INVESTIGATION OF EVAPORATIVE COOLING EFFECTIVENESS ON THE PERFORMANCE OF AIR – COOLED CHILLERS

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Abstract: The cooling performance of air – cooled systems highly depends on ambient air conditions. It is widely known that, the performance of the system decreases when the inlet air temperature increases. This effect especially occurs in summer when the ambient air temperature is high and the cooling load is at its peak value. In order to decrease the inlet air temperature, evaporative cooling can be used. Evaporative coolers can be well combined with air – cooled chillers to decrease the inlet air temperature of condenser. Evaporative cooling is simple and economical way to cool the inlet air since it does not require any mechanical refrigeration and consumes very low power by fan and pump. Therefore combining these two systems can be considered as energy efficient method. As known, evaporative cooling performance strongly depends on the effectiveness of the evaporative cooler. In this study, studies on air cooled chillers with evaporatively cooled condenser have been assessed and the evaporative cooling effectiveness on the performance of air – cooled chillers is investigated.

Keywords: evaporative cooling, effectiveness, air-cooled chillers

Introduction

A chiller is a heat transfer unit which uses mechanical refrigeration to remove the heat from a process and transfers it to the environment. There are two types of chillers which differentiate by the method they use to condense the refrigerant as it leaves the compressor in cooling cycle. Air – cooled condensers use the ambient air for this operation. Second type, which is called water – cooled condenser uses a pump to circulate the water and sends the water to a cooling tower. Air – cooled chillers are easy to maintain and do not require a cooling tower or condenser water pump compared to water – cooled chillers. However air – cooled chillers are generally capable of cooling small sized air conditioning systems such as residential split heat pumps (Hajidavalloo 2007, Hwang et al. 2001). Being simpler than a water – cooled chiller has its advantages but at the same time it comes with certain limitations. Since the cooling is done by air, the performance of the system rely on the air temperature. According to the available research in the literature, when the air temperature approaches to 50°C or higher, the performance of the condenser drops down and the compressor is forced to work under high pressure ratio resulting in more power consumption (Hajidavalloo, 2007). But at the same time if the proper conditions are provided, it is possible to increase the cooling capacity and Coefficient of Performance (COP) of the air – cooled chillers. Hwang et al. (2001) compared an evaporatively cooled condenser and a conventional air – cooled condenser for a split heat pump system. Their results showed that, evaporative condenser had higher capacity than air – cooled condenser by 1.8 to 8.1% and a higher COP by 11.1 to 21.6%.

Several research has been done to reduce the inlet air temperature of air – cooled chillers. Wang et al. (2014) performed an experimental investigation on an air conditioning system. They tried to increase COP by locating an evaporative cooling unit upstream from the condenser. They measured several thermal parameters such as relative humidity (rh), dry and wet bulb temperature to evaluate the effect of evaporative cooling on COP. Pre-cooling the air by using evaporative cooling increased the COP from 6.1% to 18% along with a power reduction on compressor by 14.3%. Camargo et al. (2005) studied the direct evaporative cooling from thermal comfort point of view and presented a mathematical model. They claimed that evaporative cooling is more efficient where the climate is hot and dry. Their results confirmed this statement by obtaining higher efficiency with higher temperatures. They also investigated the electric power consumed by the evaporative cooler as a function of the air flow. It showed that the equipment consumed approximately 200 W at the maximum air flow which is a very small amount of consumption compared to conventional air conditioning systems.

Sarntichartsak and Thepa (2013) have done the modelling and experimental analysis of an inverter air conditioner with evaporatively cooled condenser. Their main objective was to determine the proper operating strategies, capillary tube length and optimal amount of refrigerant for the system. The results revealed that lower flow rates can increase the COP more due to the lower total power consumption. For instance, COP increased by 18.32% and 31-35% at spraying rate of 200 l/h and 100 l/h, respectively. In addition, researchers also tried to reduce the refrigerant charge in evaporative cooling and found out that 1.1 kg charge could be obtained as optimum amount. In another study, the energy performance of an indirect and direct evaporative cooler assisted outdoor air system is investigated (Kim & Jeong, 2013). The experimental analysis is performed on a pilot unit that installed in a campus building and both cooling and intermediate seasons are evaluated. In order to make a comparison, the researchers were also installed a conventional variable air volume (VAV) system. They have reported that the proposed system shows 51% energy saving in the intermediate season but 36% more energy consumption in cooling season over the conventional VAV system. Researchers claimed that the reason behind the increased consumption was the limited performance of evaporative coolers in hot but humid climate.

It is clear from the previous research that evaporative cooling is a highly preferred method for reducing the inlet air temperature of air – cooled condensers, thus increasing the performance of the system. In addition, providing optimum conditions for evaporative cooling will have a positive effect on air – conditioning systems which naturally become the main objective of the many studies. However along with the inlet air temperature and humidity, evaporative cooler performance is strongly dependent on its own effectiveness. Therefore in this study, 3 different evaporative coolers with 0.6, 0.7 and 0.8 effectiveness are compared. Various inlet air temperature values (26, 28, 30, 32, 34 and 36°C) and 4 levels of relative humidity (30, 40, 60 and 80%) are taken into consideration during the analysis. Depending on these parameters the change in the evaporative cooler outlet air temperature is calculated. Air – cooled chiller performance is evaluated by COP values of the air conditioner for each case.

The Study

Evaporative cooling process depends on the thermodynamic principle of adiabatic humidification of air. The required energy for evaporation from either a wet surface or a misting system is absorbed from the air thus providing the cooling effect. At the end of the process, the cooled air gains humidity as a result of evaporation. This process is called direct evaporative cooling and can be seen on a psychrometric chart in Figure 1. On the chart, cooling occurs on the wet bulb temperature line of inlet air. The highest point on the line (2x) indicates the saturated state which is impossible to reach in practice. The real point where process usually ends (2) has around 10-30% lower relative humidity. The exact place of this point depends on the effectiveness (ε) of evaporative cooler and determines the outlet temperature (T_2).

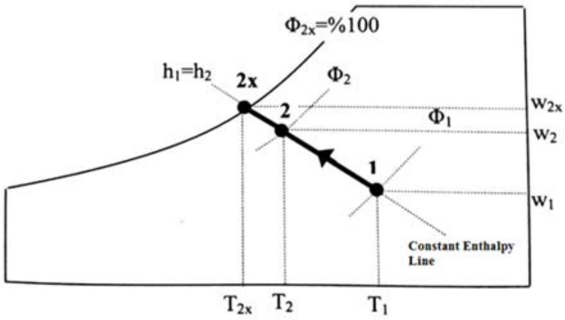

Figure 1: Adiabatic humidification of air

The following equation allows calculating the properties of outlet air;

$$\varepsilon = \frac{T_1 - T_2}{T_1 - T_{2x}} = \frac{w_1 - w_2}{w_1 - w_{2x}} \qquad (1)$$

where, T_1 is inlet and T_2 is outlet dry bulb temperature, T_{2x} is outlet wet bulb temperature, Φ is relative humidity and w is specific humidity values of corresponding points.

In this study, the effects of evaporative cooling on the chiller performance is analyzed. As it is stated by other researchers, the COP of an air conditioning system can be increased by reducing the inlet air temperature of the air – cooled condenser (Sarntichartsak & Thepa 2013, Wang et al. 2014). One of the ways to be able to reduce this temperature is to use evaporative cooling. However the evaporative cooler performance is highly dependent on its own effectiveness thus, the key consideration of the study is the comparison of effectiveness. Therefore 3 different evaporative coolers with 0.6, 0.7 and 0.8 effectiveness are investigated.

The condition of the air is also an important factor for evaporative cooling performance. It is known that evaporative cooling is more favorable in hot and arid areas (Liu et al., 2015). For this reason, along with the various inlet air temperature values (26, 28, 30, 32, 34 and 36°C), 4 levels of relative humidity (30, 40, 60 and 80%) are taken into consideration. Depending on these parameters the change in the evaporative cooler outlet air temperature is calculated.

The primary objective here is to reduce the outlet air temperature as much as possible because this air source will be the inlet air of the condenser. In order to make a performance analysis and to evaluate the effect of the inlet air temperature, the following equation (Koçak Soylu & Atmaca, 2015) is used;

$$COP = 0.0013\ \ T_{in}{}^{2} - 0.1664\ \ T_{in} + 7.1605 \qquad (2)$$
$$20°C < T_{in} < 50°C$$

In this equation, T_{in} is the inlet temperature of the condenser which is equal to T_2.

Findings

In this section, the results of the calculations will be presented. First of all, in order to accomplish main objective of the study, the effectiveness of the evaporative cooler is investigated. The outlet temperatures obtained for 3 different evaporative coolers with 0.6, 0.7 and 0.8 effectiveness is presented in Figures 2, 3 and 4, respectively. During these calculations, remaining ambient conditions for the inlet air was considered identical for all 3 situations.

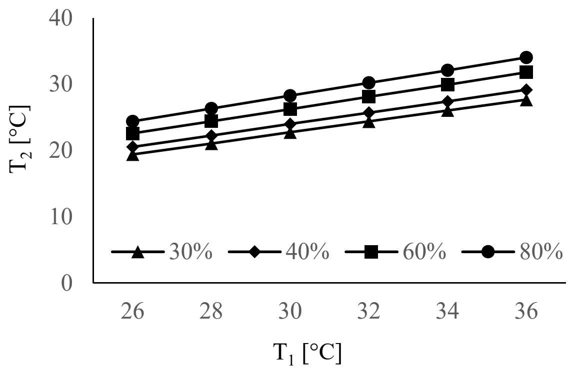

Figure 2: Outlet air temperature change at different relative humidity levels for 0.6 effectiveness

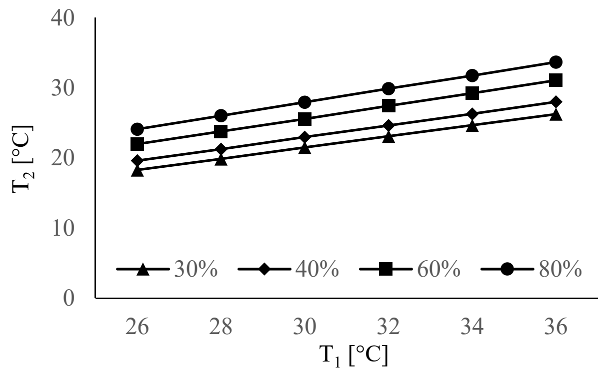

Figure 3: Outlet air temperature change at different relative humidity levels for 0.7 effectiveness

It is clear from all 3 figures that when the effectiveness increases, the outlet temperature decreases. For instance, 26°C inlet air at 30% relative humidity came out as 19.4°C, 18.3°C and 17.2°C for 0.6, 0.7 and 0.8 effectiveness, respectively. Even on the worst case scenario when the temperature is low and the relative humidity is high, the evaporative cooler with highest effectiveness still had the lowest outlet temperature compared to other two.

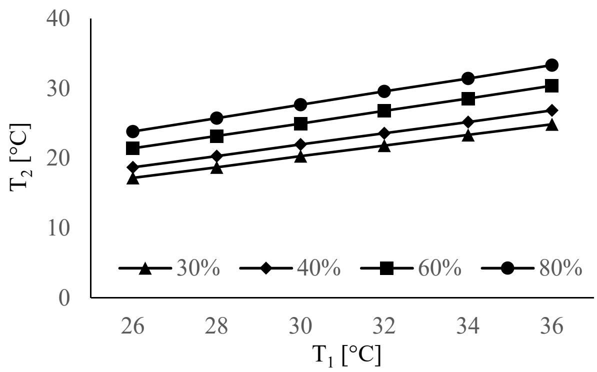

Figure 4: Outlet air temperature change at different relative humidity levels for 0.8 effectiveness

On the other hand, even with the most effective evaporative cooler, it was harder to cool the air when the humidity is increased. The evaporative cooler with 0.8 effectiveness cooled the air from 36°C to 24.9°C at 30% rh while it could only make it to 33.4°C at 80% rh. This result proves the importance of inlet air conditions and especially the relative humidity.

Performance analysis of the air – cooled chiller is evaluated by COP calculations due to the change in condenser inlet air temperature. The obtained evaporative cooler outlet temperature values are used as inlet air temperature in equation 2 and COP values for each case is calculated. The results are given in Table 1. In Table 1, each row represents the COP value obtained from the evaporative cooler outlet temperature when the inlet temperatures were again 26, 28, 30, 32, 34 and 36°C. These results are in accordance with the fact that the condenser inlet air temperature is inversely proportional with COP. In addition it is generally believed that the COP of an air conditioner decreases about 2-4% by increasing condenser temperature for 1°C (Hajidavalloo, 2007). This situation is also apply for our cases. For instance, decreasing the effectiveness from 0.7 to 0.6 increased the condenser inlet temperature from 18.3°C to 19.4°C at 30% relative humidity. This almost 1°C change in inlet temperature resulted decreasing the COP from 4.55 to 4.42 which is approximately 2.94%.

Although it should be kept in mind that significant amount of COP increase can be achieved if the evaporative cooling is applied at proper climate conditions. In Table 1, for the same inlet temperature in each row, the highest COP achieved when the relative humidity was lowest and it started decreasing while the humidity increased. As an example, for 0.7 effectiveness in the first row the COP decreases from 4.55 to 3.90 while relative humidity increases from 30% to 80%.

Table 1: The results of the COP calculations for each case

ε	**0.6**				**0.7**				**0.8**			
Φ	30%	40%	60%	80%	30%	40%	60%	80%	30%	40%	60%	80%
COP	4.42	4.29	4.07	3.88	4.55	4.40	4.13	3.90	4.68	4.50	4.19	3.93
	4.24	4.10	3.87	3.68	4.37	4.21	3.94	3.71	4.50	4.32	4.00	3.74
	4.05	3.92	3.69	3.50	4.18	4.02	3.75	3.52	4.32	4.13	3.82	3.55
	3.87	3.74	3.51	3.32	4.01	3.85	3.57	3.35	4.15	3.96	3.63	3.37
	3.71	3.58	3.35	3.16	3.84	3.68	3.41	3.19	3.98	3.79	3.47	3.21
	3.55	3.41	3.18	3.00	3.69	3.52	3.24	3.03	3.83	3.63	3.30	3.06

Conclusions

The main objective of this study was to evaluate evaporative cooling effectiveness on the performance of air – cooled chillers. In order to achieve this goal, 3 different evaporative coolers with 0.6, 0.7 and 0.8 effectiveness are compared. Performance analysis also included the ambient air conditions in terms of temperature and humidity. The analysis results revealed that with high effectiveness and at hot and arid regions, evaporative cooling is a very useful method for decreasing inlet air temperature of condensers. Air – conditioning systems can benefit from evaporative coolers with their increased capacity and lower energy consumption compared to conventional air – cooled chillers.

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