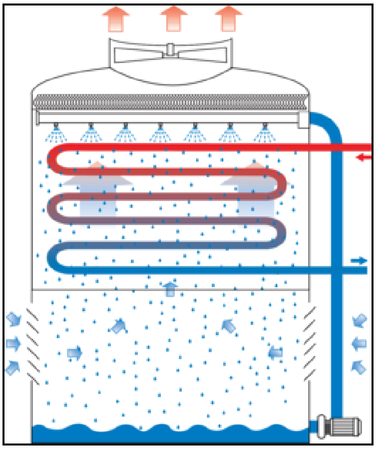

Figure 3 - Closed circuit cooling tower.

2.3. Mechanical forced draft cooling towers

These cooling towers are characterised by the fan located in the entering air stream.

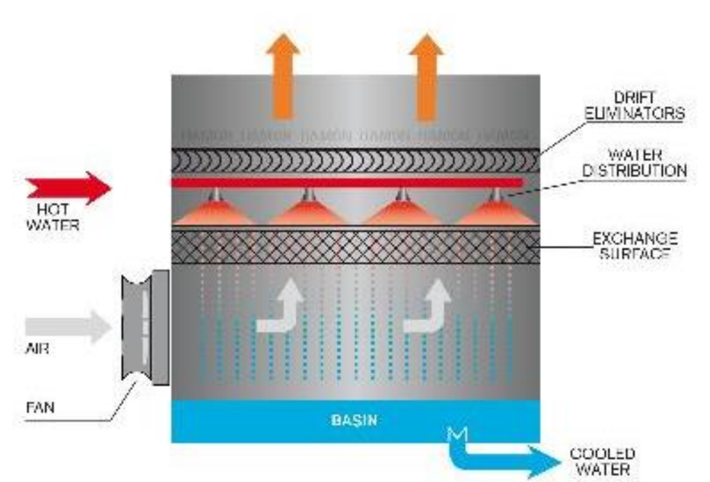

Figure 4 - Mechanical forced draft cooling tower.

2.4. Mechanical induced draft cooling towers

These cooling towers are characterised by the fan located in the discharge air stream.

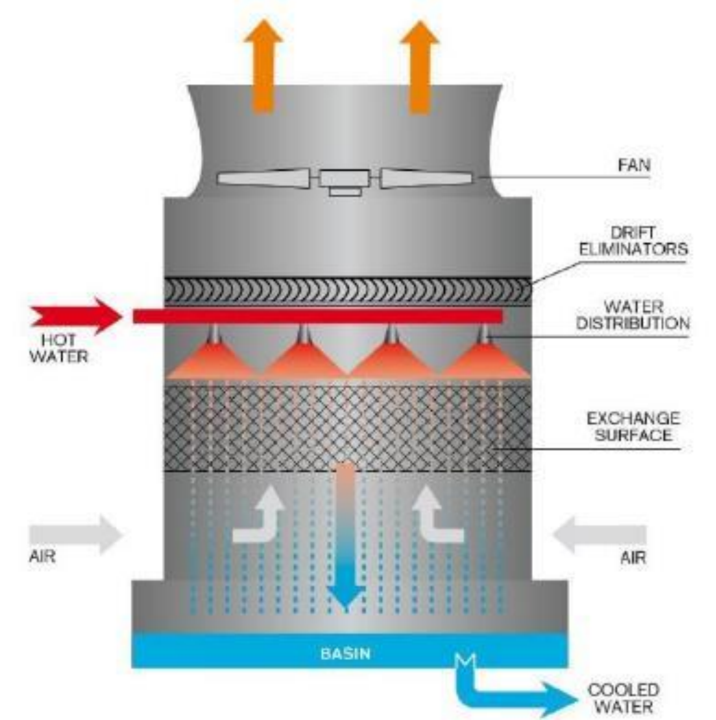

Figure 5 - Mechanical induced draft cooling tower.

3. EVAPORATIVE COOLING EQUIPMENT PERFORMANCE EFFICIENCY: THE EUROVENT INDUSTRY RECOMMENDATION 9/12-2016

Fans are being used in hundreds of thousands products and the logic behind the ‘EU Fan Regulation’ (Regulation (EU) 327/2011) is that a product with an efficient fan is also an efficient product. For evaporative cooling products, this is unfortunately not the case.

Whilst in mechanically driven cooling towers the fan is undoubtedly the main energy consumer, the fan efficiency cannot be used as the sole measure of cooling tower efficiency. Unlike with air cooled heat exchangers using sensible heat transfer, the effectiveness of thermal heat transfer is not based on the aerodynamically performance of the product. Indeed, the thermal and energy efficiency of evaporative cooling equipment is based on the effective mixing of air and cooling water streams.

The thermal performance of evaporative cooling products largely depends on the evaporation of water caused by effective mixing of water and air. The latent heat transfer, caused by evaporation, is not governed by aerodynamic principles only. In fact, aerodynamic efficiency plays only a minor role in the total heat transfer. It is for that reason that aerodynamic efficiency, for which fan efficiency is a good indicator, cannot be used to judge the thermal performance efficiency of evaporative cooling products.

By taking into account the specific nature of evaporative heat transfer, the Eurovent Recommendation 9/12-2016 has defined the thermal energy efficiency for mechanical draught open wet and closed-circuit cooling towers.

The thermal energy efficiency for mechanical draught open wet cooling towers is defined as the amount of heat rejection at specified inlet and outlet and entering wet bulb temperatures, expressed in kW heat rejection per kW absorbed shaft power at the fan drive system using water as the fluid type.

The thermal energy efficiency for mechanical draught wet closed circuit cooling towers is defined as the amount of heat rejection at specified inlet and outlet and entering wet bulb temperatures, it is expressed in kW heat rejection per kW absorbed shaft power at the fan and spray pump drive system (using water as the fluid type).

$$thermal\ energy\ efficiency = \frac{\dot{m} * c_p * (T_{in} - T_{out})}{P} \qquad (1)$$

Where:

- $\dot{m}$= water flow [kg/s]
- c_p= specific heat [kJ/kgK]
- T_{in}= water inlet temperature [°C]
- T_{out}= water outlet temperature [°C]
- P= power absorbed by fan and/or pump [kW]

According to the above definitions, the Eurovent Recommendation 9/12-2016 has also defined the minimum thermal energy efficiency target for both open wet cooling towers and for closed-circuit cooling towers. In order to be in line with the Regulation (EU) 327/2011, these targets take also into account the different kind of fans installed.

Temperatures (°C), inlet, outlet, wet bulb	kWth/kW centrifugal fans	kWth/kW axial fans
35/29,44/23,89 (ASHRAE)	40	80
35/25/20	42	84
32/27/21	36	72

Table 1: Minimum thermal energy efficiency targets for open wet cooling towers.

Temperatures (°C), inlet, outlet, wet bulb	kWth/kW centrifugal fans	kWth/kW axial fans
38,89/32,22/23,89 (ASHRAE)	16	33
38/28/20	15	30
35/30/21	15	32

Table 2: Minimum thermal energy efficiency targets for closed-circuit cooling towers.

The above approach has provided and continues to provide goals to improve the thermal energy efficiency of the evaporative cooling industry in Europe. In this respect national laws and EU regulations are encouraged to follow the Eurovent Recommendation's approach.

4. REFRIGERATION SYSTEMS: DRY COOLED VS. WATER COOLED SYSTEMS

Knowing that a major part of the electricity usage in Italy comes from the HVACR systems, any power reductions on those systems will support energy savings in general.

4.1. The compressor's lift

The following example clarifies and explains why a water cooled refrigeration system is more efficient than an air cooled refrigeration system. It investigates a refrigeration system operating at Mediterranean climate condition and it aims to calculate the compressors lift. The lift is the work done by the compressor to raise refrigerant pressure from low to high level, it can be calculated as the delta temperature between the hot water leaving the condenser and the cold water leaving the evaporator.

$$C_{lift} = LCWT\text{-}LEWT \qquad (2)$$

Where:

- C_{lift}= compressor lift [°C]
- LCWT=water temperature leaving condenser [°C]
- LEWT=water temperature leaving evaporator [°C]

As the compressor lift represents the compressors' power input, it shall be intended as a true indicator of the system energy consumption. It must be stressed that the bigger is the lift the higher is the power input.

The below Figure 6 shows the most usual schematic of a dry cooled refrigeration system and the related refrigeration cycle.

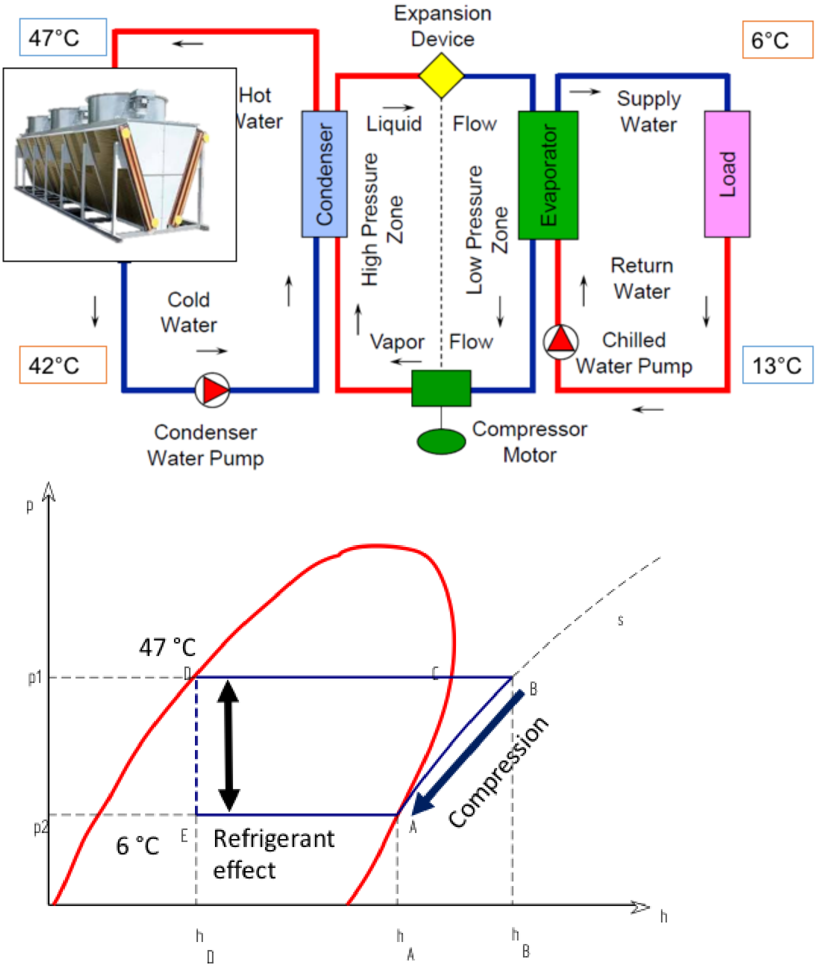

Figure 6 - Dry air cooled refrigeration system schematic and related refrigeration cycle.

The performance of a dry cooled refrigeration cycle is dependent on the ambient air dry bulb temperature. The following assumptions are used in order to analyse the performance of this refrigeration system:

- Ambient air design dry bulb temperature: 35°C
- Condenser operating conditions: 47/42°C
- Chilled water operating conditions: 6/13°C

The compressors’ lift can be calculated as: 47°C- 6°C=41°C =LIFT_{DC}

The below Figure 7 shows the most usual schematic of a water cooled refrigeration system using cooling tower equipment and the related refrigeration cycle.

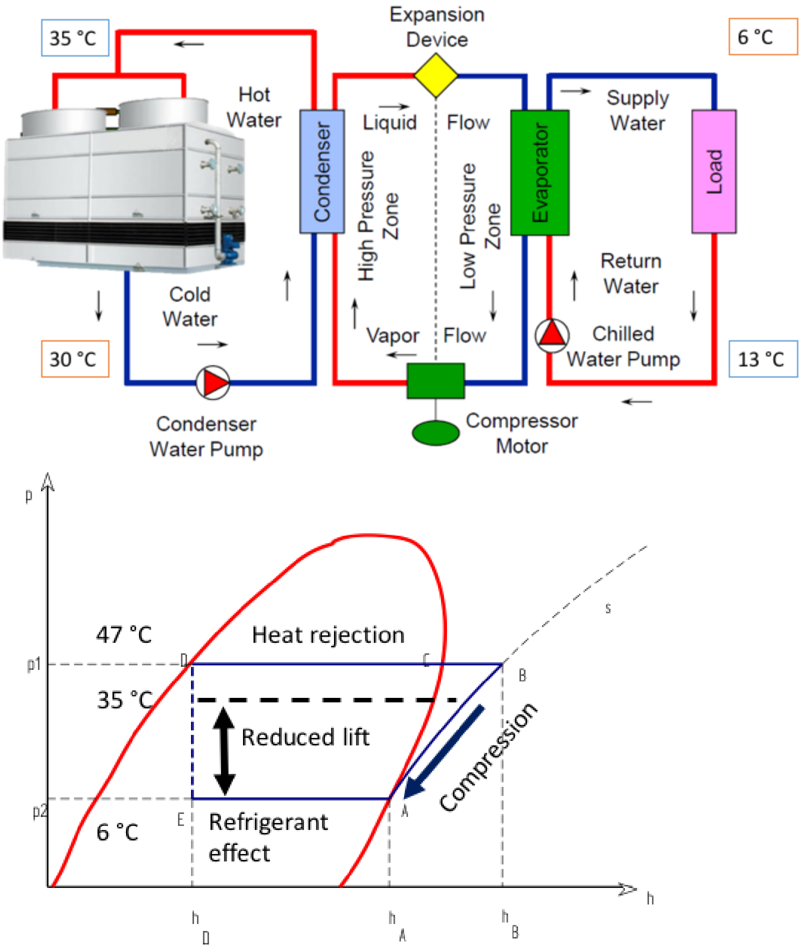

Figure 7 - Water cooled refrigeration system using cooling towers schematic and related refrigeration cycle.

The performance of a water cooled refrigeration cycle using cooling tower equipment is dependent on the ambient air wet bulb temperature (see par. 2.). The following assumptions are used in order to analyse the performance of this refrigeration system:

- Ambient air design wet bulb temperature: 25°C
- Cooling tower operating conditions: 35/30°C
- Chilled water operating conditions: 6/13°C

The compressors' lift shall be calculated as 35°C- 6°C=29°C =LIFT_{CT}

The above calculation leads to a compressors power input lower than the one in an air cooled refrigeration system and it easily confirms and provides further evidence that a water cooled refrigeration systems equipped with cooling towers is more efficient than an air cooled refrigeration system.

The refrigeration system energy saving can be calculated as:

$$Saving = 1 - \frac{Lift_{CT}}{Lift_{DC}} \tag{3}$$

Where:

- $LIFT_{CT}$=Compressor’s lift water cooled system [°C]
- $LIFT_{DC}$ = Compressor’s lift dry cooled system [°C]

At the above defined climate conditions, the lift analysis has result in an energy saving of 30%.

5. CASE STUDY: THE ATHENS OPERA THEATRE

The Atene Opera Theatre, within the Stavros Niarchos Foundation Cultural Centre, has been investigated and analysed.

This theatre has been designed by Mr Renzo Piano (architectural design), by the Arup Group (London, UK), and by the BMS Progetti (Milan, Italy).

It must be pointed out that within the LEED certification scheme, this building has been qualified as LEED Platinum.

5.1. The cooling and the heat rejection systems

The cooling system consists in 4 water cooled chillers: two at 2.000 kW capacity each and two at 1.000 kW capacity each. One of the 1.000 kW chiller is on stand-by at all times providing redundancy.

The below Table 3 specifies the chillers technical data:

#	Description	Equipment data
1	Water cooled chiller	Compressor: Centrifugal Refrigerant: R134A Cooling Capacity: 2.000 kW Water leaving /entering temperature: 7°C/13°C Condenser leaving/entering temperature: 35°C/29°C
2	Water cooled chiller	Compressor: Centrifugal Refrigerant: R134A Cooling Capacity: 2.000 kW Water leaving /entering temperature: 7°C/13°C Condenser leaving/entering temperature: 35°C/29°C
3	Water cooled heat recovery chiller	Compressor: Screw Refrigerant: R134A Cooling Capacity: 1.000 kW Water leaving /entering temperature: 7°C/13°C

		Condenser leaving/entering temperature A: 37°C/31°C Condenser leaving/entering temperature B: 60°C/53°C
4	Water cooled heat recovery chiller	Compressor: Screw Refrigerant: R134A Cooling Capacity: 1.000 kW Water leaving /entering temperature: 7°C/13°C Condenser leaving/entering temperature A: 37°C/31°C Condenser leaving/entering temperature B: 60°C/53°C

Table 3: Chillers technical data.

The below Table 4 specifies the cooling towers technical data:

#	Description	Equipment data
1	Cooling tower	Dry bulb temperature: 40°C Wet bulb temperature: 26,5°C Water entering/leaving temperature: 35°C/29°C Cooling Capacity: 2.000 kW
2	Cooling tower	Wet bulb temperature: 26,5°C Water entering/leaving temperature: 35°C/29°C Cooling Capacity: 2.000 kW
3	Cooling tower	Dry bulb temperature: 40°C Wet bulb temperature: 26,5°C Water entering/leaving temperature: 35°C/29°C Cooling Capacity: 2.000 kW

Table 4: Cooling towers technical data.

5.2. Compressor's lift calculation and energy saving

The Compressors' lift can be easily calculated as in the formula 2.

The lift due to the cooling towers installed can be calculated as:

$$LIFT_{CT} = 35°C - 7°C = 28°C \quad (4)$$

The lift due to a dry cooled system operating at the equivalent climate conditions (dry bulb temperature 40°C, water in/out temperature= 50/45°C) can be calculated as:

$$LIFT_{DC} = 50°C - 7°C = 43°C \quad (5)$$

By using the formula (3), it is possible to calculate the refrigeration system energy:

$$Saving = 1 - \frac{Lift_{CT}}{Lift_{DC}} = 1 - \frac{28}{43} = 35\% \quad (6)$$

CONCLUSION

This paper has analysed the evaporative cooling technology, its principle of operation and its thermal energy efficiency.

Within a refrigeration system, it has also been investigated the compressor's lift. This has been analysed for both a dry cooled refrigeration system and a water cooled refrigeration system. This has result in an energy saving of about 30% by using water cooled technologies.

Finally, it has been showed a case study, the Athens Opera Theatre. Based on the compressor's lift approach, the water cooled refrigeration system has resulted in an energy saving of about 35% compared to the standard dry cooled technologies.

SYMBOLS

C_{lift}	compressor lift [°C]
c_p	specific heat [kJ/kgK]
LCWT	water temperature leaving condenser [°C]
LEWT	water temperature leaving evaporator [°C]
LIFTCT	Lift due to cooling tower [°C]
$\dot{m}$	water flow [kg/s]
P	power absorbed by fan and/or pump [kW]
Tin	water inlet temperature [°C]
Tout	water outlet temperature [°C]

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