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Performance Evaluation of a Forced Draft Cooling Tower Using Cellulosic Honeycomb and Polyvinyl Chloride Fillings

Abdulrahman M. Homadi *, ***Mohammed Gh. Jehad***, ***Obaid T. Fadhil***

Department of Mechanical Engineering, Engineering College, University of Anbar, Ramadi, Iraq.

Keywords:

Approach; Cooling range; Cooling tower; Fillings; Performance.

Highlights:

- *Testing two cooling tower fillings, i.e., Cellulosic Honeycomb and Polyvinyl Chloride.*
- *Approach value and cooling range are the main factors in the study.*
- *Several parameters were studied to evaluate the cooling tower.*
- *CHC filling is more efficient than PVC filling.*

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**Corresponding author:*

Abdulrahman M. Homadi

Department of Mechanical Engineering, Engineering College, University of Anbar, Ramadi, Iraq.

Abstract: Improving the heat transfer equipment performance and understanding the effect of any relevant factors on it will contribute to energy conservation and mitigate environmental pollution. Cooling towers are among the heat transfer equipment widely employed in various fields. This study aims to investigate the effect of the cooling load, the flow rates of water and air passing through the tower, and ambient temperature on the cooling range and the approach value of the tower with two types of filling materials, i.e., CHC and PVC. To conduct the experiments, a laboratory bench-top cooling tower that operates with opposite flows for both the air and water streams was used. The study revealed that the cooling range increased with high cooling load and air flow rates; however, it decreased with rising water flow rates and ambient temperatures for both fillings. The approach value exhibited a direct relationship with cooling load, water flow rate, and ambient temperature, and improved notably with higher air flow rates through the tower. CHC filling consistently outperformed PVC filling, resulting in significantly lower mean approach value differences: 0.52°C for cooling load, 2.84°C for air flow rate, 1.73°C for water flow rate, and 2.5°C for ambient air temperature. In conclusion, CHC filling proved to be a superior choice for cooling towers, consistently achieving lower approach values in a variety of operating conditions.

تقييم أداء برج التبريد القسري باستخدام حشوات اقراص العسل السليلوزية والبولي فينيل كلوريد

عبدالرحمن محمد حمادي، محمد غانم جهاد، عبيد طلك فاضل
قسم الهندسة الميكانيكية/ كلية هندسة / جامعة الانبار / الرمادي – العراق.

الخلاصة
إن تحسين أداء معدات نقل الحرارة وفهم تأثير كل عامل من العوامل ذات الصلة على هذا الأداء سيسهم في حفظ الطاقة وخفض التلوث البيئي. تعتبر أبراج التبريد واحدة من بين معدات نقل الحرارة المستخدمة على نطاق واسع في مختلف المجالات. ان هذه الدراسة تهدف إلى معرفة تأثير كل من حمل التبريد ومعدلات تدفق كل من الماء والهواء خلال البرج وكذلك درجة الحرارة المحيط على مدى التبريد وقيمة الاقتراب لبرج التبريد باستخدام حشوتين من معدنين مختلفين. لتنفيذ التجارب، فقد استخدام برج تبريد مختبري يعمل بالدفق المتعاكس لكل من تياري الهواء والماء. اظهرت الدراسة أن مدى التبريد يزداد مع ارتفاع كل من حمل التبريد ومعدل تدفق الهواء بينما يقل مع ارتفاع كل من معدل تدفق المياه ودرجة حرارة المحيط ولكلا الحشوتين. ان قيمة الاقتراب تزداد (تتدهور) مع زيادة كل من حمل التبريد ومعدل تدفق الماء ودرجة حرارة المحيط وتتحسن بشكل ملحوظ مع زيادة معدل تدفق الهواء خلال البرج. بينت الدراسة ان قيم الاقتراب عند استخدام حشوة من CHC هي افضل منها عند استخدام حشوة من PVC حيث بلغ الفرق في قيم الاقتراب بين الحشوتين: ٠,٥٢ درجة مئوية عندما يكون حمل التبريد هو المتغير و ٢,٨٤ درجة مئوية عندما يكون معدل تدفق الهواء هو المتغيرو ١,٧٣ درجة مؤية عندما يكون معدل تدفق الماء هو المتغير و ٢,٥ درجة مئوية عندما تكون درجة حرارة المحيط هي المتغيرة. يمكن القول ان حشوة CHC هي افضل من حشوة PVC حيث اعطت قيم اقتراب اقل عند ظروف التشغيل المختلفة.

الكلمات الدالة: النهج، نطاق التبريد، برج التبريد، الحشوات، الأداء.

1.INTRODUCTION

The cooling tower is one of the parts used in many electric power plants, oil and petrochemical industries, and refrigeration systems, whose condenser is cooled by water. Improving the cooling tower's performance certainly will contribute to improving the performance of the plants, thus saving energy. Over the past years, researchers have conducted many studies to determine the effect of some factors on the cooling tower's performance. Fisenko et al. [1] proposed a new validated mathematical model of mechanical draft cooling tower performance. The ordinary differential equations system was used to describe changes in the droplet velocity, its radii, temperatures, and the change of some fluid properties of water vapor in the moist air in the cooling tower. The results showed that the thermal efficiency depends on the average cube of the droplet radius. An experimental investigation conducted by Ning et al. [2] studied the effect of nozzle drop, nozzle blockage, and packing blockage on cooling tower performance. They found that the coefficient of efficiency and the characteristic of the tower are inversely proportional to the ratio of water to air entering the tower. Rahmati et al. [3] experimentally determined the effect of the air flow rate, hot water flow rate, hot water temperature, and number of filling stages on the thermal performance of a forced air cooling tower. They concluded that the tower performance was clearly improved with the increase in the air flow rate, hot water temperature, and the number of stages of filling, while the performance decreased with the increase in the flow of hot water. Alavi and Rahmati [4] experimentally focused on knowing the effect of hot water temperature, wind speed, and water flow rate on the cooling range and cooling efficiency of a natural draft cooling tower. They used the results of the experiments to develop mathematical equations that can be used to determine the most advantageous operating conditions for the used cooling tower. He et al. [5] studied a pre-cooled natural draft dry cooling tower using two kinds of wetted medium. The study was supported by a validated MATLAB code to conduct a case study of a 120-meter-high cooling tower. The results showed that pre-cooling by wetted medium can increase the rejected heat from 45 MW to 92 MW at high ambient temperatures. Naik and Muthukumar [6] presented an analytical study to determine the rate of water evaporation in a cross-flow cooling tower. The effect of the moisture content, relative humidity, dry bulb temperature, and the temperature of the inlet hot water on the performance of the cooling tower was included in this study. The results showed that the dry bulb temperature insignificantly affected the performance of the cooling tower, whereas the other parameters had a significant impact. Zengin and Onat [7] studied experimentally and theoretically the thermal efficiency of mechanical draft counter-flow wet cooling towers. The pressure variation with air velocity for different cooling tower heights was illustrated, with the highest performance calculated at the highest tested cooling tower height. Shublaq and Sleiti [8] experimentally investigated the water evaporation loss in a cooling tower using four filters on the top of the tower. The water was saved by 17% when an aluminum metal panel filter was used. The filters were used to allow condensation of the water vapor and keep the water droplets that were transferred with the outlet air stream. An analytical study to improve the performance of a cooling tower of the natural draft type was performed by Kumar et al. [9]. They concluded that the tower's effectiveness in winter was greater than in other seasons, whereas the performance was improved significantly with the increase in the height of the tower column. Miao et al. [10] studied the effect of evaporating a certain amount of water on the performance of a natural draft dry cooling tower of 167 m height. The study included three pre-cooling system arrangements for evaporation. The results showed that, in general, all the systems can improve the performance of the tower at high temperatures. However, at low temperatures, the improvement in tower performance is unremarkable. Zhang et al. [11] presented a three-dimensional numerical simulation of a large-scale natural draft wet cooling tower to enhance its thermal performance. The impact of the axial fan position installed in the cooling tower on the thermal performance was investigated at different velocities (1-9 m/s) of crosswind when the power of the fan was fixed at 200 kW. Dong et al. [12] proposed a study related to the effect of capturing carbon dioxide CO_2 from the atmospheric air on the thermal performance of a natural draft dry cooling tower. The process of CO_2 production itself requires high energy consumption due to its low concentration in the air. In this study, a combination of conventional cooling towers and direct air capture was used as a technology to reduce the cost of CO_2 and enhance thermal performance. Dmitriev et al. [13] presented an experimental study of the effect of a developed fill pack on the thermal performance of an evaporative cooling tower. The fill pack was designed as an inclined corrugated contact element made of a plate with 6mm holes. The hydraulic and thermal characteristics of the cooling tower were studied, in addition to the pressure drop across the cooling tower. The results showed that the filled pack with a 6 mm hole was more efficient because it gave higher values of thermal efficiency and a lower pressure drop than the other studied cases. The air swirl effects of a dry cooling tower with and without crosswind on the thermal performance were simulated numerically by Dai et al. [14]. The swirl was generated at three locations of the swirl generator, and the study found that the use of angular frequency enhanced heat rejection in the cooling tower with a rate of 11–17 %. Khamooshi et al. [15] performed a numerical study to investigate the effect of wind speed and tower spacing on the heat transfer between three dry cooling towers. They concluded that the towers' thermal performance can be enhanced by enlarging the space between the three in-line towers during windy conditions. Rahmati [16] experimentally investigated the thermal performance of a wet cooling tower. The study examined (ZnO) nanoparticles and three packing types. The researcher concluded that the increase in packing layers increased the cooling efficiency. The use of nanoparticles and the increase in nanoparticles concentration enhanced the thermal performance of the wet cooling tower by 11.3%. Shirazi and Jahangiri [17] have numerically studied the thermal performance of dry cooling towers with different crosswind velocities. The study revealed that the sugarloaf-type model represented the highest performance among the examined models, where the cooling tower efficiency improved by 7.5 %. Peng and Sadaghiani [18] investigated an analytical study to enhance the cooling capacity of Heller cooling towers in a power plant station by linking a compression refrigeration cycle. The proposed system cooled the water to about 10 K, increased the exergy efficiency by about 4%, and decreased the cost by 14.8%. Solomon et al. [19] experimentally investigated the thermal performance of a wet cooling tower in an electrical thermal unit by using different methods to prevent and reduce scale formation in the condenser tubes and controlling the velocity of hot water at nozzles to increase the cooling tower efficiency. Recently, Hassab et al. [20] developed a new correlation to evaluate the thermal performance analytically for cross-flow closed cooling towers. The results showed that the developed correlation was in good agreement with the traditional relationships, where the highest percentage of deviation was relatively small. What distinguishes the current study from the previous ones is that the comparison was made between two fillings that differ in shape and metal. It is expected that the results will be different with regard to the approach and range of cooling. The sections of the rest of this study are the test rig, experimental procedure, discussion of the results, and conclusion. The goal of this study is to identify the impact of a set of operational factors on the performance of the cooling tower with two types of filling materials.

2.TEST RIG

In this study, a laboratory cooling tower type H891 manufactured by the Hilton company was used. This tower operates with opposite flows for both the air and water currents. Figure 1 shows a detailed diagram and the real device of the tower used in this study. The tower consists of three main parts:

1- Base unit: This part includes the air distribution room, a tank containing two electric heaters with capacities of 0.5 and 1 kW to represent the heat load, and a reservoir to compensate for evaporated water. This unit includes a centrifugal fan to pump air from the bottom to the top of the tower, and to control the flow, a gate is located at the air inlet, where the maximum air flow rate is 0.06 kg s^{-1}. Also, a water pump is included to circulate water from the tank to the top of the tower, in addition to the cold water collection tank and an electric control unit.

2- Filling column: It is a duct made of transparent plastic with a height of 0.5 m and a base area of 0.15 m × 0.15 m. The duct contains rows of plates made of polyvinyl chloride (PVC) or pieces of cellulosic honeycomb (CHC) materials, as shown in Fig. 2, which are collectively referred to as filling. The geometry of the two types is different, with different surface areas, which is expected to give different results. The function of the filling is to provide a large surface area for the hot water falling on it and disperse it into small droplets to facilitate its cooling. Also, in the outer wall of the filling column, there are two holes that can be connected with an inclined manometer to measure the pressure difference across the filling.

3- Column cap: it It is installed at the top of the filling column, which contains an orifice plate with a diameter of 0.008 m and a hole for measuring the pressure difference across it. A spray barrier is also included in the column cap, which is an alternative to the removal panels found in the large towers.

Furthermore, the setup included a digital thermometer equipped with six type-K thermocouples. These thermocouples were employed to provide precise measurements of air and water temperatures. An inclined manometer was used to measure the pressure-related parameters. This instrument measured both the pressure drop across the filling and the pressure difference on both sides of the orifice plate. Additionally, a flow meter has been integrated into the system to accurately measure the water mass flow rate, as depicted in Fig. 1. The accuracy of the sensors and instruments was individually considered, through which the basic variables in experiments were measured. The accuracies of the measuring instruments were illustrated in Table 1.

Table 1 Accuracy of Measuring Instruments/ Sensors.

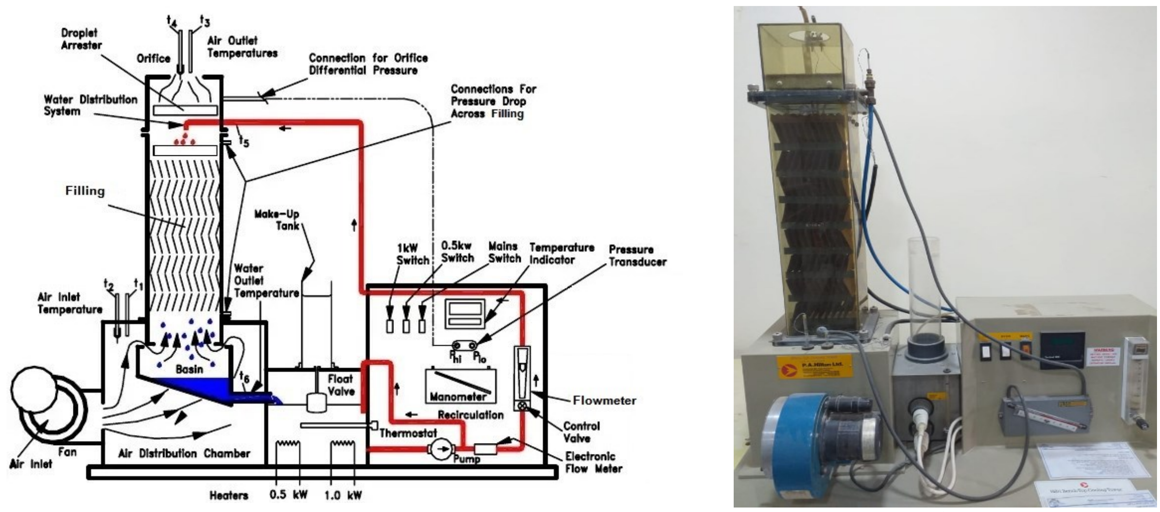
Instrument/sensor	Parameter	Accuracy
Copper-constantan thermocouple	Water and air temperatures	± 0.1 °C
Inclined manometer	Air pressure difference	± 1.0 mm H_2O
Flowmeter	Water flow rate	± 0.00125 $kg.s^{-1}$

The parameter P can represent any of the five parameters outlined in Table 2. It is fundamentally a function of various independent variables (A_1, A_2, A_3, ..., A_n), and each of these variables is subject to measurement uncertainties denoted as (u_1, u_2, u_3, ..., u_n), respectively. To determine the uncertainty associated with any given parameter, the following equation was used [21].

$$U_P = \left[\left(\frac{\partial P}{\partial A_1} u_1\right)^2 + \left(\frac{\partial P}{\partial A_2} u_2\right)^2 + \left(\frac{\partial P}{\partial A_3} u_3\right)^2 + \cdots + \left(\frac{\partial P}{\partial A_n} u_n\right)^2\right]^{1/2} \quad (1)$$

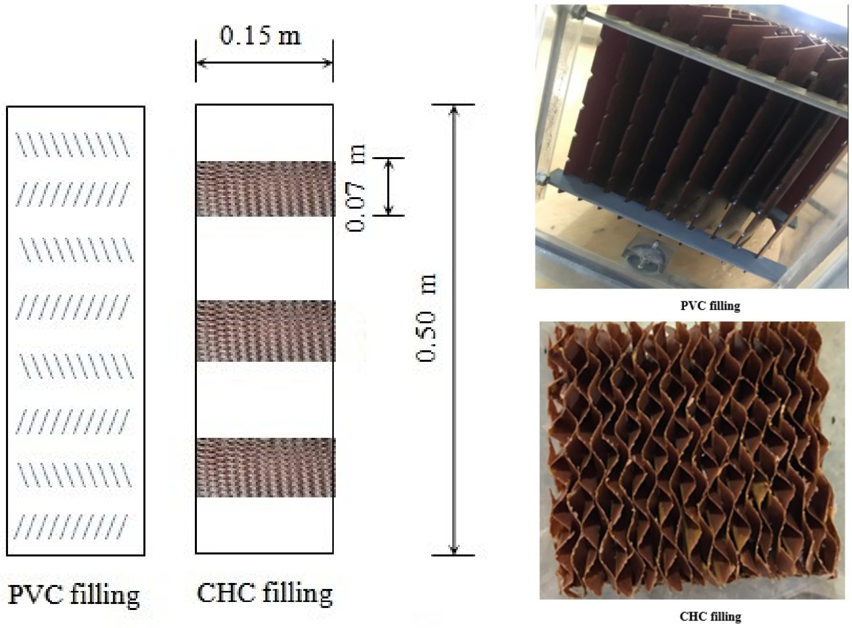
Table 2 Parameters Uncertainties.

Parameter	Uncertainty value	Uncertainty percentage
Mass flow rate of air	± 0.0331	± 3.314 %
Mass flow rate of water	± 0.0162	± 1.623 %
Cooling range	± 0.0141	± 1.414 %
Approach	± 0.0156	± 1.562 %
Ambient temperature	± 0.004	± 0.370 %



(a) **(b)**

Fig. 1 Test Rig (A) Illustrative Diagram (P. A. Hilton Cooling Tower Model H891). (B) Lab Apparatus.



(a) **(b)**

Fig. 2 Types of Filling Were Used: (A) The Arrangement (B) Photos of the Two Types.

3.PROCEDURE OF EXPERIMENTS

The practical experiments were conducted in a laboratory cooling tower placed in a controlled space. Before conducting the tests, the temperature measurement system and the hot water flow rate meter were calibrated. After that, the tower's performance was examined with two types of fillings. The first filling consisted of 8 rows, each row contained 10 plates of the PVC material, and these rows were arranged in a zigzag pattern, as shown in Fig. 2. The influence of cooling load, flow rate of hot water, flow rate of air, and ambient temperature on cooling tower performance has been studied. Each of these variables has been changed four times, whereas the test data were taken after 600 s of the tower operating under the influence of a specific variable. Various parameters were recorded experimentally, including the entering and exiting dry and wet bulb temperatures, in addition to the entering and exiting water temperatures. A digital thermometer with a selector switch was used to record air, water, and ambient temperatures. A calibrated flow meter was used to measure the flow rate of hot water entering the tower. To measure the pressure difference across the orifice plate and the filling, an inclined manometer was utilized. The cooling and approach values were calculated depending on the measured temperatures. Additionally, the mass flow rate of air through the tower was calculated using the following equation [22].

$$\dot{m}_a = 0.0137\sqrt{\frac{H}{(1+\omega_o)\,v_o}} \qquad (2)$$

The second part of the tests was done with another filling consisting of three pieces of CHC material, as shown in Fig. 2, each with a dimension of (0.15 m × 0.15 m × 0.15 m), which were placed in a proper arrangement in the filling column. It should be noticed that the pressure drop during the three CHC pieces is almost equal to the pressure drop during the PVC filling. The tower performance was also investigated with the CHC filling at the same four variables.

4.DISCUSSION OF RESULTS

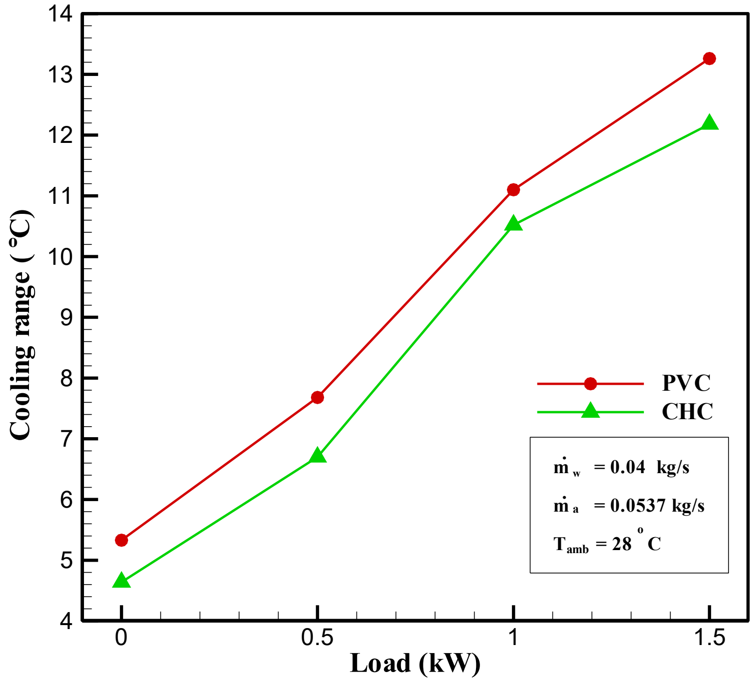
For a cooling tower, the cooling range is considered a significant parameter, while the approach value is an indicator of its performance. Each of the cooling ranges and the approach value was estimated for the two types of fillings (PVC plates and CHC material). Four variables were considered in the study, including cooling load, flow rate of hot water, flow rate of air, and ambient temperature. The cooling range and the approach value can be estimated by using the following formulas, respectively [23].

$$\textit{Cooling Range} = T_H - T_C \qquad (3)$$

$$\textit{Approach} = T_C - T_{w,i} \qquad (4)$$

4.1.Relationship of Cooling Load with Cooling Range and Approach Value

The effect of cooling load on cooling range and approach is shown in Fig. 3. Figure 3 (a) shows how the cooling range changed with the cooling load, where the load value was changed four times (0, 0.5, 1 and 1.5) kW with the water flow rate, air flow rate and ambient temperature remaining constant. Increasing the cooling load while keeping the flow rate of hot water through the tower constant means increasing the temperature of the water entering the tower. It is clear from this figure that the cooling range is directly proportional to the cooling load. The reason for this is that the higher the temperature of the water entering the tower, the rate of water evaporation increases, so the rate of heat absorbed from the hot water increases, i.e., increasing the cooling range. Fig. 3 (a) also illustrates that the cooling range with the PVC filling was better than that with the CHC filling because the surface area of the CHC filling was larger than that of the PVC filling. Fig. 3 (b) shows how to change the approach value with the cooling load. It is evident that the approach value generally increased with the increase in the load, and the nature of this increase depends on the amount of cooling load as well as the type of filling used. Increasing the cooling load will undoubtedly lead to a rise in the temperature of the cold water coming out of the tower. Assuming that the temperature of the wet bulb of air entering the tower was constant, the value of the approach increased. It appears from this figure that the value of the approach with the CHC filling was better than that with the PVC filling. The performance of the cooling tower improved as the approach value decreased. The results showed that the mean approach value when using the CHC filling was less than that when using the PVC filling by 0.25 °C.



(a)

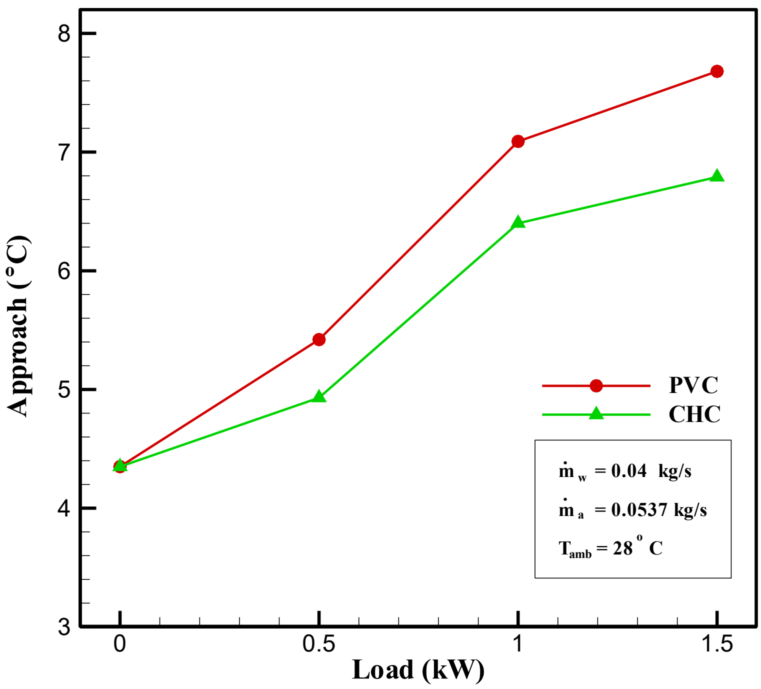
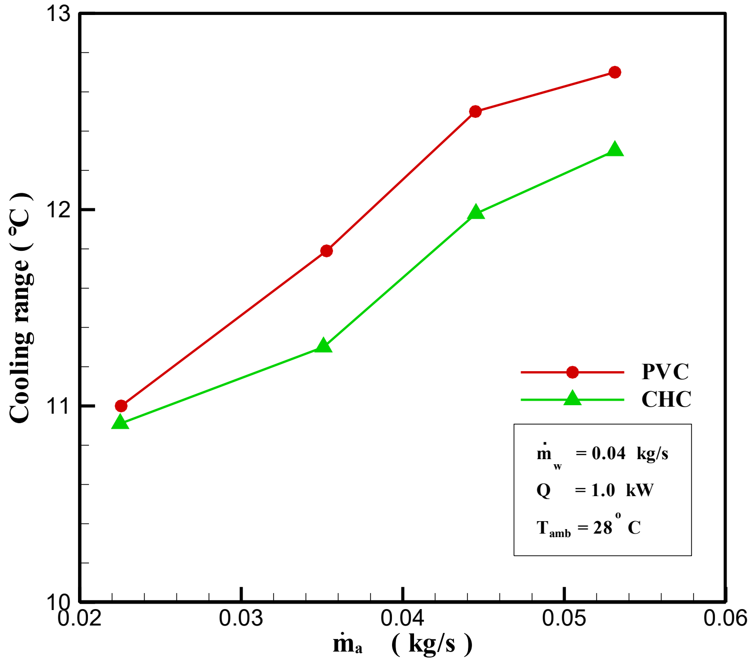


Fig. 3 Cooling Load Relationship with (a) Cooling Range, (b) Approach.

4.2.Relationship of Air Flow Rate with Cooling Range and Approach Value

The effect of air flow rate on cooling range and approach value is shown in Fig. 4. The air flow rate has been changed four times within the range of (0.022-0.0537) kg.s^{-1} at constant cooling load, water flow rate, and ambient temperature. The results showed that the cooling range improved with increasing the air flow rate, and that the amount of improvement was greater with the PVC filling than the CHC filling, as shown in Fig. 4 (a). The percentage of enhancement in the cooling range decreased within air flow rates of (0.045 - 0.0537) kg.s^{-1}, i.e., a higher air-to-water ratio. The significant increase in the ratio of air to water with a fixed cross-sectional area of the cooling tower means an increase in the speed of the air passing through the tower, which results in a decrease in the rate of heat removal from the water. The approach value improved clearly with the increase in the air flow rate, especially at relatively low air flow rates, as shown in Fig. 4 (b). Also, the approach value with the CHC filling is better (lower) than the PVC filling, with 2.84 °C as the mean difference in the values of approach between the two fillings.



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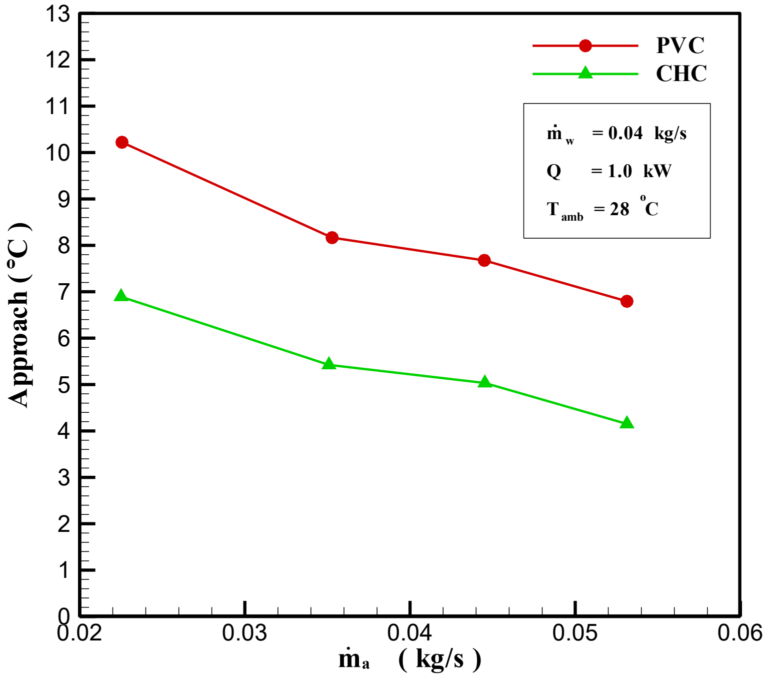
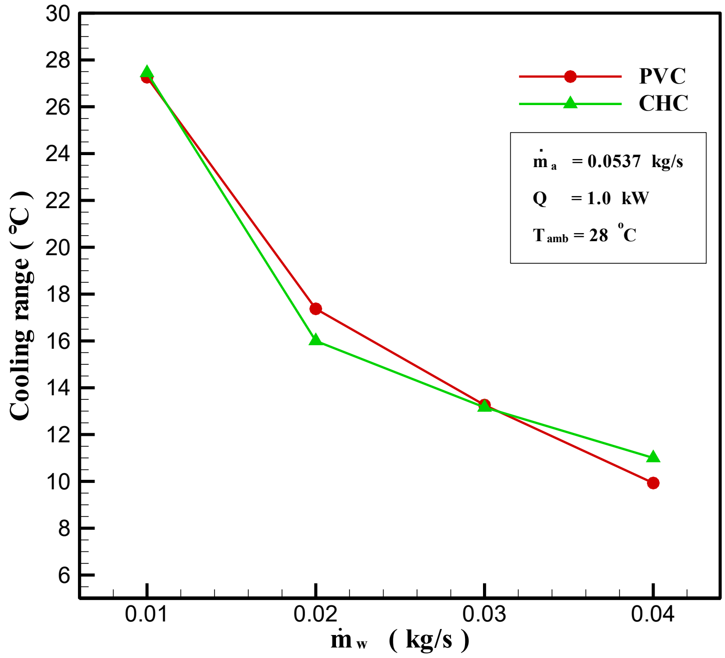


(b)

Fig. 4 Air Flow Rate Relationship with (a) Cooling Range, (b) Approach.

4.3. Relationship of Water Flow Rate with Cooling Range and Approach Value

Figure 5 (a) shows a noticeable decrease in the cooling range with an increase in the flow rate of hot water through the tower, i.e., an increase in thermal load, for both fillings. It is noticed from the figure that there was a clear reduction in the cooling range when the water flow rate was less than 0.02 $kg.s^{-1}$. The cooling range decreased clearly; this reduction in the cooling range decreased as the ratio of water to air increased. The increase in the ratio of water to air removed a specific amount of heat due to the saturation of the air with water vapor as it passed through the tower. Increasing the flow rate of hot water through the tower negatively affected the tower's performance. It is noted from Fig. 5 (b) that the approach values increased with the increase in the flow rate of hot water for both fillings. It appears that the approach values with the CHC filling were better than those recorded using the PVC filling, and the average difference in the approach values between the two fillings was 1.73 °C.



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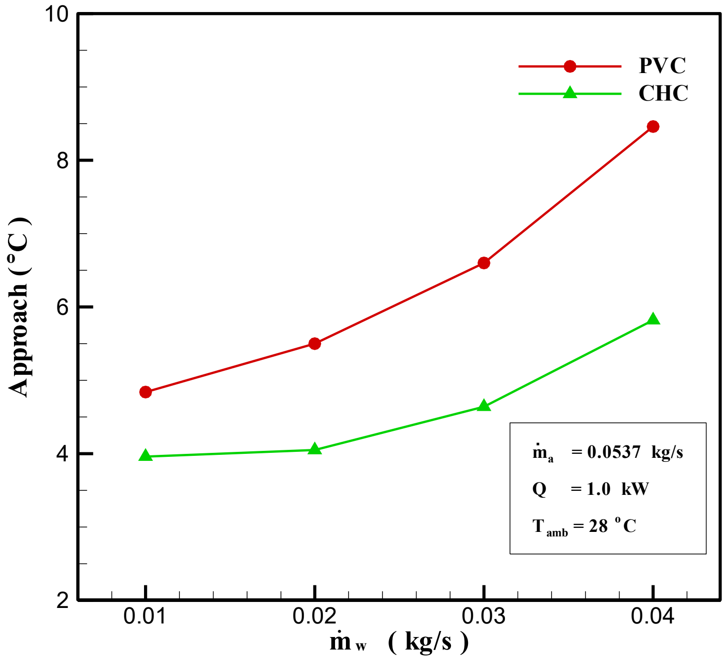
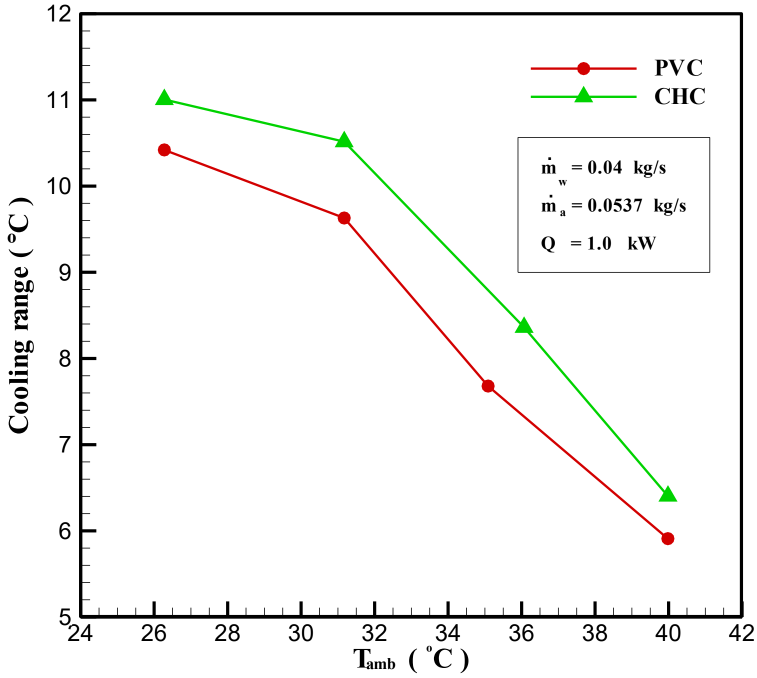


(b)

Fig. 5 Water Flow Rate Relationship with (a) Cooling Range, (b) Approach.

4.4.Relationship of Ambient Temperature with Cooling Range and Approach Value

Regardless of the type of filling, the cooling range and the approach value were clearly affected by the change in ambient temperature, as shown in Fig. 6. An increase in the ambient temperature undoubtedly decreased the cooling range, as shown in Fig. 6 (a). The cooling tower's performance deteriorated, i.e., the approach value increased as the ambient temperature increased, as shown in Fig. 6 (b). The reduction in tower performance as the ambient temperature increased can be attributed to the convergence of water and air temperatures, significantly decreasing the rate of heat transfer from water to air. Figure 6 shows that the performance of a cooling tower with CHC filling was better than that with PVC filling because the CHC filling has a larger surface area and better water dispersal than its PVC counterpart. The average difference in the approach values between the two fillings was 2.5 °C.



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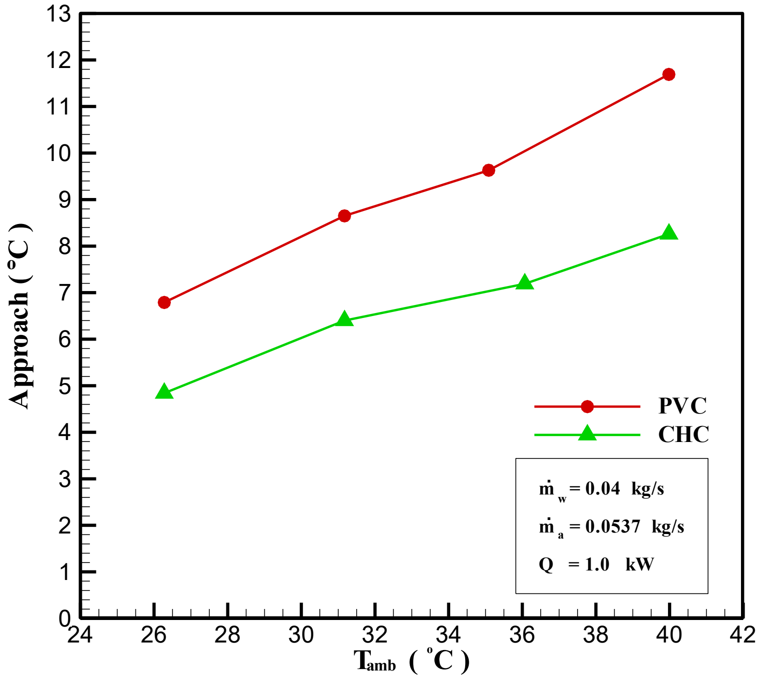

(b)

Fig. 6 Ambient Temperature Relationship with (a) Cooling Range, (b) Approach.

5.CONCLUSIONS

This experimental study determined the performance of a counter-flow cooling tower using two types of fillings: one made of PVC material and the other made of CHC material. The laboratory experiments were conducted under controlled space conditions. The effect of cooling load, air flow rate, water flow rate, and ambient temperature on cooling tower performance was tested with each of the two fillings. The following are the main conclusions:

- The study illustrated that increasing both the cooling load and the air flow rate through the tower enhanced the cooling range while detrimentally affecting the increase in water flow rate, as well as the rise in ambient temperature.
- The approach value improved with the increase in the air flow rate through the tower, while deteriorating with the increase in the cooling load, water flow rate, and ambient temperature.
- The approach value, which expresses the performance of the cooling tower, was lower (better) with the CHC filling than with the PVC filling for all of the studied cases.
- The mean difference in approach values between the two fillings was 0.52 °C for cooling load, 2.84 °C for air flow rate, 1.73 °C for water flow rate, and 2.5 °C for ambient air temperature.
- These results suggest that CHC filling is a more effective material for cooling towers than PVC filling.

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NOMENCLATURE

CHC	Cellulosic honeycomb
H	Pressure difference on both sides of the orifice plate, (mm of H_2O)
$\dot{m}_a$	Mass flow rate of air, kg/s
$\dot{m}_w$	Mass flow rate of water, kg/s
PVC	Polyvinyl chloride
Q	Cooling load, kW
T_{amb}	Ambient temperature, °C
T_C	Cooled water temperature, °C
T_H	Hot water temperature, °C
$T_{w,i}$	Wet bulb temperature of the air entering the tower, °C
Greek symbols	
v_O	specific volume of the air leaving the tower, (m^3 /K g)
ω_O	moisture content of the air leaving the tower, (kg/kg dry air)

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