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Increasing evaporative cooler efficiency by controlling water pump run and off times

S. Hossein Elahi *, S.D. Farhani

Department of Mechanical engineering, Arak University of Technology, 38181-41167 Arak, Iran

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ABSTRACT

One of the major problems with using the evaporative coolers is reduction in cooling capacity and cooling efficiency in high humidities and insufficient cooling capacity at high temperatures. In this paper a method is introduced which increases the cooling capacity, especially at higher temperatures and also it could maintain the cooler efficiency in high humidity weather. In this method the water pump Instead of operate continuously, it works intermittently and a control unit with its sensors control the operation time by tracing changes in outlet air or pads condition. In evaporative coolers by switching off the water pump, though a slow increase in the outlet air temperature is expected, the temperature falls gradually which means the cooler cools the air down more efficiently. This phenomenon could be attributed to pads lower temperature due to evaporation of some portion of water on pad fibers. This method by using this missing character of the evaporative coolers, makes the cooler perform the same as the two-stage indirect/direct evaporative cooler; in the two-stage cooler, the already cooled air entered to a direct evaporative cooler but with this device the entered air encounters with pads that have already been cooled.

1. Introduction

Nowadays, long after industrial revolution, air conditioning is become a major part of the buildings and it consumes large portion of annual energy consumption and life cost of the buildings. Temperature rises due to climate changes and global warming and comfortable modern lifestyle has increased the demand for air conditioners no longer regarded luxurious. Energy consumption of air conditioners has been a topic of interest in HVAC industry. Evaporative coolers by consuming less energy are potential alternatives. Evaporative coolers are simple type of air conditioning devices that have been around for a long time, in which air is cooled through the evaporation of water. The warm air in these coolers is cooled by using heat and mass transfer processes [1–3]. These devices are widely used in hot and dry areas such as India, Africa, middle east, Spain, Australia and also USA. In these areas the dry bulb temperatures (DBT) are around 40 °C with relative humidity less than 30%, those offers an excellent opportunity to use evaporative coolers [4].

The evaporative coolers only have simple fans and pumps and they do not use high cost, high energy consumption and high depreciation devices such as compressors. For this reason, low installation and operating costs, high maintainability [1], low energy consumption- 75-80% energy saving [1,5–9], being environmentally friendly [10–12] are main advantages of this air conditioning system. Moreover, in these coolers high volumetric flow rate provides a steady stream of fresh air into the house which reduces the age-of-air in the building dramatically, in such way that a complete air change occurs every one to three minutes [12,13].

Beside lots of advantages in evaporative coolers, some people believe that evaporative coolers would increase air humidity beyond the human comfort because increasing humidity to 70 to 90% may reduce the cooling effect of human perspiration [10]. Although relative humidity was increased in homes with evaporative coolers, the rate of increase was only about 10–16% RH which is not further than the human comfort conditions (25°C and 55% RH [14]) [15,16]. Since moisture is introduced by evaporative coolers, these cooler suspected to create conditions that support house dust mite (HDM) growth in regions where they are normally absent. Therefore, homes with evaporative coolers were significantly more likely to test positive for HDM allergens [16–18]. However, recent researches show that humidity levels were still blow the critical equilibrium humidity required for HDM survival [15,19]. Finally, these coolers do not aerosolize or transmit biological organisms

* Corresponding author.
E-mail address: H.Elahi@Arakut.ac.ir (S.H. Elahi).

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in the cooling water and the wet pads could filter incoming pollutants more effectively than dry filters [20].

High water consumption is one of the weaknesses of evaporative coolers to the extent that by using these coolers the annual household water consumption would be increased about 3% on average [21]. However, considering the water which would be used for electricity generation, the evaporative cooler consumed 67–90% more water than typical air conditioning systems [9,21].

Unlike other air conditioners which need airtight space to operate, evaporative coolers possess an open system. They rely on the flow of air through the building to navigate the cooled air. In these coolers it is important to create good ventilation in the room in order to push the humidity out to keep the ambient temperature comfortable and prevent moisture build-ups. This constant circulation would fresh the indoor air and by humidifying dry air it can reduce dry air symptoms such as itchy eyes, throat, or skin. Some evaporative coolers may also operate as humidifiers in the hot season for farming [1,22–24]. In other air conditioning systems which normally have a closed system, the cooling devices must be in operation even if no one is at house or building. These systems take 4–6 h to cool the inner warm air to a desired temperature. Nevertheless, an evaporative cooler has a special feature that distinguishes it from other air conditioners and it could be called “Fan Feature” which is due to its open system. Fans by moving the air could quickly remove heat from the building and also create wind chill effect which evaporates moisture and blowing heat away from the skin [13]. When the evaporative cooler starts to work, it can reach its maximum cooling capacity for less than 10 min and by high volumetric flow rate and “fan feature” it could provide comfort to humans very quickly. It seems unnecessary that air conditioning devices operate before entering the house. For this reason, thermostat controls could not operate properly in evaporative coolers and after turning the cooler off, the wind chill effect no longer exists and high humidity, very quickly, makes uncomfortable feeling.

Despite many benefits these coolers have, there has not been much research and development researches available worldwide [12]. Therefore, at least in the last 50 years and after the advent of mechanical vapor compression cycle, there is no optimization in these coolers and gradually they are being eliminated in competition with other air conditioning systems and devices [10]. It seems that simple structure and low price of evaporative coolers make it unattractive to researchers and manufacturers. If 20 million sets of these coolers are replaced with typical air conditioning systems, which use vapor-compression or absorption refrigeration cycles, then more than 60 million barrels of oil energy would be consumed and as a result 27 billion pounds more of carbon dioxide would be released in the atmosphere [25]. In Iran, replacement of evaporative coolers with air conditioners has led to a sharp rise in power consumption on hot days, which has resulted in growing peak load demand and consequently electricity shortage in those days. The researches has attempted to increase the efficiency of evaporative coolers which includes water distribution system [26–28], modifying mechanical parts [26], replacing pads which has more efficient heat and mass transfer [12,27–33] changing pad pattern [34–36] or pad structure [37], decreasing water consumption [38] and reducing the potential for accumulation of salt on the pads [39]. Intermittent water supply is used in high absorption capacity pads which hold significant amount of water for a relatively longer period [40].

However, depending on the climate, temperature and humidity of the inlet air are major problems evaporative coolers have to face with [7]. Instability of the ambient air condition may cause abnormal and unsteady operation even with the most effective settings [41]. In high humidity, in addition to reducing cooling capacity, the efficiency of air conditioners is also reduced. Controlling the dry bulb temperature could greatly stabilize the efficiency of the cooler, these could be done by adjusting supply water temperature which affects directly on dry bulb temperature [42,43]. Another alternative would be using a two-stage, indirect-direct, process where dry bulb temperature is controlled by the indirect stage. Each of these systems have similar performance or even higher in comparison with direct evaporative coolers. However, complexity and high initial cost are their major limitation [44]. These systems in compare with conventional direct evaporative cooler would minimum double the energy consumption, but increase the cooling capacity by a maximum of 20%. In this condition, they have no superiority over typical air compressor-based air conditioners.

In general, it seems no effective solution or a device is introduced so far which could overcome this major problem in evaporative coolers. In high temperatures the cooling capacity of evaporative cooler is not sufficient to provide comfort condition. In high humidity conditions, performance of evaporative coolers gets worse and the efficiency and cooling capacity would be reduced simultaneously. This neglected and remaining problem shows that how much of this type of air conditioners has been missed so far and how much improvement and optimization they still need.

In this study a solution and a device has been proposed which to some extent, it could overcome this problem. In this solution a combination of two aforementioned systems are indirectly implemented for increasing efficiency. For this purpose, the performance of the water pump would change from continuous to intermittent operation and depending on the amount of water required by the pads, it turns off and on. For this reason, a control unit is introduced to control the operation time and command the pump to be on or off. This device decides to turn the pump on or off by tracing changes in parameters such as outlet air humidity and temperature, pads conditions and etc. This device increases the cooling capacity at higher temperatures. Moreover, in high humidities, in addition to not allowing the cooling capacity to be reduced, it keeps the cooler efficiency almost constant. The tests have been performed for two evaporative coolers with different dimensions and aeration capacities in Iran. The effect of intermittent performance of the water pump on air outlet temperature, relative humidity, air conditioner efficiency, water consumption, cooling capacity and air conditioning coefficient of performance (COP) have been investigated.

2. Experimental set-up

Fig. 1 shows a schematic of a commonly used evaporative cooler used for testing. These coolers are made in cubic form. An evaporative cooler typically consists of pads, a centrifugal fan and a water pump. Pads provide required surface area for water evaporation. Fan draws outer hot air and pushes that through those pads and water pump supplies water from reservoir to cooling pads. The air is sucked into the cooling chamber through the three sides of the cooler. The three sides are covered with porous pads. The moisture content of the air passing through the pads increases and the air temperature of the air passing through the pads decreases due to evaporative cooling. The cooled air finally is driven into the channel by the fan.

Two types of cooler were employed for test from AABSAL company: front discharge evaporative air cooler models AC40 and AC70 with

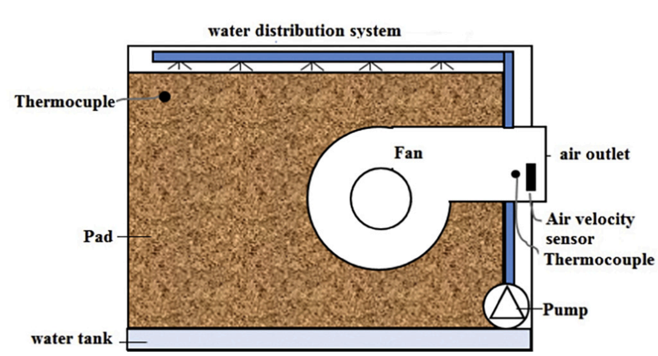


Fig. 1. Schematic of conventional evaporative cooler.

wood fiber pads. These models are the classical air cooler with front draft. They are the most common type of cooler in Iran. Table 1 shows the properties of these two types of coolers:

To determine and trace the effect of water pump on cooler performance when the pump is turned on and off, a temperature and humidity sensors are placed on outlet air channel close to centrifugal fan and two temperature sensors are attached to each pad, one is mounted on the outer surface of the pad and the other one is installed inside in the middle of the pad; these two sensors are positioned at the same location (Fig. 1). A data logger is used for recording data for each sensor. The temperature of the supplied water is measured by the thermocouple and is about $21 \pm 0.5\ ^\circ C$.

The evaporative efficiency of the cooler can be calculated from the following Eqs. [45]:

$$\varepsilon = 1 - exp\left(-\frac{h_c A_s}{\dot{m}_a C p_u}\right) \tag{1}$$

$$\varepsilon = ((T_{a1} - T_{a2})/(T_{a1} - T_{wb1})) \tag{2}$$

where A_s, Cp_u, T_{a1}, T_{a2}, T_{wb1}, h_c and $\dot{m}_a$are the pad's surface and specific heat capacity the mixture of dry air–water vapor, inlet air temperature, outlet air temperature, inlet air wet-bulb temperature, heat transfer coefficient and dry air mass flow rate, respectively. According to thermodynamic modeling, the specific heat capacity for the mixture of dry air–water vapor in the vicinity of the liquid water film is defined as follow as [45]:

$$Cp_u = Cp_a + \omega Cp_v \tag{3}$$

where Cp_a,Cp_v *and* ω are dry air specific heat capacity, vapor specific heat capacity and humidity ratio, respectively. The humidity ratio is calculated from the following equation [45]:

$$\omega = 0.622\frac{P_v}{P - P_v} \tag{4}$$

where P *and* P_v are atmospheric pressure and water vapor saturation pressure, respectively. The following equation can be obtained from the equation of mass conservation for the mixture of air and water vapor [46]:

$$\dot{m}_{ws} = \dot{m}_a(\omega_2 - \omega_1) \tag{5}$$

where ω_1, ω_2 *and* $\dot{m}_{ws}$ are the humidity ratio in the inlet and outlet air and water consumption mass flow rate, respectively. The heat transfer coefficient is calculated as follow as [46]:

$$Nu = 0.01\left(L_c L^{-1}\right)^{0.12} Re^{0.8} Pr^{0.33} \tag{6}$$

where L_c, L, Re *and* Pr are characteristic length and thickness of the cooling medium, Reynolds number and Prandtl number, respectively. The cooling capacity is calculated from the following equation [45]:

$$Q = \dot{m}_a Cp_a(T_{a1} - T_{a2}) \tag{7}$$

The performance coefficient of the air conditioner can be defined as follows [45]:

$$COP = \frac{Q}{W} \tag{8}$$

where W is power consumption, which includes pump and fan power. Evaporative cooler can be considered as a cross-current heat exchanger. Thus, the overall heat transfer coefficient in the evaporator cooler is calculated as follows

$$U = \frac{\dot{m}_a Cp_u(T_{a2} - T_{a1})}{A_s(T_{a2} - T_{a1}) \Big/ ln\left(\frac{T_{a2} - T_{wb1}}{T_{a1} - T_{wb1}}\right)} \tag{9}$$

3. Uncertainty analysis

There is a set of fixed and random errors for each quantity in the laboratory measurement. The accuracy of the measurement quantities is given in Table 2. The uncertainty ranges of the cooler efficiency measurements by Moffat's method [47] in this study is in the range of ±2%-± 5.8%.

4. Water pump duty in evaporative cooler

When cooler is switched on, water pump starts and continuously provides water to the pads. Pads are soaked with water until they are saturated. The excess water that drips out from the bottom of the pad is collected in a tank and recirculated to the top by water pump. The question arises whether there really is a need to permanently drench the pads by water pump. When the pads are saturated with water, some water would remain on the surface of the pads and could not be absorbed. This remained water and the water which is soaked by the pads fibers could supply the required water for evaporation for a while. As a result, the pump does not need to operate continuously. Perhaps, at first glance, it seems that power consumption of a typical water pump (30–120 watts) is not very important, but if the energy consumption of each pump multiplied by the number of existing coolers in a country e.g. about 10 million in Iran it becomes a huge amount of energy.

5. Parameters for water pump control system

The most important challenge in controlling the timing of the water pump is to determine when the pads are saturated with water and no longer need the pump to be in service and vice versa when the pads are drying and the water pump needs to be turned on again. More importantly, what parameter of the evaporative cooler need to be controlled so that the control unit could decide when to turn water pump on or off based on that parameter. For this reason, when the pump is switched on and off, the changes in temperature and humidity should be investigated by the sensors which installed in the cooler. For this purpose, the following experiment was performed:

The main fan and the water pump shortly afterward were switched on and the temperature and humidity changes in all sensors were traced. After a while, when the temperature remained constant, the water pump was switched off then the changes in temperature and humidity was recorded by data logger. During the whole test, the main fan has been switched on and its speed has not changed. Fig. 2 and 3 shows typically changes in temperature and humidity in on and off modes.

When main fan of AC40 cooler starts the temperature and humidity of outlet air were 31.2°C and 28% RH respectively. Pads' temperature was between 31 and 32 °C. After 80 s, pump was turned on and started to

Table 1
Technical information of the coolers.

Cooler type	Electricity Consumption (W/h)	Water consumption* (lit/h)	Water pump electricity consumption (W/h)	Air volume flow rate (cfm)
AC40	530	33	60	3500
AC70	890	45	60	4900

* In 35°C and 20% RH.

Table 2
Accuracy of measurement parameters.

Measurement	Accuracy
Ratio humidity	±2% RH
Temperature	±0.2 °C

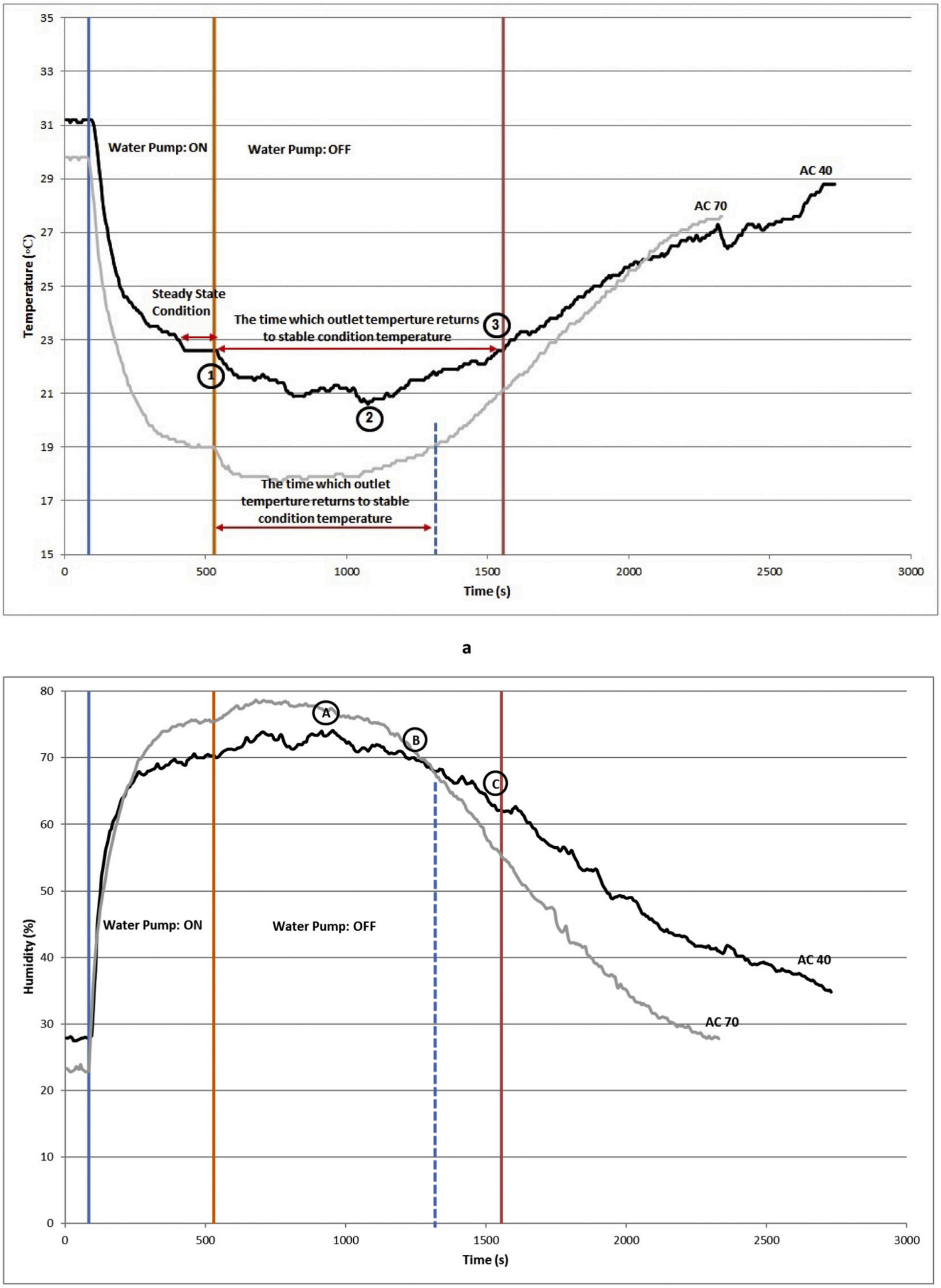


Fig. 2. a: Variation in a) Temperature and b) Humidity of outlet air with time when water pumps transforms into On/Off states.

supply water from reservoir tank onto pads. The evaporation of water from pads allows cooling the air. So the outlet air temperature fell down and the humidity increased fast. After 345 s from starting water pump, point 1 in Fig. 2a, the outlet temperature turned into a stable condition and the temperature of outlet air became constant. In this situation the cooler would possess the highest cooling efficiency and it cooled down the air for about 8.6 °C and increased humidity from 28% to 70% RH. The changes in humidity slightly vary with changes in temperature; when the cooler starts and water pump is switched on, the humidity of outlet air increases fast until the cooler humidity reaches to approximate percentage of 60% RH (Fig. 2b). After that, the humidity increases slowly until it approaches 70% RH which is the steady condition. Finally, If the water pump works continuously the outlet air temperature and humidity would be approximately constant and would be 22.6 °C and 70% RH respectively.

6. Hidden feature of evaporative cooler

An interesting phenomenon was observed when the pump was switched off while the main fan was still working. When the pump stopped working it was expected that the temperature of outlet air increases gradually. Surprisingly, the temperature of outlet air fell

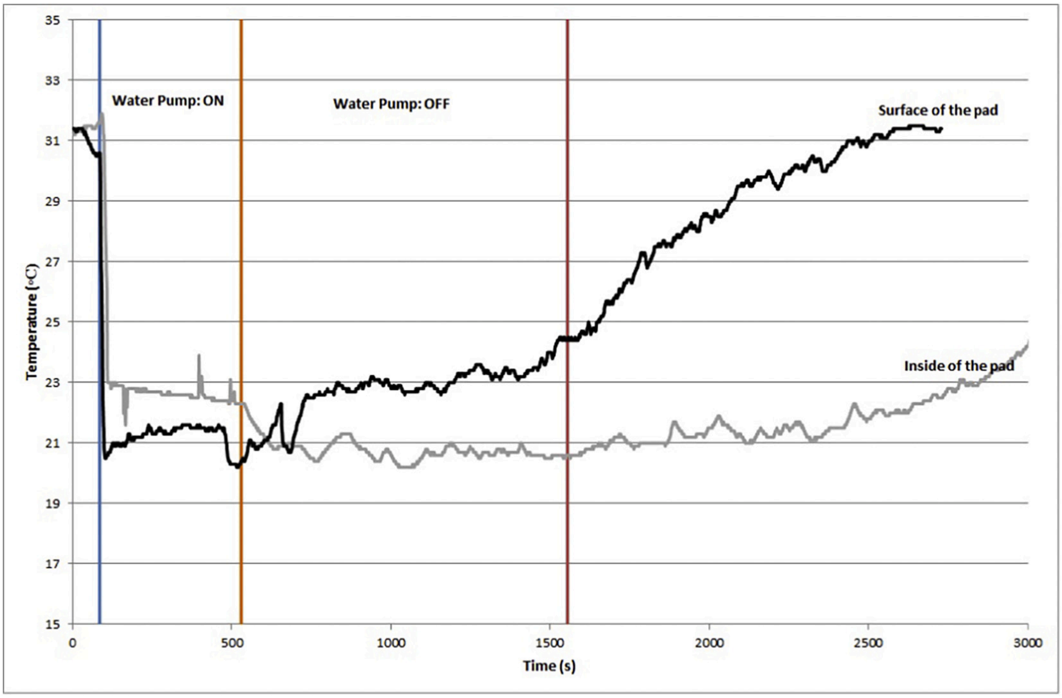


Fig. 3. Variation in Temperature a) on surface and b) inside of pads with time when water pumps transform into On/Off states.

gradually and the humidity rises to maximum of 74% RH, this means the cooler cooled the air down more efficiently. This phenomenon continued around 9 min, from point 1 to point 2 in Fig. 2a, which the outlet temperature reduced until pads became dry. When the pads began to dry, the humidity of the outlet air began to decrease and a bit later temperature also started to increase. Duration in which temperature in the outlet air decreases depends on the ambient temperature, humidity and the airflow rate. During this time the pump is off, the water pump uses no electricity, the cooler also cools the outlet air better which means the cooler works quite more effective.

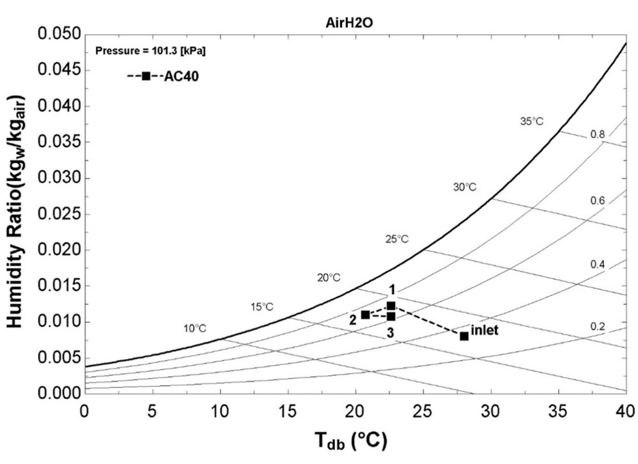
To understand what happens when pump is switched off it should be referred to a simple phenomenon in evaporative coolers. When the pump is working, the water on pads almost has similar temperature of water in tank, so the air passed through pads always encounter with temperature of the water in the tank. When pump is switched off, a large amount of unabsorbed and absorbed water remains on and within pad's fibers. The unabsorbed water is remained on fibers due to wetting phenomenon. This water has the same temperature of water in tank but

Fig. 4. Pad's condition when the temperature returns to its steady-state condition.

when the air passes through pads, it vaporizes remained water, which causes lower temperature of both outlet air and remained water. In fact, a portion of energy required for evaporation is supplied from remained water on which in return causes temperature reduction in pads. Subsequently, the passing air encounter pads with lower temperature that causes more reduction in outlet air temperature. Whilst the pump works continuously, water with the reservoir temperature incessantly poured on the pads which prevents the reduction of the pad's temperature.

The interesting thing is that after the pump is switched off and the outlet air temperature returns to steady condition temperature (point 3 in Fig. 2a), the humidity of the outlet air is about 8% RH less in comparison with the condition where water pump works continuously. This means the cooler could reach the same temperature with lower humidity and consequently lesser water consumption. Fig. 4 shows pad's condition after turning pump off and temperature returns to its steady condition. In some area pads were completely dried, therefore pads did not have the maximum cooling capacity but the outlet air was at the lowest temperature equal to the temperature when pump works continuously or in other words when temperature is steady-state. This could be attributed to the lower temperature of remained water in pads which somehow compensates the pads water shortage.

Fig. 5 illustrates the three points of Fig. 2 on psychometric diagram. In both types of coolers after the pump has been switched off, better comfort condition has been achieved [47]. This means if the pump does not operate continuously, the effectiveness of conventional direct evaporative cooling could be remarkably increased. When pads were almost dried, the outlet temperature was increased and the humidity was decreased (Fig. 2 a & b). At this moment the water pump should come into service again. When the pump start working, the point 3 in the psychometric diagram, Fig. 5, would return to point 1. This cycle would continue between point 1, 2 and 3.



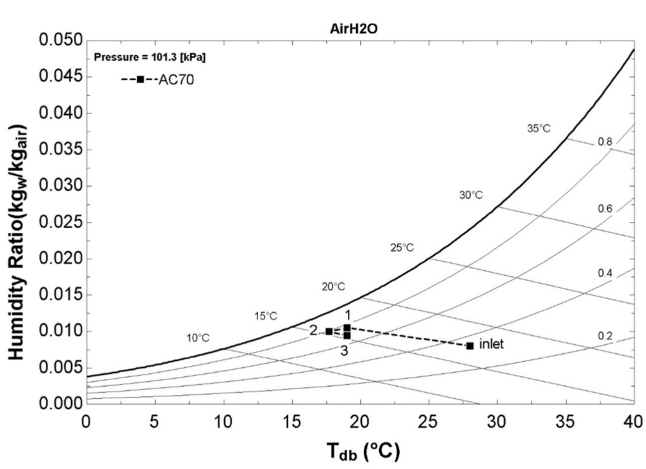


Fig. 5. Cooling modes of DEC on the Psychometric chart when the pump is switched off a) AC40 and b) AC70. Points 1,2 & 3 in this figure are the same points in the Fig. 2a.

The water pump cycle consists of two steps, the time which pump is off and the time which pump is on and the smart control unit is required to control the needed time of the pump to switch on and off. Based on the data in Fig. 2, 3 and 4the fallowing methods could be used to control the water pump cycle. Each of these methods is commanded the unit control by a specific sensor. All of these methods have the same performance on the cooling capacity and efficiency, energy and water consumption and their differences is in reliability, ease of installation, complexity of designing the control unit and finally the probability of errors on operation.

6.1. *Temperature control in outlet air*

A thermal sensor could be attached to the outlet channel of the cooler. When the cooler starts running, water pump supplies water on pads until the pads are saturated by the water and the cooler gets to the steady-state condition and the outlet air temperature is almost constant i.e. point 1 in Fig. 2a. This temperature is recorded in a control device and the water pump is switched off. As mentioned above the outlet air temperature starts getting down and when the pads become dry, the temperature rises up. While the temperature becomes closer to the recorded temperature, point 3 in Fig. 2a, the water pump starts to work. This cycle is continued as long as the cooler is running.

Since the temperature of steady-state condition would be affected by temperature and humidity of environment and also fan speed therefore, in every cycle the temperature of steady-state condition must be recorded.

6.2. *Humidity control in outlet air*

Same as previous method, humidity sensor can be attached to the outlet channel. In humidity control, the pump is switched on until increasing rate of humidity is subsided and steady-state condition is achieved. When water pump is switched off until the pads begin to dry and outlet air humidity starts to reduce, at this time the water pump would starts to work. The humidity threshold to start water pump is somehow easier to establish because the outlet air humidity is less dependent on ambient temperature and humidity and also fan speed [42,43,48]. Three points in humidity-time diagram, Fig. 2b, could be chosen for threshold definition: the first is the time which humidity starts to decrease, point A, the second is the humidity of steady-state condition, point B, and finally the last is the humidity of the point that temperature returns to temperature of steady-state condition, point C. The third one has the advantage that the pump is not switched on for a longer time and as mentioned before the steady-state condition temperature could be obtained by less relative humidity and therefore the water consumption is less.

6.3. *Timer control*

Timer control is the easiest, cheapest and the most reliable way to control pump cycle with no need for sensor and installation. Based on the type of the cooler and fan speed the duration of the pump is determined and the control unit operates using these predefined data. Since changes in ambient humidity and temperature could not be traced by the control unit the data must be prepared on the basis of the warmest and driest day or dominant climate during the warm season. However, the timer control despite having many benefits, cannot have a very good performance compared to other methods.

When the water pump works and pads absorb water time that cooler reaches to steady-state condition depends on the cooler type and structure and environmental condition has no effect on this time. Therefore, the time that pump should be switched on could be controlled by a simple timer. This time span for these coolers is about 5–6 min.

6.4. Wet control on pads

Wet sensors also could be used for controlling water pump cycle. In this technique several wet sensors are attached to different locations of pads, the location of the sensors should be selected carefully. When the pump is switched on sensor should be wet later than the rest area of pads and when the pump is switched off, it should be dried earlier. When the cooler starts running, the water pump is switched on until all (or most) of the sensors become wet. Similarly, when pads dry, some of wet sensors become dried and control unit commands water pump to start again.

These method is not as reliable as previous methods, because things such as water splashes, mineral scale-up and biofouling which is common in evaporative coolers [21] may affect the performance of these sensors.

6.5. Temperature control on pads

As same as the previous method, thermal sensors can be attached to pads in different locations. When the pump is on, water stream would drench sensors and the temperature falls down. Similar to wet sensors, pump is switched on until all, or most, of the sensors show reduction in temperature. Later, after switched off the pump pads lose their water and start to dry out. At this time, some of temperature sensors dried and temperature begins to increase. So, control unit would switch the pump on again.

Fig. 3 shows changes in temperature of two sensors; one mounted on surface and another inside of the pad. These sensors recorded different temperature-time diagram. When the pump is turned on, sensors show a sudden drop in temperature but the surface-mounted sensor shows much lower temperature. But when the pump is switched off, these two sensors recorded different trends. The temperature in surface mounted sensor begin to increase while the inside sensor starts to decrease and exhibits a similar behavior to the outlet air temperature sensor. The trend implies that the evaporation starts from the outer surface of the pad; for this reason, this sensor shows lower temperature. Moreover, due to high evaporation, surface of the pads does not have enough water storage and when pump is switched off, the remaining water vaporizes quickly and the temperature rises.

The function of the sensors in this method, also, could be interrupted due to the issues mentioned for wet sensors and more fluctuations in the temperature-time diagram for pads confirm this. Moreover, it is very difficult for control unit to decide when to turn the pump on or off according to the sensors behavior. This makes the control unit to be very complex and the reliability falls down.

6.6. Combination of methods

To control timing of water pump, one of the previous methods could be used alone or a combination of these methods could be used to increase the performance and reliability. For instance, as mentioned before the time to put pump into service could be controlled by a simple timer and temperature or humidity sensors could be used for controlling the time to put water pump out of service. For increasing the reliability of the water pump controller, two or more methods could be simultaneously used for water pump cycle. For example, temperature and humidity control in outlet air could simultaneously be used for controlling the time which pump should be switched on or off.

7. Effective factors on cooler performance and control unit

Air humidity and temperature and also main fan speed are the main factors which affect the diagram in Fig. 2. As mentioned before for a specific cooler these factors do not change the trend of the diagram and only the minimum temperature and the time which the cooler is switched off would be changed. By increasing temperature and fan speed and decreasing humidity, the period of time in which pump is switched off would be reduced, but the period of time in which cooler is switched on is almost independent of these factors and cooler design parameters such as pad absorption capacity, pad area, water pump flow rate, water distribution system, and etc. could be effective.

By increasing the inlet air temperature from 28 to 41°C and having humidity of about 30% ± 2.5% RH, the lowest temperature increases but the temperature difference between steady-state and minimum temperature and consequently control unit efficiency would be increased. Since inlet air dry-bulb temperature has almost no influence on the efficiency of the evaporative cooler [10,49,50], the control unit could have higher efficiencies in higher temperatures. Changes in the humidity from 19 to 35 and having temperature of about 32 ± 1.5°C are somewhat more complicated and it's not easy to determine its impact on the lowest temperature and efficiency. It seems that there is an optimum humidity for the lowest temperature and also control unit efficiency. When the inlet air is very dry, pads dry faster and the lowest temperature would be closer to the steady-state temperature and the time which outlet temperature returns to steady–state condition is less. However, in general, the evaporative coolers are more efficient at lower humidity and the cooler itself has a higher efficiency. For this reason, control unit has no remarkable effect on increasing the efficiency. Assuming that two types of coolers have the same efficiency, which is usually a good assumption, in AC70 (Fig. 2) when the test was in progress the ambient humidity was lower and the cooler cools down the air about 9.8°C which is 1.4°C more than AC40. This means in lower humidity the efficiency of the coolers is more. In AC70 the difference between steady-state condition and minimum temperature is about 1.3°C but in AC40 is 2°C. Moreover, the time which outlet temperature returns to steady–state condition in AC70 is 245 s less. This indicates that control unit has lower impact on efficiency of AC70.

The cooling efficiency of direct cooling is between 60% to more than 80% depends on pad media [51]. The t_{wb} for test condition of AC40 and AC70 coolers is 18.2°C and 16.8°C respectively [52]. When the pump is working continuously, in steady-state condition, the maximum cooling capacity of AC40 and AC70 coolers are 8.6 °C and 9.8 °C, respectively. In this situation the cooling efficiency of AC40 is 71% and of AC70 is 76% which lies within typical range of evaporative coolers. When the pump is switched off, the minimum achievable reduction in temperature is 10.6°C for AC40 and 11.1°C for AC70. It is desirable that at maximum cooling capacity, the cooling efficiency of these coolers remains almost equal, about 86%, which is very high for coolers with wood fiber pads [4,51]. From the above results, it can be concluded that the unit control compensates the reduction of the coolers efficiency which is affected by ambient condition especially air humidity.

The last factor which could affect the control unit efficiency is the main fan speed. With increasing the main fan speed the lowest temperature slightly increases, pads dry faster and the time which outlet temperature returns to steady–state condition decreases, which finally reduces the control unit efficiency. For cooler type AC40 when the main fan speed changes from 1000 rpm to 1500 rpm the difference between lowest temperature and the steady-state temperature is only 0.1 °C but the time which temperature returns to steady-state condition decreases by 66%.

8. Energy and water saving

The cooling efficiency of both coolers has been obtained by Eqs. (1) and (2) and shown in Fig. 6. It can be seen that the results of these two

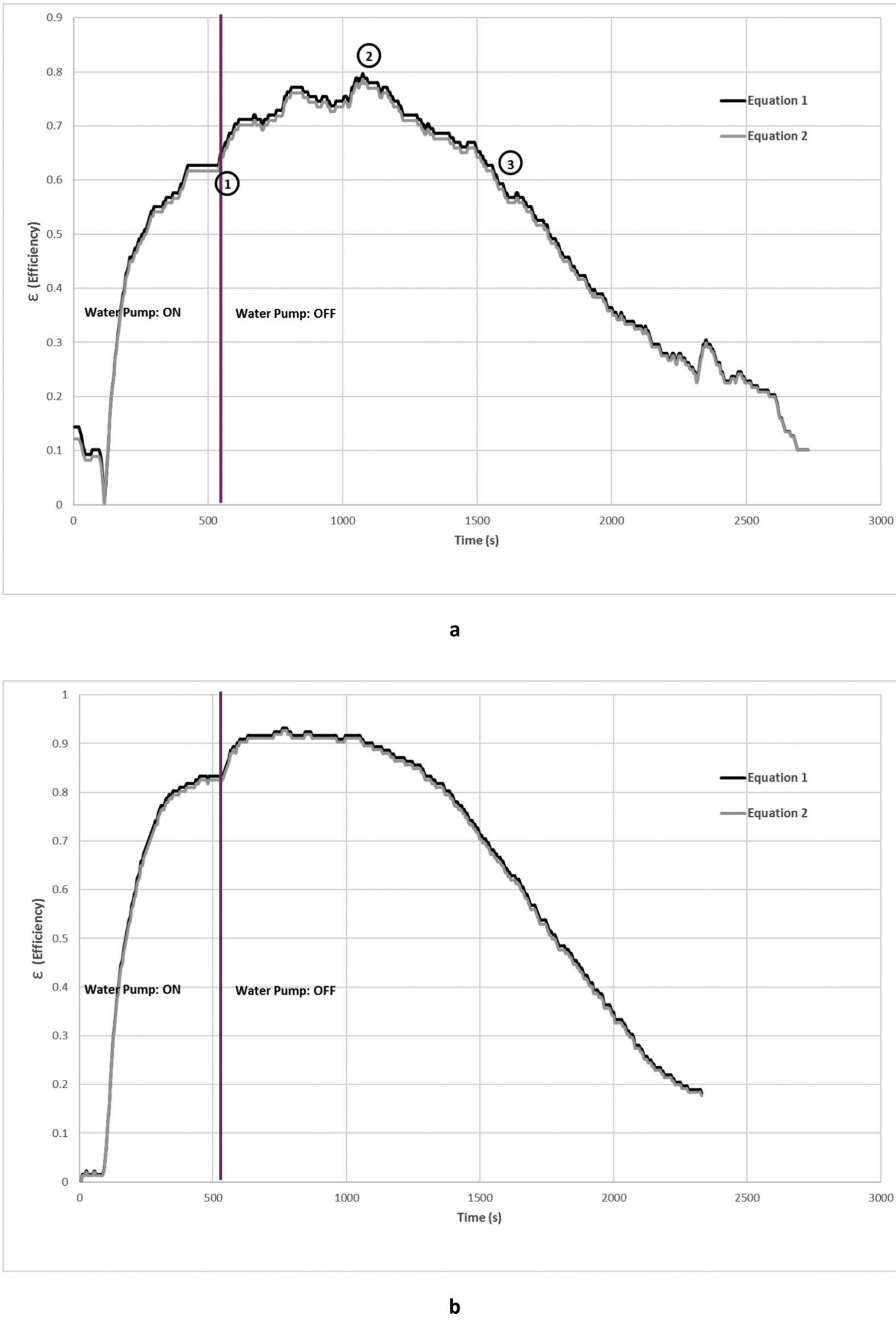


Fig. 6. Comparison of evaporative cooler efficiency using Eqs. (1) and (2) a) AC40 and b) AC70. Points 1,2 & 3 in this figure are the same points in the Fig. 2a.

equations are well matched and difference between them is on average less than 2%.

An energy efficient use with reduction of energy consumption of the evaporative cooler is achieved by using a water pump controller. This could be calculated by assuming that the water pump is switched off when the cooler is in steady-state condition (point 1 in Fig. 2a) and the outlet air temperature is almost constant and switched on when the temperature returns to the steady-state temperature (point 3 in Fig. 2a). When the pump is switched off, the evaporative cooling efficiency reaches to its maximum value of 81.3 and 87.9% for AC40 and AC70 respectively. Afterwards, evaporative cooling efficiency and relative humidity decreased as the outlet air temperature increased. This assumption coincides with the best performance of this device. The variations of evaporative cooling efficiency after the pump is turned off for AC40 and AC70 cooler in terms of relative humidity are shown in Fig. 7. When the pump is switched off, the relative humidity and cooling efficacy increase together until the temperature reaches to the point 2 in Fig. 2a. After that when the pads begin to dry, the relative humidity and cooler efficiency start to decrease.

Changes in the cooler cooling capacity with time are shown in Fig. 8. It is observed that after the pump is turned off, the cooling capacity increases to its maximum value and then decreases. Cooling capacity is increased by reduction of outlet air temperature.

Changes in the overall heat transfer coefficient of the evaporative coolers with time are shown in Fig. 9. The results show that when the pump is switched off, the rate of water evaporation increases and the overall heat transfer coefficient in the coolers increases to its maximum value. When the pads begin to dry, the rate of water evaporation decreases, consequently the heat transfer coefficient decreases.

Fig. 10 illustrates changes the coefficient of performance (COP) of the evaporative coolers with time. Changes in COP are similar to changes in cooling capacity. The maximum COP occurs when the pump is off and its value for AC40 and AC70 is 45.44 and 34.12, respectively. The COP increases by about 28–30% when the pump is running intermittently, compared to the continuous operation condition.

The time duration which the pump must be in service to achieve a steady-state condition is 360 s, the time duration which the temperate returns to the steady-state condition is 1000 s and a typical water pump's wattage can vary between 30 and 80 W/h and the 60 W/h water pump is more common. This means for only 36% of the time when the cooler is working, the water pump needs to be turned on. Therefore, the average consumption of the pump will be about $60 \times 0.36 = 21.6$ W/h. Considering negligible energy that the control unit consumes, total energy consumption will be set to 22 W/h. The amount of electric energy savings for evaporative cooler type AC40 is about 7.2%.

The point to consider is that by using the water pump controller, the cooler cools the air down more efficiently, this further decrease in outlet temperature is not constant and at most, reaches to 2 °C. By considering the previous conditions, the average further reduction in outlet temperate when the pump is switched off is about 1.1 °C. If this 1.1 °C is multiplied by the ratio of time duration when the water pump is switched off to the total time, 0.74, the total average reduction is obtained. This means, on average, the cooler with a control unit reduces the air temperature 0.7 °C more and for the evaporative cooler type AC40, the cooling capacity (the amount of temperature reduction) increases by 8.1%. If the amount of energy reduction is combined with cooling capacity increase, then total increase in efficiency could be 16.5%.

When the water pump works continuously, cooler cools the outlet air temperature by 8.6 °C and increase the humidity by 42.5% so that the humidity reaches 70.4%. When the pump is switched off the humidity increases and at maximum it reaches 74.1% (point 1 in Fig. 2b) which means the cooler consumes more water. But as time passes, the humidity of the outlet air decreases, so when the temperature of outlet air retunes to steady-state temperature, humidity is about 62.1% (point 3 in Fig. 2b & Fig. 7) which is less than when the pump operates continuously while the temperature is the same. At the time the pump is turned off, the average air humidity of the outlet air is about 70.3% which is very close to when the cooler works continuously, although the average air temperature is 1.1 °C cooler. For AC40, when the pump is running continuously, the relative humidity ratio and relative humidity are 0.0123 $\left(\frac{kg_w}{kg_{air}}\right)$ and 70.4% respectively and the amount of consumed water is $28.3\frac{m^3}{hr}$. But when the pump is running on a cycle within points 1, 2, and 3, the average relative humidity ratio and relative humidity are 0.0114 $\left(\frac{kg_w}{kg_{air}}\right)$ and 70.3% and the amount of consumed water is $23.4\frac{m^3}{hr}$. This means when the pump works intermittently, the cooler consumes water 20.9% less.

Finally, 64% of the time when the cooler is switched on, the water pump needs to be turned off which cause of reduction in degradation of the water pump. The pump is 15–17 min off after 5–6 min working. This time allows water pump to be cooled which reduces the risk of pump seizure especially for amortized water pumps.

9. Conclusion

In this paper, a simple and efficient solution to reduce energy and water consumption in evaporative coolers was presented. The efficiency

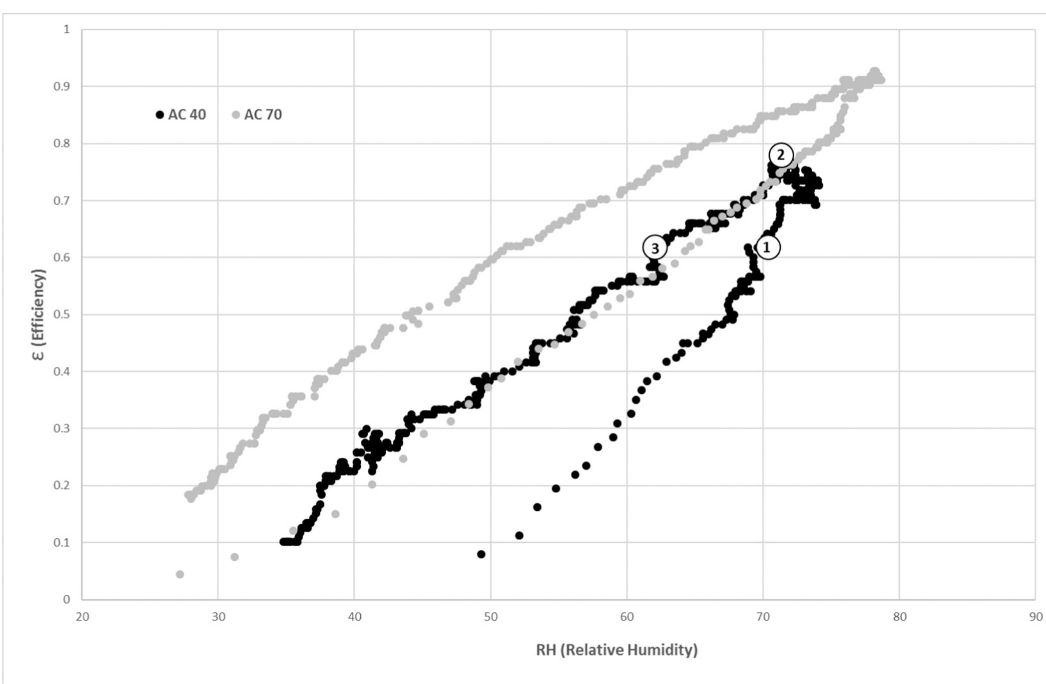


Fig. 7. Changes in cooling efficiency with outlet air humidity ratio after the pump is turned off. Points 1,2 & 3 in this figure are the same points in the Fig. 2a.

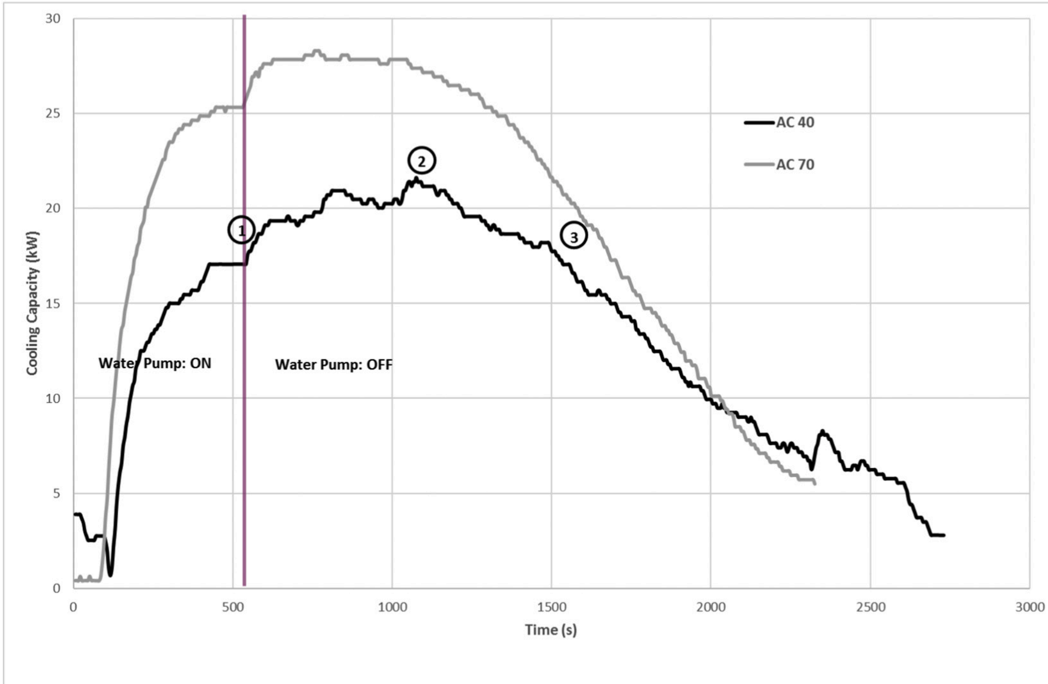


Fig. 8. Changes in the cooling capacity with time. Points 1,2 & 3 in this figure are the same points in the Fig. 2a.

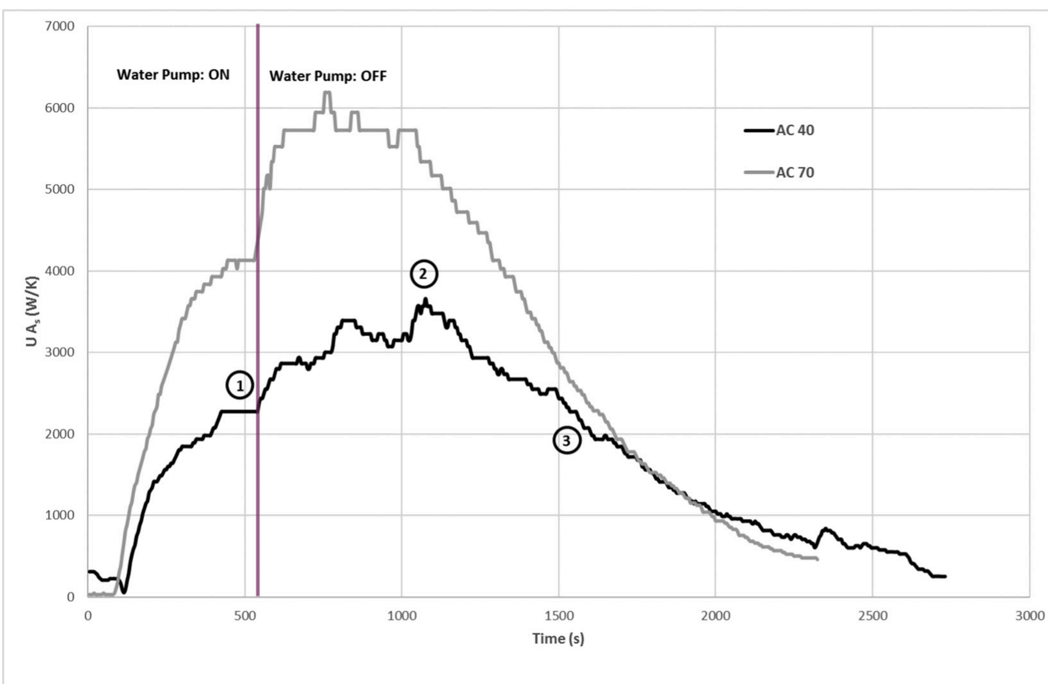


Fig. 9. Changes in the overall heat transfer coefficient with time. Points 1,2 & 3 in this figure are the same points in the Fig. 2a.

of coolers could be improved by adding a small and cheap control device to the common evaporative coolers. This controller does not make any changes to the cooler structure and cooler performance, this device only converts continuous water supply to intermittent water supply. In other words, this control unit controls the time which the pump should be operate or not. Cooler with this device will perform very close to two-stage indirect/direct evaporative coolers in which both heat exchanger and wetted pads are employed in series. In two stage indirect/direct evaporative coolers, in the first stage, indirect evaporative cooler lowers the inlet air temperature and then the pre-cooled air passes through the wetted pads. But water pump control unit causes the temperature of the pads to decrease more and outlet air passes through the pads with much lower temperature. In this paper, different methods were proposed for controlling the water pump cycle, each has been tested and the advantages and disadvantages of each method were presented. For choosing the proper method, several factors must be considered such as reliability, ease of installation and cost. The results of this study show that efficiency, performance coefficient, cooling capacity, energy saving and

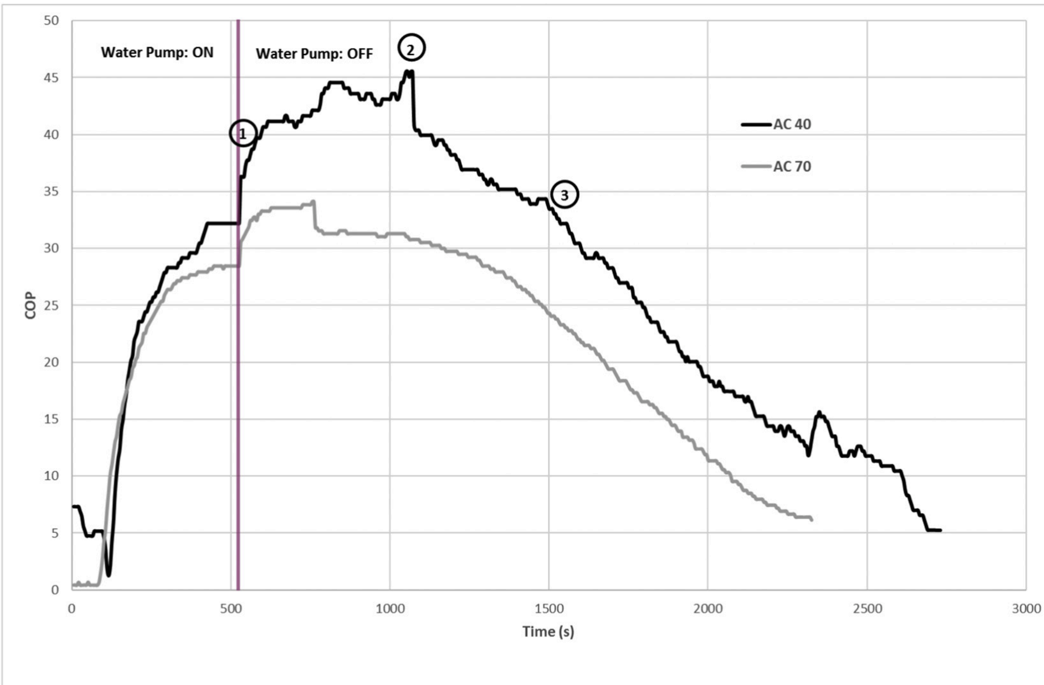


Fig. 10. Changes in cooler performance with time. Points 1,2 & 3 in this figure are the same points in Fig. 2a.

water consumption have changed by about 16.5%, 28–30%, 8%, 7.2% and 20.9, respectively. Therefore, the proposed method in this study, while simple and cheap, could increase the efficiency and cooling capacity of the evaporative cooler and reduce the consumption of electrical energy and water.

Evaporative coolers are well-designed for a specific whether condition (mostly for dry weather). For this reason, in humid weather, the efficiency of the coolers decreases. In other words, by increasing the humidity of the air, the cooling capacity decreases more than expected. The control unit tries to increase the efficiency of the cooler which is not designed for high humidity weather.

Finally, concerns about energy consumption, climate changes and rising demand for higher comfort, make evaporative coolers a popular alternative to central air conditioning in arid and semi-arid climate. There is also a potential for using these coolers in the future for regions such as UK [53] where by global warming would have increase in the summer wet-bulb depression. For this reason, much attention must be given to an evaporative cooling. Typically, with temperature near 40 °C and humidity of 10%, direct evaporative cooler could deliver air at 21–24 °C which is reasonably comfortable. However, in some hours of the hot season, even in dry climate, comfort level might not be achieved. But most of the season the outlet air temperature would be acceptable. Nevertheless, perhaps, the largest obstacle to wider acceptance of evaporative cooling technologies is those hours which the desirable comfort is not achievable. For those hot days conventional air conditioners could be desirable and reasonable. For this reason, a hybrid system, evaporative cooler and compressor-based air conditioner, in the way that only one of these two systems works at the time, is the best choice to be used during the hot seasons.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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