Improving the Energy Performance of Air-Cooled Chillers with Water-Spray Mist Pre-Cooling: An Application

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SUMMARY

The main objectives of this paper are (i) to introduce a new water-spray mist-cooling system with a tor (mesh material) (WSMCST), (ii) to assess its performance, which is based on pre-cooling the ambient air entering the condensers to decrease compressor power consumption, and (iii) to energetically compare with the conventional systems. The WSMCST was designed and tested within the scope of a project supported by the Scientific and Technological Research Council of Turkey (TUBITAK). It mainly consists of atomization nozzles, water pipework, a filter assembly and a high pressure pump with around 70 bars. It also involves a tor around each of the air intake sides of the air-cooled condenser. More mesh material is fixed to cover the corners and any other exposed areas of the condenser.

The water-spray mist-cooling system (WSMCS) with a tor (mesh material) was applied to two air-cooled chillers with a nominal capacity of 600 kW each in a textile factory, located in Izmir, Turkey. Based on the experimental data obtained from the measurements during a period of 3 months from June to August 2009 under ambient temperatures ranging from 25^{o} C to 39^{o}C, the energy efficiency ratio (EER) increased from 2.96 to 3.36, corresponding to a rise of 13.5% in the EER, while an increase of 5.9% in the cooling capacity was obtained. It has also been observed that no negative effects (i.e., direct contact of water with the condenser coils and hence, avoiding scaling problems) on the cooling system occurred.

Keywords: Air-cooled chiller, Efficiency, Pre-cooling, Water mist,

INTRODUCTION

In cities in the subtropical climate, chillers have long been used to provide comfort cooling in buildings throughout the year. These chillers produce chilled water to compensate for cooling loads within air-conditioned spaces through air handling units or fan coil units. The operation of chillers accounts for about 60% of the electricity used for air-conditioning, which can amount to 25–40% of the total electricity consumption in a commercial building [1].

The coefficient of performance (COP) of water-cooled chillers is much higher than that of air-cooled chillers. Yet in many places air-cooled chillers are widely used. The popularity of air-cooled chillers is due to the ease of installation, the simplicity of operation and maintenance, and the lower installation and maintenance costs as compared to water-cooled chillers. Although some governments have relaxed the restrictions on the use of fresh water for heat rejection systems in certain districts, air-cooled chillers continue to be used in many places as they are not likely to be replaced because of their great capital investment and long service life of around 15 years. Considering that air-cooled chillers are still common in many buildings and industrial facilities in subtropical regions, it is desirable to increase their COP through improving the design and operation of their components [2]. The chiller COP values can be improved by using various ways, i.e., with the improved condenser features of condensing temperature control, variable speed condenser fans, etc.

Evaporative cooling is another means to improve the COP of air-cooled chillers [3-5]. Evaporative cooling of ambient air is not a new concept for air-conditioning systems, but its application on pre-cooling air entering air-cooled condensers is not common [6].

Applications of evaporative cooling range from comfort cooling in residential, agricultural, commercial and institutional buildings, to industrial applications for spot cooling in mills, foundries, power plants, and other hot environments. regarded as energy-efficient, environmentally friendly and cost-effective as air handling equipment). A direct evaporative cooler in front of an air-cooled condenser lowers the temperature of the air before it enters the condenser, so that the refrigeration capacity is increased, the power consumption is reduced and the coefficient of performance (cop) of the chiller is improved. Water can be saved because the water circulating rate of a condenser cooling system is much higher than that of a direct evaporative cooling system [5].

An evaporative pre-cooler to be installed in front of an air-cooled condenser can reduce the temperature of outdoor air entering that condenser while consuming less than 15% of the cooling water required by cooling towers and evaporative condensers [4]. Some studies conducted on the performance assessment of pre-cooling of inlet air to condensers of air-cooled condensers have been summarized elsewhere [3]. The potential and benefits of using evaporative pre-coolers hinge on the extent to which the condensing temperature can drop and whether the decrease in compressor power due to this drop can outweigh the pump power in addition to the fan power. Zhang et al. [5,7] have indicated that the use of evaporative pre-coolers can bring about a 14.7% increase in the COP of air-cooled chillers working in a hot and dry environment. The pre-coolers are expected to have high effectiveness when cooling outdoor air in a hot and dry climate, but they can function properly even when the climate is hot and humid.

Among adiabatic cooling systems used in a wide range of applications, the water-spray mist-cooling system with a tor or mesh material (WSMCST) is noteworthy. The WSMCST is not a new concept, and these systems have been successfully applied to various types of industries. The application of a WSMCST associated with a chiller system, however, is not common. Especially, the WSMCST differs from the previously installed and operated ones due to the fact that it is monitored in real-time and electronically controlled.

The main objectives of this paper are (i) to introduce a new WSMCST, which operates based on pre-cooling of the ambient air entering the condensers to decrease compressor power consumption and is designed and tested within the scope of a project supported by the Scientific and Technological Research Council of Turkey (TUBITAK), and (ii) to present some preliminary results obtained from the measurements in a textile factory in Izmir, Turkey.

SYSTEM DESCRIPTION

Apart from installing an evaporative pre-cooler in front of an air-cooled condenser, the evaporative cooling of ambient air is done more directly via a water mist cooling system, which produces a cloud of very fine water droplets via atomization nozzles. So, the ambient air entering the condenser is cooled from its dry bulb temperature to wet bulb temperature while the droplets are fully vaporized.

A schematic of the WSMCST is illustrated in Figure 1 [8]. This system mainly consists of three subsystems, namely (i) a water treatment and control unit, (ii) a high pressure pulverization unit with atomization nozzles, and (iii) a specially developed microprocessor. It also involves a tor around each of the air intake sides of the air-cooled condenser. More mesh material is fixed to cover the corners and any other exposed areas of the condenser.

When a variable-flow rate high-pressure water pumping system operates to deliver water through the pipework at a high pressure of 40-70 bar, the water is released through the low flow atomization nozzles to form a mist of very fine droplets. These droplets can be easily vaporized by the ambient air before entering the condenser and a reduction in the temperature of that air follows the adiabatic cooling process with constant specific enthalpy.

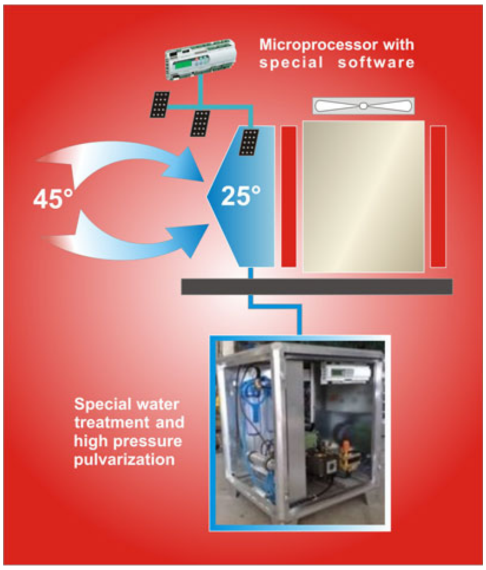


Figure 1. A schematic of the WSMCST developed

Using the developed WSMCST, it is possible to obtain pre-cooling temperatures varying between 5 and 20 K. The energy consumption of the system is relatively low, accounting for 2% of energy saving obtained from the air-cooled chiller. The water consumption price of the system also amounts to 10% of the price of energy saving. In other words, the system does not cause any flow resistance to the air stream. No additional fan power, therefore, will be incurred. It takes up only a small amount of electric power to drive the high pressure pump and negligible amount of water for mist generation.

Depending on the layout of the condenser coil, the nozzles should be evenly distributed in front of the entire condenser surface in order to ensure that all the air entering the condenser can be pre-cooled by vaporizing the mist. A certain distance should be maintained between the atomization nozzles and the condenser in order to prevent the unwished mist, which the air stream carries from falling on the condenser fins and coil without undergoing the vaporization process. In the selection of the number of nozzles, water circuits and pump sets, the right determination of the mist generation rate required and the working mode of the mist systems play a big role. The design outdoor conditions and the total heat rejection airflow rate of a chiller are also the two major parameters to determine the peak mist generation rate required.

The tor cooling system is designed to produce a maximum pressure drop of 20 Pa, so that any significant flow resistance to the air stream of condensers could not be caused. The mist nozzles are determined depending on the geometry of the unit and the weather data of the installation place. The system maintains the minimum and maximum mist generation rates required and evaporates the whole water droplets produced via atomization nozzles.

ANALYSIS

The cooling load of an air-cooled chiller unit is calculated using measured parameters of the water side of the evaporator. If the temperatures of the water at the inlet and exit points of the evaporator are measured, then the cooling load is calculated from

$$\dot{Q}_{cool} = \dot{m}_w \bullet C_p \bullet (T_r - T_f) \qquad (1)$$

where $\dot{m}_w$ is the mass flow rate of the water, C_p is the specific heat of water, while T_f and T_r are the flow (or supply) and return temperatures of the water, respectively.

If the water flow from the evaporator is passed through an calibrated orifice plate, and the pressure differential (ΔP) is measured across that orifice plate, the mass flow rate of the water is then calculated using

$$\dot{m}_w = C \bullet E \bullet A\sqrt{2 \bullet \Delta P \bullet \rho} \qquad (2)$$

where C is the discharge coefficient, E is the velocity of approach factor, A is the cross-sectional area and ρ is the density of the water.

The cooling load in Btu may be obtained from [3]

$$\dot{Q}_{cool,Btu} = 3412.14 \bullet \dot{Q}_{cool} \qquad (3)$$

The coefficient of performance (COP) is calculated as

$$COP = \frac{\dot{Q}_{cool}}{\dot{W}_{elec,total}} \qquad (4)$$

where $\dot{W}_{elec,total}$ is the total power consumption of the chiller unit, which is based on the measurements.

DATA USED

In the analysis of Turkey's weather data for evaluating adiabatic cooling values, an average of the data obtained from three various of sources [9-11] was taken. In this regard, the weather data of 76 Turkish cities were analyzed and the maximum adiabatic cooling temperature values for these cities were obtained to range from 3 to 17 K, as listed in Table 1.

Table 1. Variation of maximum adiabatic cooling temperature values according to the Turkish cities

Maximum adiabatic cooling temperature values to be realized (K)	Cities in Turkey
> 15	BATMAN, ŞANLIURFA, MARDİN, ELAZIĞ, DİYARBAKIR, ADIYAMAN, SİVAS, KİLİS
15-12	IĞDIR, BURDUR, BİNGÖL, KARAMAN, BAYBURT, AKSARAY, MALATYA, VAN, MARMARİS, GAZİNATEP, AMASYA, MUŞ, UŞAK, HAKKÂRİ, FETHİYE, KIRIKKALE, ERZİNCAN, KAHRAMANMARAŞ, GÜMÜŞHANE, MUĞLA, MANİSA, BİTLİS, KIRŞEHİR, ISPARTA, ARDAHAN, BODRUM, BLECİK, ANKARA
12-10	ADANA, TOKAT, AYDIN, DENİZLİ, ÇORUM, KASTAMONU, KÜTAHYA, KONYA, KAYSERİ, AĞRI, İZMİR, BALIKESİR, BURSA, AYVALIK, BOLU, ARTVİN, KUŞADASI, ANTALYA, ÇANKIRI, ESKİŞEHİR, ZONGULDAK
10-7	BARTIN, ERZURUM, EDİRNE, KIRKLARELİ, KARS, KOCAELİ, YALOVA, HATAY, AFYON, SAKARYA
7-5	İSTANBUL, ÇANAKKALE, TARSUS, İSKENDERUN, RİZE

The hourly and daily dry and wet bulb temperature values for the cities of İzmir, İstanbul, Ankara, Antalya and Diyarbakır in the different climatic regions were also analyzed. It was determined that the WSMCST having a real time monitoring system could be economically and safely utilized at the temperature values of 24.5 °C and above. Based on this determination, the increase in the efficiency values for air-cooled chillers was evaluated at the temperatures of above 24.5 °C. In the analysis made for the five cities, the time intervals larger than 24.5 °C were obtained, while the average temperature values of these cities in the season with above 24.5 °C were established. Using these average temperature values, the adiabatic cooling temperature values to be applied to these cities were determined, as listed in Table 2.

Table 2. Adiabatic cooling temperature values to be applied to the Turkish cities analyzed

Cities	Duration h	Average DB temp. °C	Average WB temp. °C	Average pre-cooling temp.* K	Seasonal pre-cooling Kh
Ankara	663	26.3	16.3	8.3	5503
Antalya	1872	28.0	18.6	7.7	14414
Diyarbakır	2306	30.0	14.7	12	27672
İstanbul	611	25.6	19.7	4.2	2556
İzmir	1749	27.3	19.8	7.5	13117

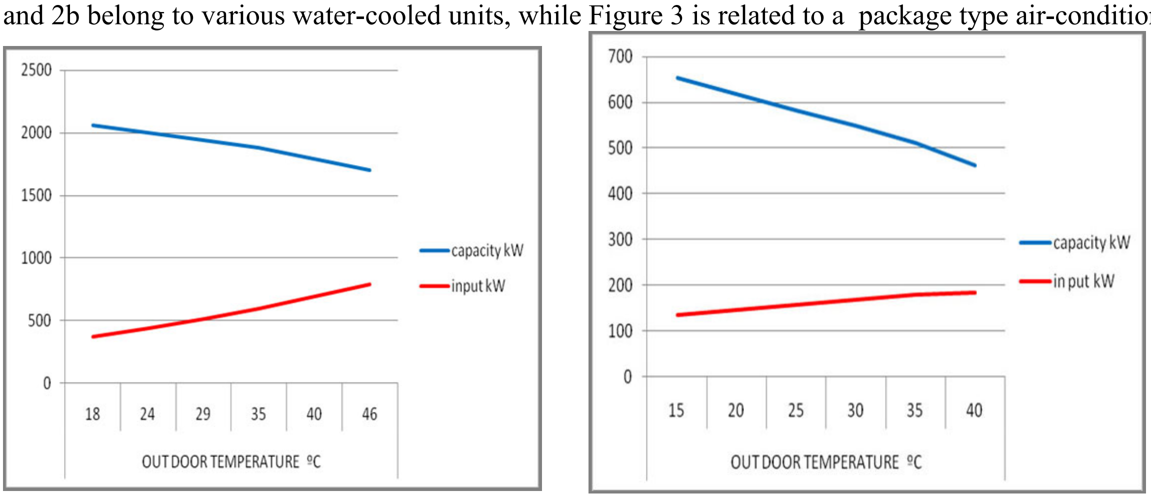
*These indicate the cooling temperature values of above 18 °C, at which air-cooled chillers could be operated without any trouble.

It is clear from Table 2 that these cities indicate different adiabatic cooling durations. For example, the time at which the adiabatic cooling is made at a maximum level is 1 p.m. to 2 p.m. for Izmir, while that is 8 a.m. to 9 a.m. for Antalya. These kinds of deviations have shown that the adiabatic cooling benefits to be obtained from any region differ depending on the cooling working seasons. For this reason, in the application of the WSMCST, the efficiency calculations should be based on the weather data along with the time interval at which the cooling system is operated.

RESULTS AND DISCUSSION

Parametric Investigation of Adiabatic Pre-Cooling Process

The efficiency increase of the adiabatic cooling assisted-air cooled chillers was investigated. Figures 2a and 2b belong to various water-cooled units, while Figure 3 is related to a package type air-conditioner.



(a) (b)

Figure 2. Variation of capacity values for various water cooled units depending on different outdoor air temperatures

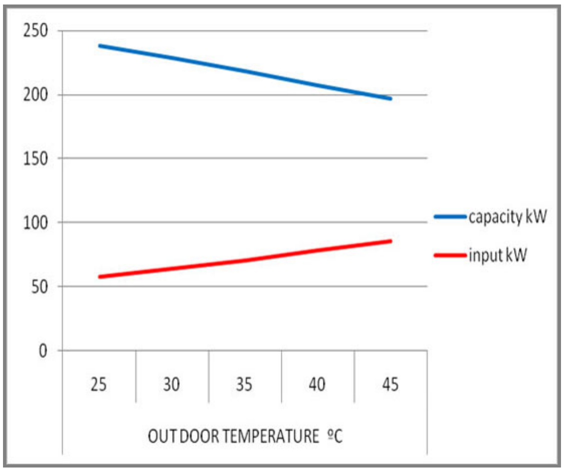
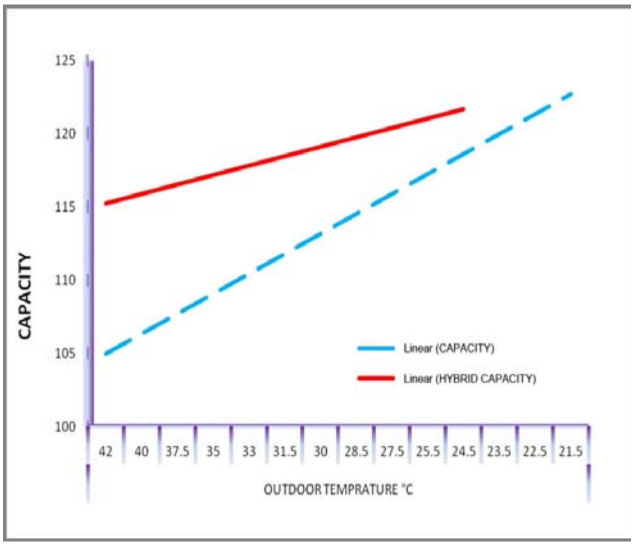
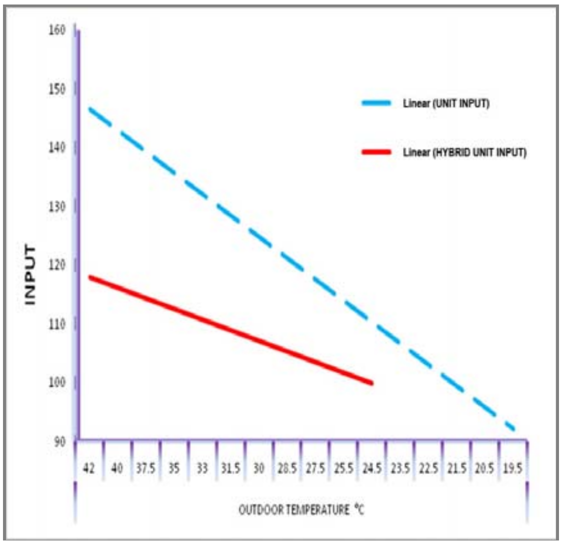


Figure 3. Variation of capacity values for a package type air-conditioner depending on different outdoor air temperatures

As can be seen from Figures 2 and 3, the capacities and energy consumption values of cooling devices change depending on their brands, models and constructions, while their capacities vary depending on the outdoor air temperatures. In the seasons where the outdoor air temperature values rise, the energy consumptions of the units increase as the capacities of the units decrease. It is possible to pre-cool the air at the inlet of the condenser to 5-20 K using an adiabatic cooling system. It should be noticed that an adiabatic cooling to be made in front of the condenser will lead to a significant capacity increase or energy saving Figures 4a through 4c illustrate the benefits to be obtained from the cooling systems utilizing an adiabatic cooling process depending on the various outdoor air temperature various.

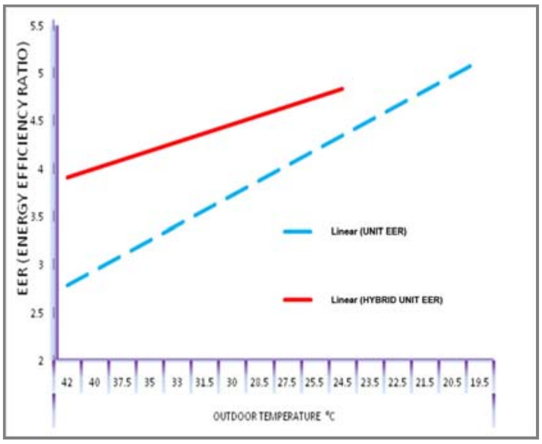


(a)



(b)

Figure 4. Variation of capacity values for cooling systems utilizing an adiabatic cooling process depending different outdoor air temperatures



(c)

Figure 4 (Continued). Variation of capacity values for cooling systems utilizing an adiabatic cooling process depending on different outdoor air temperatures

As can be seen from Figure 4c, the energy efficiency ratio (EER) increases up to 50% depending on the outdoor air temperatures, the construction of the device and the pre-cooling temperature values to be made in front of the condenser.

An Illustrative Example

The WSMCST was applied to air-cooled chillers in a textile factory, located in Izmir, Turkey [12]. In the factory, there are 8 air-cooled chillers with a total nominal cooling capacity of 4200 kW and a total input power of 1412 kW. In the case of the application of the WSMCST to these units, a capacity rise of 420 kW and an energy saving of 381,240 kWh have been proposed. The price of the new unit to be purchased, which will yield to an increase in the cooling capacity, costs 50,000 €, the cost savings to be achieved amount to 46,000 € and the cost of the adiabatic pre-cooling to be applied is 90,000 €, while the payback period is about 6 months.

Figures 5a through 5c show various types of adiabatic cooling applications. The WSMCST utilizing a real time monitoring subsystem was applied to two units in this facility to pre-cool the condenser air (Figure 5a). A cooling pad (Figure 5b) was also applied to one unit to make a comparison between cooling tor and pad sets. In the cooling pad application, it was observed that the original fans of the cooling devices remained insufficient and some difficulties occurred in the application of the cooling pad to the cooling unit. This cooling pad application was then given up due to its unwished effects. In the tor-assisted application, a time-dependent control was utilized, but the unnecessary water consumption was decreased to 30-40%. In the application utilizing a real time controlling and monitoring unit (the so-called smart humidity control system), this water consumption could be lowered to about 95%.

(a) (b) (c)

Figure 5. Pictures of various types of adiabatic pre-cooling applications
(a): Cooling tor (mesh) application utilizing a real time controlling and monitoring unit
(b): Cooling pad application (c) Tor-assisted fogging cooling application

The results obtained from the WSMCST with a real time controlling and monitoring unit are indicated in Figure 6, where zone 1 and zone 2 indicate a variation of water amounts given to the system.

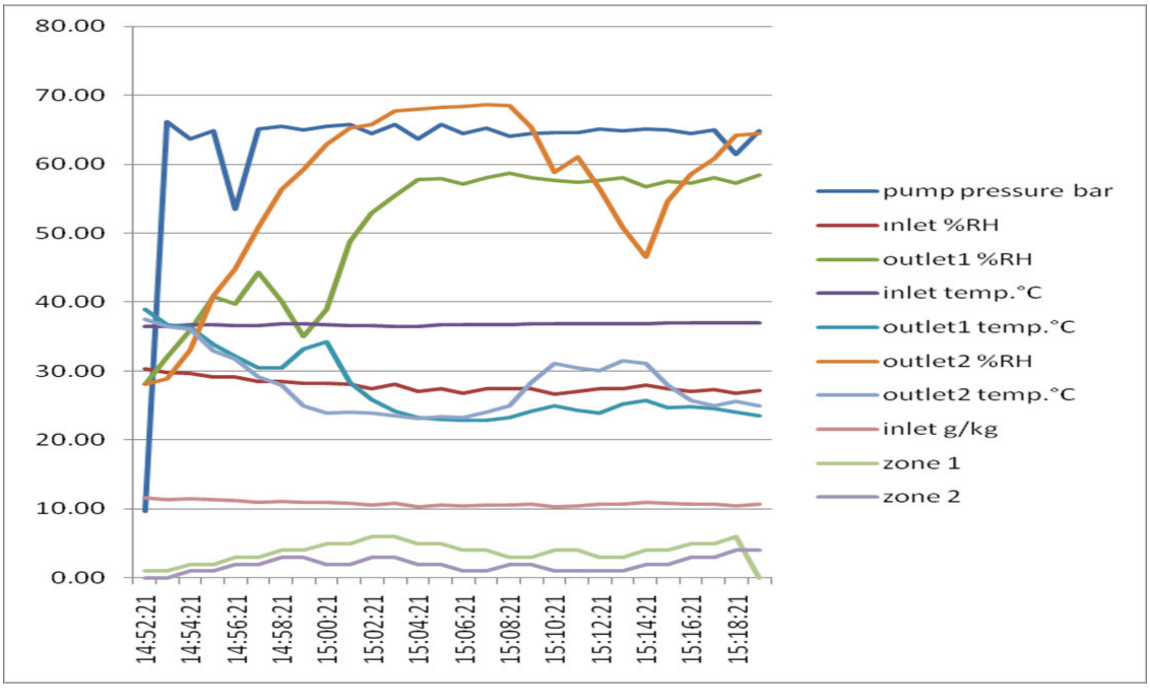


Figure 6. Some measured data of the WSMCST with a real time controlling and monitoring unit

In this figure, the simultaneous temperature drops depending on this water amount is clearly seen. The differences between zone 1 and zone 2 result in wind effects. The WSMCST with a real time controlling and monitoring unit was operated three times (a total of 10 hours) without using tor. It was observed and determined that during this operation unnecessary water consumption increased and the temperature drop in front of coils decreased.

Table 3 lists the data of the WSMCST installed in a textile factory in Izmir, Turkey. Figure 7 illustrates some operational data of the WSMCST with a real time controlling and monitoring unit, which was designed using the data given in this table and tested in a season where the outdoor air conditions were extreme.

Table 3. Data of the WSMCST installed in a textile factory

Data used	Value
Dry-bulb (DB) temperature	36 ^{o}C
Wett-bulb (DB) temperature	24 ^{o}C
Condenser volumetric air flow rate	180000 m^3/h
Maximum pre-cooling to be realized	10.6 K
Water content of the air	4.1 g/kg
The maximum water requirement of the system	14 L/min
Number of spray mist nozzles	208
Total water volumetric flow rate of spray mist nozzles	16 L/min

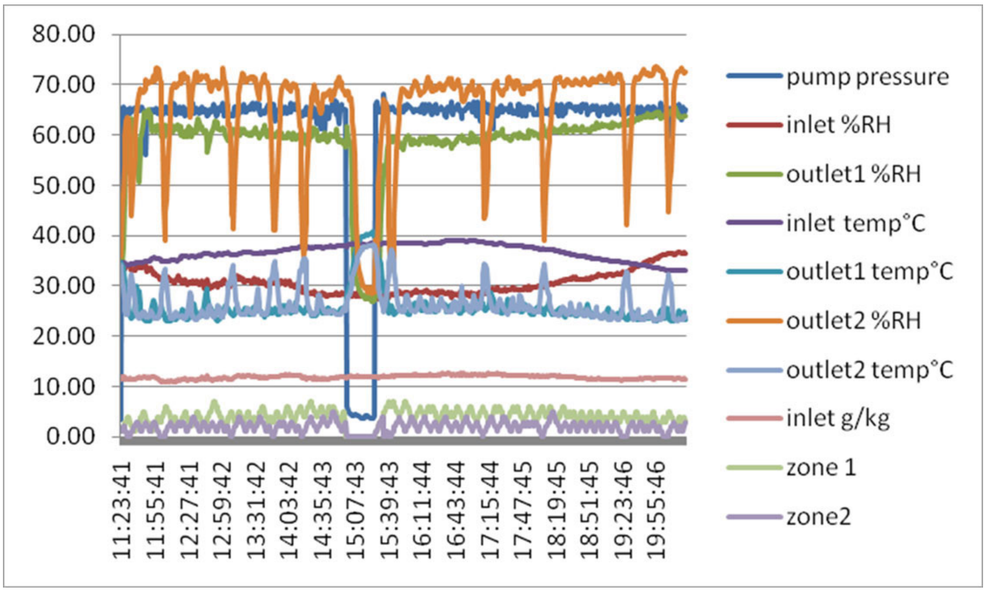


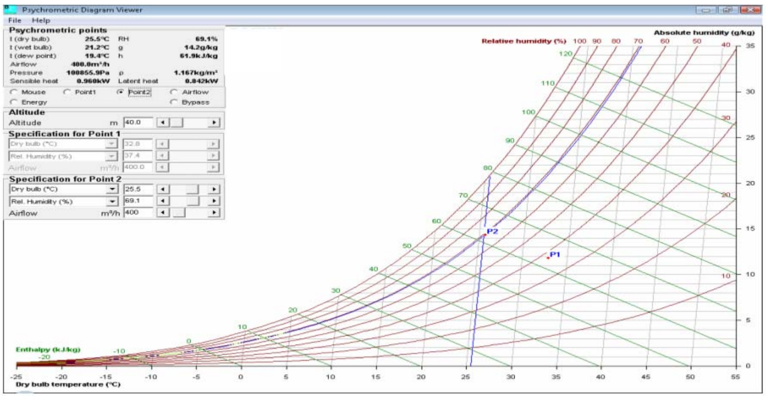
Figure 7. Some operational data of the WSMCST with a real time controlling and monitoring unit under extreme outdoor air conditions

Using the smart humidity control system developed, the outlet air temperature is accurately maintained. This control system makes a psychometric analysis by detecting the thermodynamic conditions of the immediate entry air and by calculating the real time maximum water amount that can be transferred to the air and together with an authentic algorithm converts the evaporative cooling transaction as it can be remote monitored, controlled and interruptible situation. Some values obtained through the smart humidity control system are given in Table 4, while these values appear in a special designed way on the internet.

Table 4. Some values obtained through the smart humidity control system developed

Description	Value
Outdoor air temperature	33.1 °C
Outdoor air relative humidity	31.8%
Inlet absolute (specific) humidity	10.1 g/kg
Target absolute humidity	14.4 g/kg
Target adiabatic cooling outlet temperature	22.3 °C
1st circuit absolute humidity	12.8 g/kg
2nd circuit absolute humidity	13.2 g/kg
3rd circuit absolute humidity	- 0.6 g/kg
1st circuit stage	3/7
2nd circuit stage	2/7
3rd circuit stage	0/7
Pump pressure	65.6 bar

The water amount given may be saved through utilization of the tor-assisted two-stage adiabatic cooling system. For monitoring the cooling temperature realized in front of the coils, 14000 data were collected over a period of 250 hours in the months of June through August 2009. Some values obtained are illustrated in Figure 8.



OUTDOOR TEMPERATURE	
DB °C	32.8
WB °C	21.5
ADIABATIC COOLING OUTLET	
DB °C	25.5
WB °C	21,2
TEMPERATURE DROP	7.3

Figure 8. Data regarding the tor-assisted two-stage adiabatic cooling system

For making energy saving calculations, the energy input to the system was measured using energy analyzers and an orifice plate was also installed to measure the volumetric flow rate of the chilled water in the textile factory investigated. As can be seen from Table 5, the EER increased from 2.96 to 3.36, corresponding to a rise of 13.5% in the EER, while an increase of 5.9% in the cooling capacity was also obtained.

Table 5. Improvements through utilization of the WSMCST with a real time controlling and monitoring unit

CHILLER UNIT	
Condenser inlet temperature	32.8 ^{o}C
Cooling capacity	659 kW
Inlet power	223 kW
EER	2.96
CHILLER UNIT WITH ADIABATIC COOLING	
Condenser inlet temperature	25.5 ^{o}C
Cooling capacity	698 kW
Inlet power	208 kW
EER	3.36
Increase in EER	13.5%
Increase in the cooling capacity	5.9%

CONCLUSIONS

Air-cooled chillers have been widely used to provide cooling energy and account for significant energy consumption in commercial buildings. In this regard, the use of adiabatic cooling systems has gradually become widespread for increasing the energy utilization efficiency of water-cooled units equipped with air-cooled condensers. Among adiabatic cooling systems used in a wide range of applications, the water-spray mist-cooling system with a tor (mesh material) plays a big role.

Some concluding remarks obtained from the results of the present study may be listed as follows:

- Based on the measurements obtained from the evaporative pre-cooling applied to air-cooled chillers in a textile factory, located in Izmir, Turkey, the use of mist spray pre-cooling increased the EER in various temperatures by up to about % 14 in the months of June through August 2009. It was also observed that the units, which had a high pressure defect at least five times a month, did not cause any defects during the same months. It was determined that an additional 5% increase in the COP could be obtained based on the studies conducted in the last weeks.

- Based on the in situ measurements and observations made in the last week of the experimental studies, the pre-cooling temperature of 7.3 K could be risen to 10 K under the conditions of the city of Izmir.
- Based on the research and development studies conducted, it may be concluded that its is simple and easy to apply a WSMCST with a real time monitoring system to any given air-cooled chiller system, gas turbine thermal power plants, cogeneration systems and geothermal power plants in order to improve their energy utilization efficiency values.
- It was determined that the installation of the WSMCST with a real time monitoring system enables its investment cost to recover in one season.

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