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ABSTRACT

This paper presents an experimental investigation of the application of direct evaporative cooling to reduce energy consumption in a residential sized split Air-Conditioning system. Direct evaporative cooling is employed at the air-cooled condenser of a split air-conditioning system to pre-cool the ambient air flowing over the condenser coils. Different ambient conditions of air were simulated using a heater to mimic typical high temperature environments. Rigid cellulose pads with thickness ranging from 2-6inches (5.1cm-15.24cm) served as the heat exchange medium for air-water interaction, and were tested to determine the influence of the pad thickness in pre-cooling the ambient air before it flows over the condenser coils to extract heat from the refrigerant in the condenser. It was observed that a 1^0C drop in ambient air temperature causes the condensing temperature of the refrigerant to drop by 0.6^0C. This drop in condensing temperature of the refrigerant causes a decrease in power consumption of the unit, accompanied by an increase in Coefficient of Performance (COP). Results obtained shows that up to 44% increase in COP, and a 20% decrease in power consumption can be achieved by employing evaporative cooling. Additionally, the COP was found to increase by 4% for every 1^0C drop in refrigerant condensing temperature. The water consumption pattern of the hybrid system is monitored to provide a realistic estimate of the operating cost, and profitability of the hybrid system. It was observed that 0.34liters of water is consumed for every percent increase in COP. To provide a realistic estimate of the daily water consumption of the hybrid system, the operation time was increased from 1-4hours, in step increments of 1hour. The volume of water consumed was found to increase by a factor of 1.8, 2.5, and 3.2, for 2hrs, 3hrs and 4hrs of operation respectively. This shows that as the operating hours of the hybrid system in a day increases, the volume of water consumed will decrease.

1. INTRODUCTION

Air-Conditioning (AC) systems are part of the family of Vapor Compression units that produces a cooling effect by alternate compression and evaporation of a refrigerant. Over the years it's been observed that these systems account for nearly 30% of all energy used in commercial and residential buildings. Additionally, electricity demands by these systems have been observed to peak during summer, or in areas with high daily ambient temperature(McKenzie, Pistochini, Loge, & Modera, 2013). In Air-Conditioning systems, the heat of compression is usually rejected at the condenser, which is typically air-cooled. This means that a lower temperature sink (air in this case) is necessary for heat transfer from the source (refrigerant in the condenser). This becomes nearly impossible under high temperature environment, when the air is almost at the same temperature as the refrigerant. The result of this is that little condensation occurs and this results in less liquid reaching the evaporator. Ultimately, a reduction in cooling capacity occurs and the compressor is forced to do more work because the thermal expansion valve attempts to open up in order to allow more flow of refrigerant, thus increasing the flowrate of the refrigerant.

It is therefore imperative to ensure that condensation of the refrigerant proceeds in a way that does not reduce the system efficiency or Coefficient of performance (COP).

The goal of new research on air-conditioning systems is to develop more energy efficient systems**.** Applying evaporative cooling at the condenser of existing split air-conditioning systems have been observed as a possible means of achieving the aforementioned goal. Evaporative cooling works by absorbing energy from air and using this energy to evaporate water into the air. This cause a drop in the temperature of the air and an increase in its humidity ratio.
According to(Turner & Chen, 1987), the output (cool air) from an evaporative cooling (EC) unit can be staged to cool the AC condenser coil. The degree to which air can be cooled is controlled by several factors such as the media pad thickness, velocity of the incoming air and its temperature, in addition to the humidity(Bhatia, 2012). (Sheng & Agwu Nnanna, 2012) studied the effect of frontal air velocity, dry bulb temperature of the incoming air and the water temperature on the cooling efficiency of a cellulose media pad. Their results showed that at higher incoming air temperature, the cooling efficiency was increased. In addition, greater cooling was achieved at low water temperatures. They also obtained a correlation between the cooling efficiency and frontal air velocity for the range $0.8<v<3$m/s. (Wu, Huang, & Zhang, 2009) carried out a numerical investigation of heat and mass transfer in an evaporative cooler. They used GLASdek as the evaporative media and studied the influence of frontal air velocity, pad thickness, inlet air dry-bulb and wet-bulb temperatures on the cooling efficiency of the evaporative cooler are calculated and analyzed. Results indicated that the cooling efficiency decreases with increasing inlet frontal air velocity and increases with an increase in pad thickness, and gradually, the influence becomes less notable. The results from the simulations were compared with the experimental result for the same conditions to validate the present models and method. Recently there has been a trend towards applying direct evaporative cooling to Vapor compression cycles to improve their heat rejection capacity at the condenser. (Hajidavalloo & Eghtedari, 2010) retrofitted the condenser of a 1.5 TR split air conditioning system by an evaporatively cooled condenser and showed that energy savings of the order of 11–20% as the outdoor temperature varied from 36 to 49^{0}C, can be achieved, and COP can be approved by up to 50%. However, they did not quantify the water consumption characteristics of the system, they only mentioned that the system consumes a small amount of water.(Wang, Sheng, & Nnanna, 2014) retrofitted cellulose media pad in front of the condenser of a residential sized split air-conditioning unit. They studied the P-h and T-S diagram, and obtained a COP increase of 6.1-18% and up to 14.3% drop in power consumption for ambient air-temperature ranging from 24-45^{0}C. Evaporative cooling retrofits is not limited to air-conditioning systems. (Nasr & Hassan, 2009) applied evaporative cooling to the condenser of a refrigerating system by making use of cloth sheets wrapped round copper serpentine (which acts as the condenser) and inserted in a shallow basin. The cloth sucks water by capillary action and wets the tubes. Inlet air flowing over the condenser got cooled by evaporation of water on the tubes. (Chan & Yu, 2002) applied condensing-temperature control in a water chiller and obtained savings between 18-29%. (Huan, Shijun, Hongxing, & Jianlei, 2000) applied direct evaporative cooling to an existing Air-cooled Chiller, using corrugated holed aluminum foil fillers (CHAF fillers), as the cooling pad, and showed that the effectiveness of the evaporative cooling process depends on the frontal air velocity, and specified an optimum velocity of between 2.0ms^{-1}-2.8ms^{-1}. Review of the above literatures proves evaporative cooling to be a good option to augment the performance of air-conditioning systems, however, water is consumed during the process and is very expensive in some areas or not readily available. This study aims to provide an accurate description of the water consumption characteristics of an Air-conditioning system employing direct evaporative precooling of the condenser air. In addition, correlations are established which can be used by government agencies, and other decision makers to predict the performance of such systems in any climate, and serve as a guide to implementation of such technology in a place. Aside the compressor, the pump which supplies water to the cooling pad is also optimized to reduce energy consumption, by avoiding constant recirculation of water.

2. MATERIALS AND METHODS

2.1 materials

A 1.5TR (ton of refrigeration) residential sized split air-conditioning system was used for the experiment. K-type thermocouples and pressure transducers attached at different points of interest are used to measure the temperature and pressure of the refrigerant (R-410A) across the refrigeration cycle. This were connected to a bench-link data logger (manufactured by Keysight technologies), and data was collected at an interval of 2s for the duration of the experiment. Temperature readings are read with ±1% accuracy, while pressure readings are within an accuracy of ±1.5%. A heater was installed downstream of the condenser fan, as shown in Figure 2, to simulate different outdoor conditions. The heater temperature was varied from 25^{0}C-42^{0}C, to test the performance of the system under typical outdoor conditions. The air-cooled system was fitted with evaporative cooling pads manufactured by Dial. The pad was used as the heat exchange medium for air-water contact, as shown in Figure 1. The pad was cut consistent with the rectangular shape of the condenser to cover the entire surface area (56cm X 60cm) of the condenser. A water distribution network was locally fabricated to deliver water to top of the pad, and evenly saturate the pad. The water distribution network was constructed out of a ½'' ID rubber hose, 60cm (2ft) in length, to cover the entire width of the pad. Holes with a diameter of 0.086inches (made with size 44 drill bit) were bored along the length of the hose. The holes are made on two sides of the hose, having a distance of 0.5cm between each pair of hole (on both side). This was necessary to give the water leaving the holes a near conical pattern, which ensures a more uniform distribution. A total of 64 holes, 32 on each side and separated by 2cm gap were made on the hose. Placing the hose at a distance of 2cm from the top of the pad and at its center ensures water dripping from the hose reaches the air entering (site for intense evaporation) and air leaving face of the pad without going past the pad extremes. The flute angles of the pad serves to direct water on all surfaces of the pad. This design also ensured that water dripped to the bottom of the pad, and there was no carry-over of water droplets. A water sump was placed beneath the pad to collect excess water beyond that needed for the pad saturation. The pads which came in standard thickness of 12inches, and 8inches were cut to desired thickness of 2, 4, and 6inches and were used for the experiment. A water recirculation bath was employed to distribute water to the spray network placed 2cm above the pad, water from the sump is also collected and recirculated during the experiment.

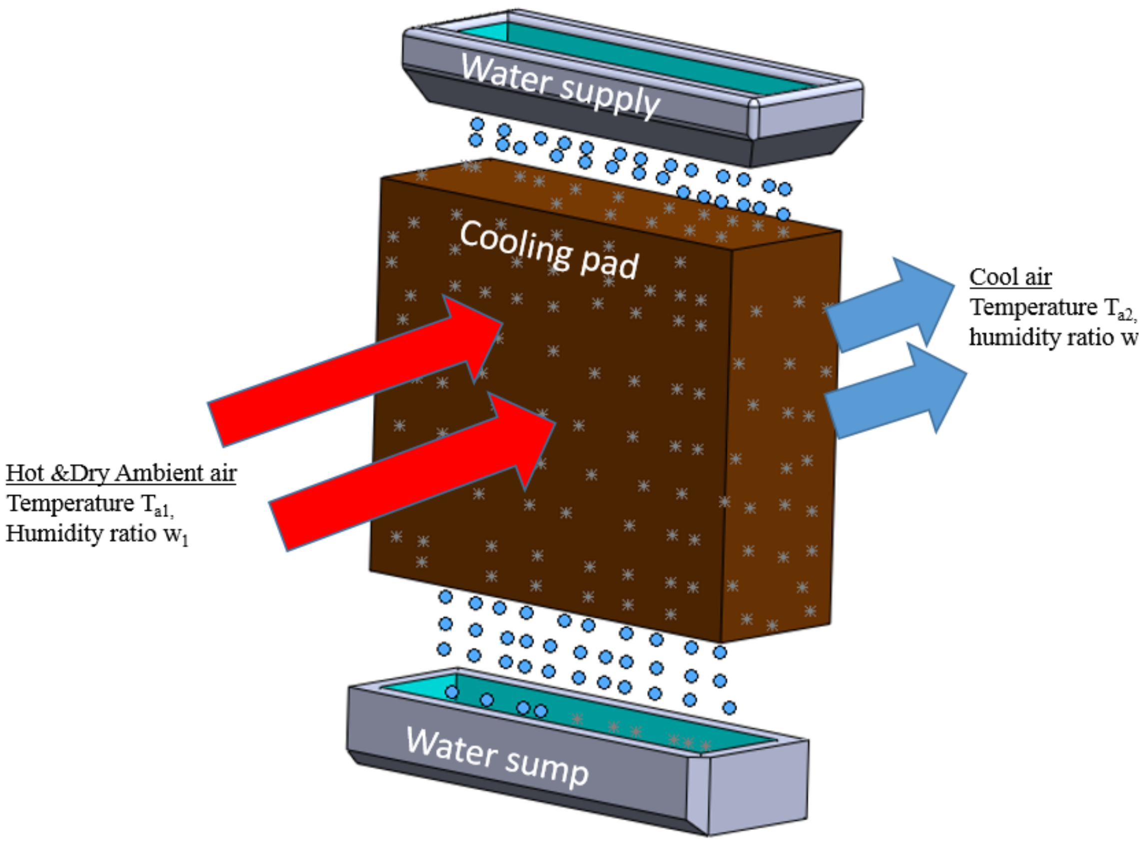

Figure 1: How evaporative cooling works

2.2 methods

The experiment consist of two stages, the first stage involves running the air-conditioning system at a set outdoor condition, without evaporative cooling (this is referred to as the air-cooled case). In the second stage, evaporative cooling is initiated at the condenser, at the same outdoor condition as the first stage. The heater temperature was varied from 25^0C -42^0C with relative humidity of about 48.9% at the lower temperature limit to about 20.1% at the upper limit, to mimic typical outdoor condition. The unit was left to run for an hour, to ensure steady state was achieved and also to mimic a realistic operation of an air-conditioning unit. Temperature and Pressure of the refrigerant across the cycle were recorded using K-type thermocouples connected to the data acquisition system. Additionally, the current drawn by the compressor was measured using a current clamp attached to the compressor power line. Within a time interval of two minutes, the second stage of the experiment was initiated by turning on the water supply. This is necessary to ensure that inlet air conditions are constant, so as to provide an accurate comparison of the conventional case with the hybrid system (evaporative cooling case). Water at room temperature (21^0C) was supplied to the top of the cooling pad at a flowrate of 2gpm, and excess water dripped to the sump at the base of the pad and was recirculated. Air properties such as temperature and relative humidity of the air before and after the cooling pad were logged using relative humidity probes with USB support (Omega RH-USB), as shown in Figure 2. The relative humidity sensors had an accuracy of ±3% relative humidity, and ±1^0C temperature. The unit was operated for an hour, to ensure steady state is reached and also to monitor hourly water consumption of the system. After one hour of operation, the current drawn was measured as before, refrigerant temperature and pressure were also recorded and used for subsequent calculations of the COP.

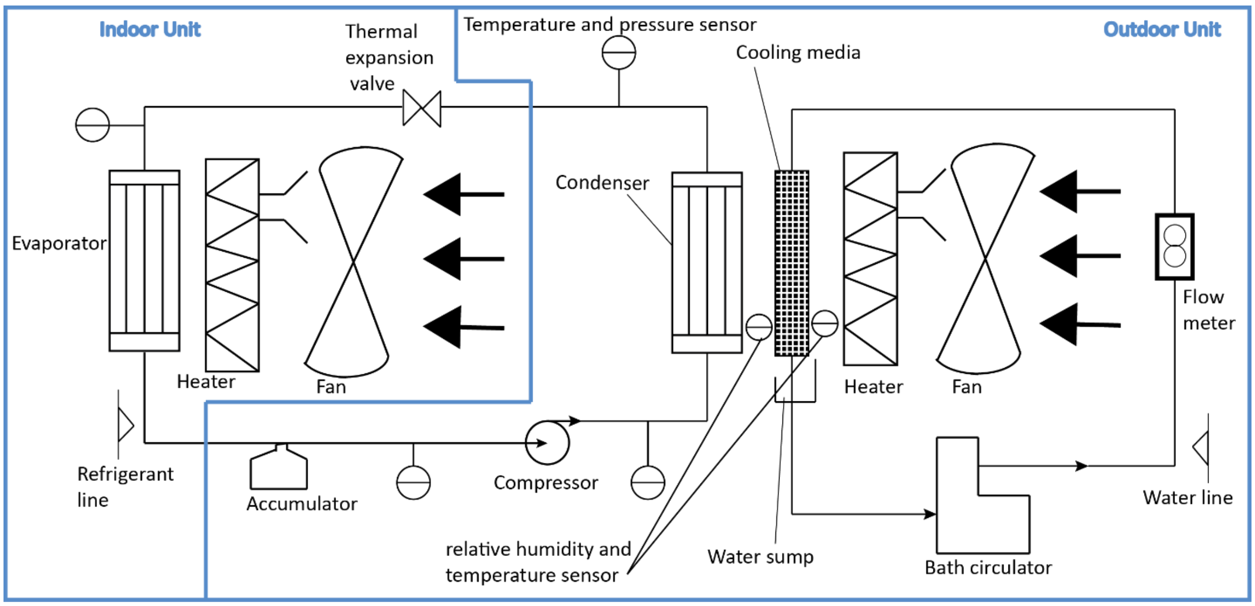

Figure 2: Experimental Set-up

3. RESULTS AND DISCUSSION

3.1 cycle efficiency

The COP is a measure of the efficiency of Vapor Compression cycles like an Air-Conditioning cycle. The COP is obtained from the ratio of the output from the system to the input needed to create that output. The output in this case is the cooling/refrigerating effect, which can be determined from the enthalpy difference of the refrigerant across the evaporator. The input is the compressor work which is evaluated from the enthalpy difference of the refrigerant across the compressor. The refrigerant enthalpy is computed from pressure and temperature data obtained during the experiments.

$$COP = \frac{cooling\ capacity}{compressor\ work} = \frac{h_1 - h_4}{h_2 - h_1} \tag{1}$$

$$\varepsilon = \frac{COP_{dec} - COP_{ac}}{COP_{ac}} \times 100 \tag{2}$$

ε represents the enhancement in COP as a result of applying evaporative cooling, the subscript 1, represents the exit of the evaporator, 4 is the inlet, 2 is the exit of the compressor.

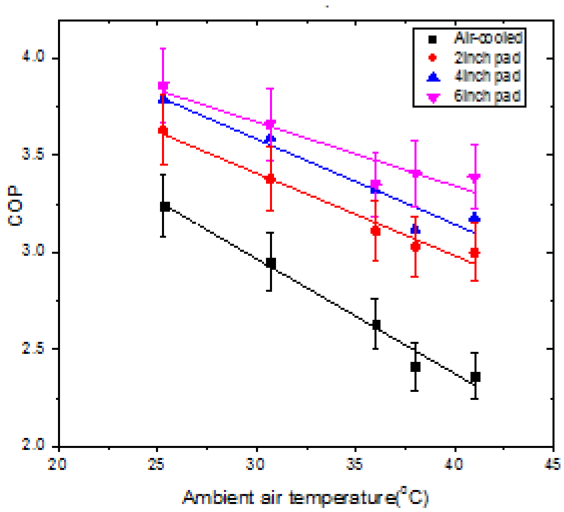

Figure 3: COP of the system at different ambient Temperatures

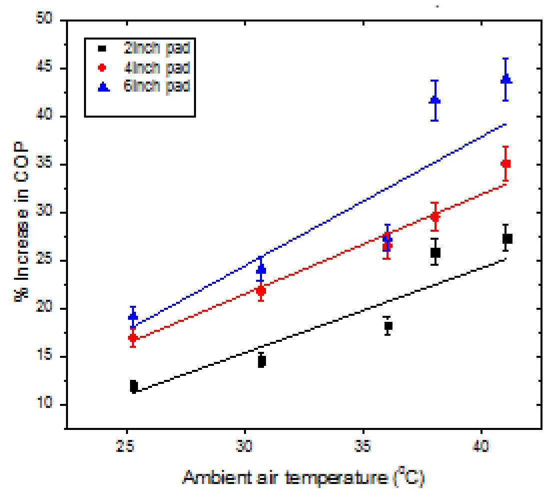

Figure 4: Percentage drop in COP at different ambient at different ambient air temperature

Figure 3 Shows that the COP of the system was enhanced by application of evaporative cooling, no matter the thickness of the pad used. This shows that any decrease in the temperature of the air flowing over the condenser coil will cause an increase in the COP by increasing the rate of heat loss by the condensing refrigerant. The COP is seen to decrease as the ambient temperature increases. This is due to the increase in temperature and pressure of the refrigerant leaving the condenser, which causes an increase in compressor work, and by equation (1), an increase in compressor work will cause a decrease in COP and vice versa. Additionally, as the ambient air temperature increases, its capacity to cool the condenser reduces. Even with the application of evaporative cooling, the COP still decreases at higher ambient air temperature. The 6inch pad was found to do best in comparison to the rest. This is because of the greater residence time (~0.1s) of the air passing through this pad, which created a better opportunity for air-water interaction, and caused a greater temperature drop of the incoming air. However, our results shows that no significant increase in COP is achieved by using the 6inch pad at a temperature of about 25^0C. At such low temperature the 2inch pad was sufficient to cause an adequate increase in COP. Passing air at this low temperature through a pad with greater depth, had no significant advantage, rather it only resulted in wastage of water and pump power. Similarly at temperatures between 30^0C -36^0C, the 4inch pad will suffice, using the 6inch pad will only result to slight increase in COP but will also result to greater water consumption. Moreover, for outside air temperatures above 36^0C, the 6inch pad will produce better enhancement in COP.

Figure 4 shows that there is a greater percentage increase in COP at higher temperatures compared to lower temperatures. This is also noticeable by comparing the margin at different temperatures of each of the evaporative cooling case with that of the air-cooled base line, shown in Figure 3. This shows that evaporative cooling works best where and when it is needed (under high temperature conditions where the COP of an air-conditioning system is reduced, and evaporation of water is favored). The maximum percentage increase in COP obtained was 44%, 35%, and 27% for the 6inch, 4inch, and 2inch pad respectively. Evaporative cooling and greater enhancement in COP is favored at higher temperatures because of the increase in the evaporation rate, this causes a greater drop in air temperature. However, at lower temperature, evaporation rate is decreased, and in such case, the usefulness of evaporative cooling is greatly diminished.

3.2 compressor work and power consumption

The compressor work is obtained by an energy balance around the compressor, and is given by:

$$W_c = m_R(h_2 - h_1) \qquad (3)$$

Equation (3) states that the compressor work (W_c) is the product of the mass flowrate (m_R) of the refrigerant and the enthalpy difference of the refrigerant across the compressor.

The Power (W_p) consumed by the compressor can be determined by the product of the current (I), voltage (V) and the power factor. The power factor (***Φ***) of our compressor is given as 0.84. The power factor takes account of some portion of the electrical energy supplied to the compressor which is not used for useful work but rather converted to heat.

$$W_p = I \times V\ cos\emptyset \tag{4}$$

The power consumed by split air-conditioning systems depends on the weather condition of the place. Result shows that for the air-cooled unit, at ambient temperature of about 25.3^{0}C, the power consumed was about 1.7KW, an increase in ambient temperature to 41.3^{0}C also increased the power consumption to about 2.1KW, almost a 24% increase. This increase in power with air temperature was also observed even when evaporative cooling was employed.

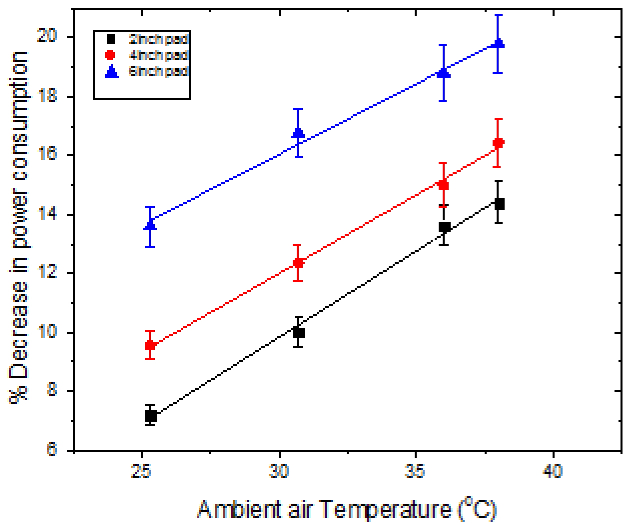

Figure 5*:* Percentage drop in Power consumption at different ambient temperatures

The COP is inversely proportional to the compressor power consumption. Applying evaporative cooling raises the COP, by decreasing the power consumption. Just as in Figure 4, greater decrease in power consumption is observed at higher temperatures, because evaporative cooling is favored under such condition. The 6inch pad is found to cause the greatest percentage decrease in power consumption, followed by the 4inch pad. A 20% decrease in energy consumption was achieved for the 6inch pad, 18% for the 4inch and 14% for the 2inch pad, as shown in figure 5.

3.3 mass flow-rate of refrigerant (R410A)

The mass flowrate was computed from equations (4) and (5) by setting W_p equal to W_c. An expression for the mass flowrate is

$$m_R = \frac{I \times V\ cos\emptyset}{h_2 - h_1} \tag{5}$$

A plot of the Mass flowrate of the refrigerant as a function of the ambient air temperature, clearly reveals that as the condenser air temperature increases, the mass flowrate of refrigerant increases, as shown in Figure 6 below. This happens because more work will be performed by the system in circulating the refrigerant, and thus more electrical current will be drawn by the compressor. Applying evaporative cooling cause a drop in air temperature. Using the 6inch pad will cause the least mass flowrate of refrigerant, followed by the 4inch and then the 2inch pad. This is because the 6inch pad produces the greatest reduction in the air temperature flowing over the condenser, and thus the compressor does the least work under this condition. At low condenser temperatures, the compressor has less work to do and the system will run more efficiently.

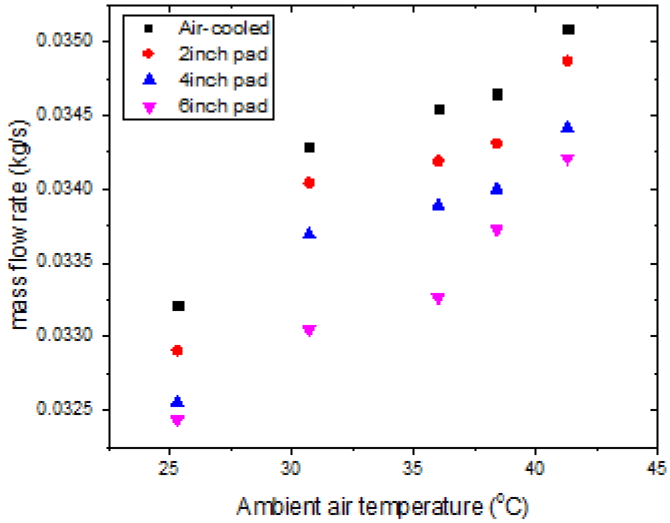

Figure 6: Mass flow-rate of the refrigerant with increase in ambient temperature

3.4 water consumption

The amount of water consumed is typically made up of two components; water consumed for the air cooling process, and secondly, water used for bleed off to avoid buildup of minerals and dirt's in the sump. The water consumed was computed by measuring the amount of water supplied at the beginning of the experiment, using a measuring cylinder and subtracting that remaining from this value at the end of the experiment.

The amount of water lost by evaporation (M_{we}) or consumed was also verified using equation (6).

$$M_{we} = \rho V_a (w_2 - w_1) \tag{6}$$

W_2 and W_1 represents the exit and inlet air relative humidity, V_a is the volumetric flowrate of the air and ρ is the density. The results obtained on water consumption shows that the quantity of water consumed depends on the temperature of the air to be cooled and also on the thickness or depth of the pad, as evidenced in Figure 7. The water consumed was found to increase between 5-13litres for a temperature range of 25-41.3^{0}C using the 6inch pad, 4.3-10litres, and 4.3-6.5litres using the 4inch and 2inch pads respectively for the same range of temperature. The increase in the volume of water with increase in pad thickness is as a result of the increase in wetted surface area. Similarly, the volume of water evaporated increased as the ambient air temperature increased, this shows that high temperature favors evaporation.

The graph in Figure 7 is based on 1hr of operation. To provide a better description of the water consumption pattern of our system under typical daily operation time, the hours of operation was increased from 1hr to 4hrs with uniform step of 1hr. The amount of water used will vary with the type of media used, supply air volume, temperature and humidity content of the outside air and the number of operating hours. As shown in Figure 8, the volume of water consumed at any given temperature for any given pad thickness increases as the operation time increases. However, it was observed that the volume of water did not increase proportionally with the time step. For instance, the volume of water consumed for 2hrs of operation was less than twice that consumed for 1hr of operation, and that consumed for 3 hours of operation was less than thrice that consumed for three times that consumed for 1hr of operation and that consumed for 4hrs was less than four times that consumed for 1hr of operation. This happens because as time passes, there's a build-up of air with high relative humidity, and low temperature across the depth of the pad, so that as new incoming air enters the pad, at any temperature, it's relative humidity is raised to that of the air within the pad and thus the exit temperature of the air is maintained partly by mixing of the incoming air with the cooler air packets within the pad, and partly by the evaporative cooling process. This results in less water consumption as time progresses.

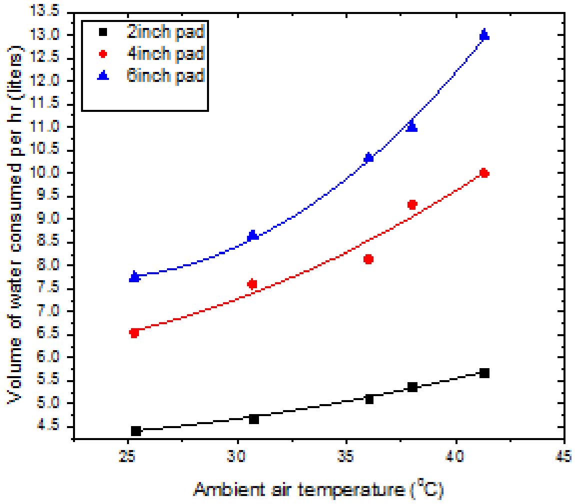

Figure 7: Hourly water consumption for each pad thickness at different ambient temperature

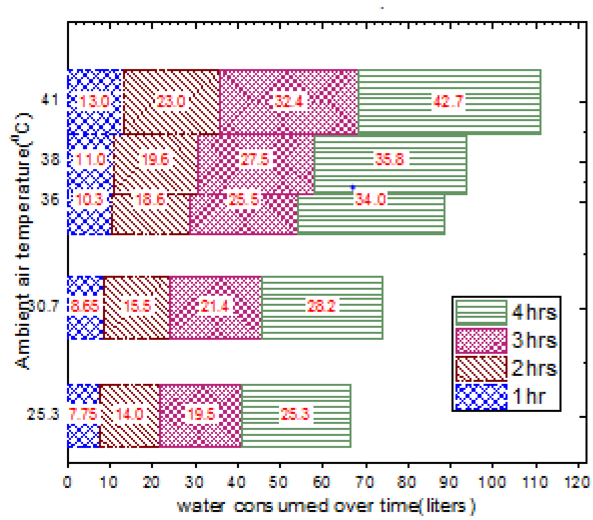

Figure 8: Variation of water consumed as operation time increases at different ambient temperature for the 6inch pad

3.5 optimization of pump power consumption

The possibility of turning on the pump at intervals without causing a spike (of more than +1^{0}C, which is the limit of accuracy of the measuring instrument) in the air temperature exiting the pad was investigated. This test was carried out at three different inlet air temperatures, for the three different thickness of pad considered. It took approximately 12minutes for the air temperature to reach steady state, for the range of temperature considered. The pump is turned on and the temperature of the air drops until a steady state value is attained, and it is then turned off and the air temperature is allowed to attain the initial value after which the pump is turned on again and the cycle is repeated again. The time interval over which the steady state temperature of the air is maintained while the pump is turned off is determined. Our results shows that the thickest pad (6inch) was able to maintain the steady state temperature of the air leaving the pad, over a longer time compared to the 4inch and 2inch pads, as shown in Figures 9-11. This is because of the larger wetted surface area which increases the drying time of the pad when the water supply is turned off. The 2inch pad is able to maintain the steady state exit air temperature for an average of 3mins over the temperature range considered, while the 4inch pad is able to maintain the temperature for an average of 4mins, and the 6inch pad for an average of 6mins. This implies that for one hour of operation of the pump, using the 2inch pad the pump could be turned off for a total time of 6mins. This will not only save energy used in recirculation of water by the pump but will also reduce wastage of water through leaks and also prevent flooding of the pad, which results from constant dumping of water on the pad. For the 4inch pad and 6inch pads, the pump can be shut-off for 8mins and 12minutes respectively in one hour of operation. In terms of energy savings, operating the pump in this fashion will reduce power consumption by 20% with the 6inch pad, 14% with the 4inch pad and 10% with the 2inch pad.

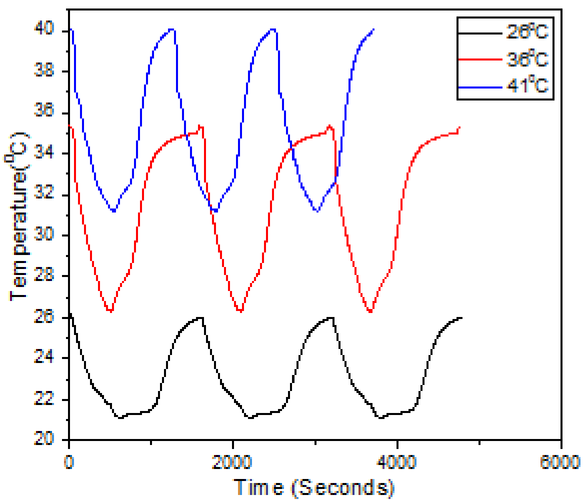

Figure 9: Temperature profile of the air in the 2inch pad

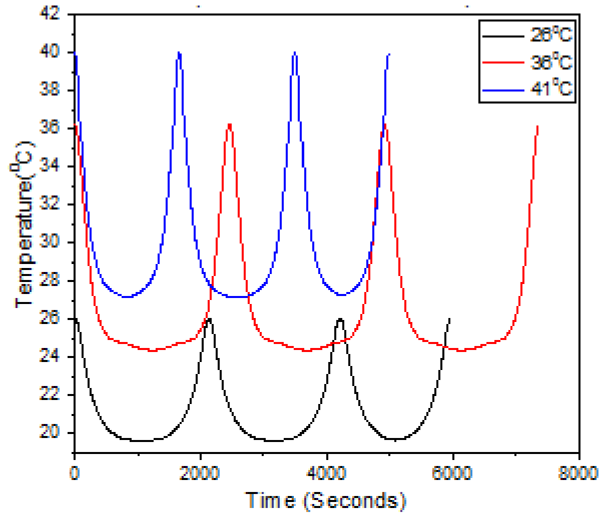

Figure 10: Temperature Profile of the air in the 4inch pad

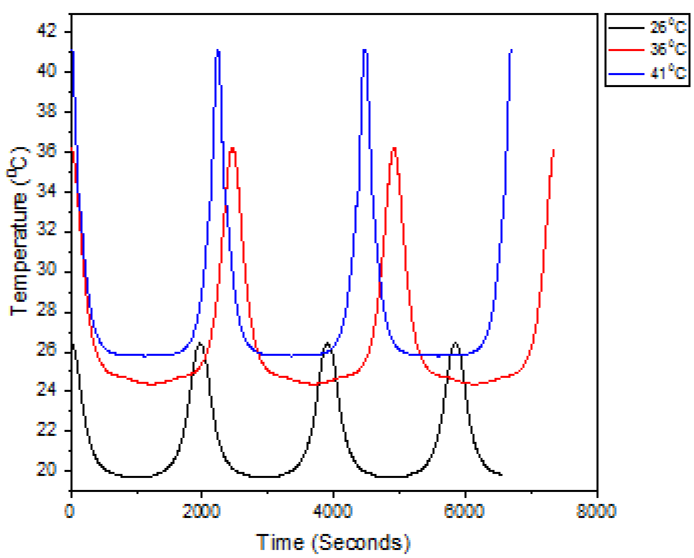

Figure 11*:* Temperature profile of the air in the 6inch pad

4. CONCLUSION

Evaporative precooling of condenser air is an effective means of reducing energy consumption in air-conditioning systems. The COP of an air-conditioning system can be enhanced by up to 44% by employing evaporative pre-cooling of the ambient air flowing over the condenser coils and power consumption can be reduced by up to 20% by employing evaporative cooling. Evaporative cooling works best when and where it is needed, it is favored under high temperature conditions where the performance of our air-conditioning system is greatly reduced. A greater enhancement in COP and overall savings is achieved at extreme temperatures because more evaporation occurs under this condition. Water is used up during the evaporative cooling process, the volume of water consumed is a function of the relative humidity/temperature of the air, air velocity, the number of hours of operation, and the pad depth.

This work shows that while water consumption increases with increase in operation time, it does not increase proportionally with time; the amount of water consumed after two hours of operation is less than twice that consumed for one hour of operation, similarly that consumed for three hours and four hours of operation is less than three times and four times of that consumed after one hour of operation, for any given ambient air condition. This work also shows that applying direct evaporative cooling is not only environmentally friendly but also reduces cost of operating conventional Split Air-Conditioning system. The retrofitted system will save about \$0.04 per hour of operation. The savings in Electricity is about three times the cost of water consumed. Using a 2inch pad under the air conditions tested will conserve water but produces lesser enhancement in COP at high temperatures above 30^0C. The total annual saving depends on the region, and the number of hours evaporative cooling is employed. Depending on the number of hours of operation in a day, water consumption will still decrease and this will translate to more savings. Intermittent operation of the pump is beneficial not only in terms of savings in energy used by the pump and reduction in water consumption, but also prevents buildup of water in the pad pores.

REFERENCES

Bhatia, I. a. (2012). Principles of Evaporative Cooling System.

Chan, K. T., & Yu, F. W. (2002). Applying condensing-temperature control in air-cooled reciprocating water chillers for energy efficiency. *Applied Energy*, *72*(3-4), 565–581. doi:10.1016/S0306-2619(02)00053-3

Palmer. (2002) Evaporative cooling design guidelines manual.

Hajidavalloo, E., & Eghtedari, H. (2010). Performance improvement of air-cooled refrigeration system by using evaporatively cooled air condenser. *International Journal of Refrigeration*, *33*(5), 982–988.

Huan, Z., Shijun, Y., Hongxing, Y., & Jianlei, N. (2000). Enhanced performance of air-cooled chillers using evaporative cooling. *Building Services Engineering Research and Technology*, *21*(4), 213–217. doi:10.1177/014362440002100401

McKenzie, E. R., Pistochini, T. E., Loge, F. J., & Modera, M. P. (2013). An investigation of coupling evaporative cooling and decentralized graywater treatment in the residential sector. *Building and Environment*, *68*, 215–224. doi:10.1016/j.buildenv.2013.07.007

Nasr, M. M., & Hassan, M. S. (2009). Experimental and theoretical investigation of an innovative evaporative condenser for residential refrigerator. *Renewable Energy*, *34*(11), 2447–2454.

the NEWS. (2004). Retrieved April 11, 2016, from http://www.achrnews.com/articles/94189-more-refrigerant-flow-problems

Sheng, C., & Agwu Nnanna, A. G. (2012). Empirical correlation of cooling efficiency and transport phenomena of direct evaporative cooler. *Applied Thermal Engineering*, *40*, 48–55.

Turner, R. H., & Chen, F. C. (1987). Research Requirements in the Evaporative Cooling Field. *ASHRAE Transactions*, *93*(pt 1), 185–196.

Wang, T., Sheng, C., & Nnanna, A. G. A. (2014). Experimental investigation of air conditioning system using evaporative cooling condenser. *Energy and Buildings*, *81*, 435–443.

Wu, J. M., Huang, X., & Zhang, H. (2009). Numerical investigation on the heat and mass transfer in a direct evaporative cooler. *Applied Thermal Engineering*, *29*(1), 195–201. doi:10.1016/j.applthermaleng.2008.02.018