Experimental Evaluation of Optimum Water to Air Flow Ratio in an Induced Draft Wet Cooling Tower

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Abstract - Cooling towers are devices used to dissipate waste thermal heat to the ambient environment. Appropriate cooling water and air flow rates are necessary to ensure optimum cooling power and cooling efficiency. Also, a simple design is required for cost effectiveness and minimal maintenance issues. This paper experimentally evaluates the cooling power, cooling efficiency, as well as the optimum water to air flow ratio in a spray type induced draft wet cooling tower. The cooling tower, 6 kW cooling capacity, was developed to operate without packings. The experiments were conducted for three different air flow rates and six different water flow rates. Four different inlet water temperatures of 35, 40, 45 and 50 °C were used. The temperature range is a typical range for inlet water temperature to the cooling tower for an absorption cooling system. For each of the inlet water temperatures, air and water flow rates were varied. The effects of this variation on cooling power and cooling efficiency were studied. Effect of varying water to air flow ratio on cooling power and cooling efficiency were studied. Results showed that the cooling power increased with increasing water flow rate, while the cooling efficiency decreased with increasing water flow rate. Decreasing the air flow rate was seen to cause a decrease in both cooling power and cooling efficiency. Maximum cooling power and cooling efficiency of 5.33 kW and 53% respectively were obtained. An optimum water to air flow ratio of 1.6 was obtained. The cooling tower was seen to have operated satisfactorily without packings.

Keywords - cooling tower, cooling power, cooling efficiency, flow ratio, thermal energy

1 INTRODUCTION

Energy utilization in systems such as power generation, combustion, refrigeration and air conditioning usually leads to generation of surplus thermal energy which must be removed as waste heat for the optimal performance of the system. Forced convective fluid flow and heat transfer arises in a range of engineering problems particularly when viscous fluids are heated and the heat transfer involved is low (Adegun et al., 2017). One of the ways to achieve waste heat removal from these systems is to dissipate the heat rejected to the atmosphere. This energy dissipation can be achieved by the use of cooling towers; which are devices that are used to dissipate waste thermal heat to the ambient environment (Pooriya et al., 2016). In dry cooling towers, cooling water is passed through finned tubes forming a heat exchanger, so only sensible heat is transferred to the air (Goshayshi and Missenden, 2000).

Wet cooling towers operate by rejecting waste heat carried by the cooling water via direct contact with the atmospheric air. The process is a combination of evaporative cooling and convective cooling to cool the water to the required temperature (Muangnoi et al., 2014). From economic point of view, it is better to use wet cooling towers rather than dry cooling towers in hot weather regions, due to the better thermal performance of the former (Muangnoi et al., 2014). Performance of wet cooling towers is influenced by many factors such as: inlet cooling water temperature, volume flow rate of water, mass flow rate of air and packing types. To obtain better performance of wet cooling towers, optimum values of these parameters need to be obtained. Studies have been carried out on various types of cooling towers, both theoretically and experimentally aimed at obtaining optimum values of operating parameters for enhanced performance. Bedekar et al., 1998, carried out an experimental study of performance of a counter flow packed bed mechanical cooling tower. They concluded that tower performance decreased with an increase in the water to air flow ratio. Pooriya et al., 2016 experimentally investigated the effect of various parameters on the thermal performance of a wet cooling tower. They concluded that the mass flow rate of air was the most effective parameter in the efficiency enhancement. Smrekar et al., 2006 theoretically optimized the thermal energy transfer across a natural draft cooling tower to increase the cooling efficiency. They subsequently suggested correlations to find an optimum ratio of water to air flow rates. Papaefthimiou et al., 2012 developed a thermodynamic model to simulate the effect of weather conditions on the thermal performance of wet cooling towers.

Lu et al., 2004 used a mathematical model to optimize the performance of a counter flow wet cooling tower with a view to minimizing the total energy consumption in the condenser water loop. Ramkrishnan and Arumugam 2013 conducted experiment on a forced draft cooling tower using different types of burnt clay as packing materials. They concluded that the heat and mass transfer coefficients were influenced by the water to air flow ratio, inlet water temperature and dry bulb temperature. Also, higher cooling tower effectiveness was achieved with lower water to air flow ratio. However, for small scale absorption cooling purposes where cooling water stream temperature is usually not higher than 50°C, the cooling tower could be operated without packings. Cooling tower operated without packings reduces fabrication cost as well as minimizes maintenance requirements. In this work, the cooling power, cooling efficiency as well as optimum water to air flow ratio was determined experimentally for a 6 kW wet cooling tower developed to operate without packings.
2 MATERIALS AND METHODS

The cooling tower was developed as an induced draft counter flow wet cooling tower operating without packings. It was developed for a solar absorption air conditioning system to take away the heats of condensation and absorption from the absorption chiller.

2.1 WORKING PRINCIPLE AND THEORY OF THE COOLING TOWER

Figure 1 shows the schematic of the cooling tower. Hot water enters at the top of the cooling tower from where it flows through a circular distribution manifold (7). The water exits the distribution manifold through attached nozzles (8) which allows the hot water to fall downwards through the spray zone (9) to the water basin (11) in spray form. This facilitates heat transfer and makes up for the packings that have been omitted. At the top of the cooling tower is attached a centrifugal fan (5), which draws air from the atmosphere into the cooling tower through inlet louvers (10) located on opposite sides of the cooling tower. The air flows up the cooling tower through the spray zone in counter flow direction to the cooling water and exits at the top of the cooling tower. The resulting cold water at the basin is pumped using a water pump (2) to the point of application.

The cooling tower was developed based on the Merkel’s method, which follows from the Merkel equation (Kroger, 2004) as shown in equation 1:

\[
\frac{Kav}{m} = C_{p_w} \int_{T_{w,i}}^{T_{w,o}} \frac{dt}{H_s - H_a}
\]  

(1)

The factor \( \frac{Kav}{m} \) is the tower characteristic where:
- \( K \) is the air mass transfer coefficient
- \( a \) is the water contact area per unit volume of tower
- \( V \) is the volume of the spray zone
- \( \dot{m} \) is the mass flow rate of water
- \( T_{w,i} \) and \( T_{w,o} \) are the inlet and outlet water temperatures to the cooling tower respectively
- \( C_{p,w} \) is the specific heat capacity of water
- \( H_s \) is the enthalpy of saturated air at local water temperature
- \( H_a \) is the enthalpy of the local air stream

The tower characteristic was then calculated according to Kroger (2004) using equation 2:

\[
\frac{Kav}{m} = \frac{C_{p,w} \left( T_{w,i} - T_{w,o} \right)}{\Delta H}
\]  

(2)

Where \( \Delta H \) represents the total increase in the enthalpy of air stream, evaluated using equation 3:

\[
\Delta H = \left( \frac{m_a}{\dot{m}} \right)_{opt} C_{p,w} \Delta T_w
\]  

(3)

2.2 EXPERIMENT

The experiment carried out in this study was aimed at evaluating the cooling tower performance as well as determining the optimum water to air flow ratio for optimum performance of the cooling tower. Performance of the cooling tower was measured in terms of (i) Cooling power: which is a measure of the heat loss from the cooling water stream while circulating in the cooling tower. (ii) Cooling efficiency: which indicates the overall effectiveness in which the cooling water stream is cooled. The cooling power and cooling efficiency are key parameters in evaluating cooling tower performance (Wei et al., 2017 and Pooriya et al., 2016). These parameters were evaluated at varying mass flow rates of the cooling water and air as well as varying cooling water inlet temperatures. The cooling tower fan has blades that span over a diameter of 0.35 m. It has three graduated speeds of 0.5 m/s, 0.7 m/s, and 0.9 m/s from which the air flow rates were obtained using equation 4:

\[
\dot{m}_a = \rho Av
\]  

(4)

where:
- \( \dot{m}_a \) is the mass flow rate of air
- \( \rho \) is the density of air
- \( A \) is the area covered by the fan blades while in motion
- \( v \) is the fan speed (m/s)

2.2.1 Experimental Procedure

The experiment described here was conducted at the Department of Mechanical Engineering, Ahmadu Bello University, Zaria, Nigeria. The experimental set up consists of a heating compartment which is made up of a storage tank attached to a liquefied petroleum gas (LPG) burner. The LPG gas burner provided thermal energy to the water in the storage tank up to the required temperature. A digital thermocouple was suspended in the storage tank to measure the temperature of the water. The gas burner was then switched off on the attainment of the required temperature. The water was pumped from the storage tank through flow control valve to the cooling tower where it entered at the inlet of the distribution manifold at the top of the cooling tower.

The volume flow rate of water was measured using a flow meter, while a thermocouple placed at inlet to the distribution manifold and attached to a thermocouple thermometer was used to measure the inlet water temperature. The water sprays down to the water basin, where a thermocouple was used to measure the outlet water temperature. The fan speed was varied to attain the desired mass flow rate of air. The inlet and outlet air temperatures to the cooling tower were measured using digital infrared thermometer at the inlet and exit air.
channels to the cooling tower respectively. For this experiment, three different air flow rates which are (0.0795 kg/s, 0.0568 kg/s and 0.034 kg/s), six different water flow rates (0.058 kg/s, 0.071 kg/s, 0.085 kg/s, 0.098 kg/s, 0.12 kg/s and 0.13 kg/s) and four different inlet water temperatures (35°C, 40°C, 45°C and 50°C) were used.

For each air flow rate, the inlet water temperature was set one at a time to the four different temperatures, while the water flow rate was varied over the six different flow rates. For each of the four inlet water temperatures, at a particular flow rate, experiment was run three times after which an average value of the outlet water temperature was used. During the experiment, dry bulb and wet bulb temperature of air were measured using a wet and dry bulb hygrometer. Average wet bulb temperature was found to be 23°C and this was used in the computations. Effect of the mass flow rate of air, volume flow rate of water and inlet water temperature on the performance parameters: cooling power and cooling efficiency were evaluated.

The measuring instruments used with their specifications are listed below

i. Digital thermocouple thermometer: model no.: T407291, measuring range: -50 – 1300°C, accuracy: 0.1%+1°C
ii. Digital flow meter: model no.: PT – 11, measuring range: 0.1L/hr – 100L/hr, accuracy: ±4%
iii. Digital infrared thermometer: model no.: PM6350D, measuring range: -50 – 800°C, accuracy: ±1.5°C
iv. Wet and dry bulb hygrometer: model no.: HX – D28, measuring range: -30 – 50°C, accuracy: 5% RH.

The following relations were used in performance evaluation:

i. Cooling efficiency ($\varepsilon$): This was evaluated using equation 5:

$$\varepsilon = \frac{T_{w,i} - T_{w,o}}{T_{w,i} - T_{w,\text{wet b}}}$$

where: $T_{w,\text{wet b}}$ is the wet bulb temperature of the air

ii. Cooling power ($Q$): This was evaluated using equation 6:

$$Q = \dot{m}_w C_{p,w} (T_{w,i} - T_{w,o})$$

where: $\dot{m}_w$ is the mass flow rate of water.

$C_{p,w}$ is the specific heat capacity of water.

The water to air flow ratio was computed by dividing each of the six different water flow rates by each of the three air flow rates. Effect of varying the flow ratio on cooling power as well as cooling efficiency was studied to obtain an optimum water to air flow ratio. Figure 2 shows the schematic of the experimental set up, figures 3 and 4 shows the cooling tower and heating compartment respectively.
3 RESULTS AND DISCUSSION

Figure 5 shows the variation of cooling power with cooling water flow rate at varying air flow rates of 0.795, 0.0568 and 0.034 kg/s, for inlet water temperatures of 35, 40, 45 and 50°C. The water flow rate was varied from 0.058 to 0.13 kg/s. From the figure, it can be observed that the cooling power increases as the water flow rate increases for all inlet water temperatures. The trend is the same for the three air flow rates considered as seen. This is because increasing the cooling water flow rate enhances the heat transfer process by having more heat released to the atmosphere. This result is consistent with the findings of Jiang et al., 2013.

It can be observed from the figure that the cooling powers at corresponding inlet water temperatures and flow rates are highest at air flow rate of 0.795 kg/s, followed by cooling powers at air flow rate of 0.0568 kg/s, while the cooling powers at air flow rate of 0.034 kg/s are the lowest. This indicates that there is a decrease in cooling power when the air flow rate is decreased for all water flow rates. This is because, reducing the air flow rate reduces the heat and mass transfer processes between the flowing air and the cooling water, thereby reducing cooling tower performance. Similar results have been reported in the works of Xia et al., 2011 and Sarker et al., 2009. From the figure, at inlet water temperature of 50°C and water flow rate of 0.13 kg/s, maximum cooling powers of 5.33 kW, 4.74 kW and 3.46 kW were obtained at air flow rates of 0.0795, 0.0568 and 0.034 kg/s respectively. This indicates that the cooling tower was able to achieve the desired cooling.

Figure 6 shows the variation of cooling efficiency with cooling water flow rate at varying air flow rates of 0.0795, 0.0568 and 0.034 kg/s, for inlet water temperatures of 35, 40, 45 and 50°C. The water flow rate was varied from 0.058 to 0.13 kg/s. From the figure, it is observed that the cooling efficiency decreases as the water flow rate increases for all inlet water temperatures and for the three air flow rates considered. This is because as the water flow rate increases, the pump energy consumption also increases thereby reducing cooling efficiency. This result is consistent with the findings of Jiang et al., 2013. However, the cooling efficiency is seen to increase with increasing inlet water temperature, for the three air flow rates considered. This is because higher inlet water temperatures lead to greater temperature differences, thereby increasing cooling efficiency. Also from the figure, it can be observed that for corresponding inlet water temperatures and water flow rates, the cooling efficiency decreases as the air flow rate decreases. This is because reducing the air flow rate reduces the heat and mass transfer processes between the flowing air and the cooling water. This causes very small temperature difference between the inlet and outlet cooling water, thereby reducing cooling efficiency. This finding is similar to that of Pooriya et al., 2016. From the figure, at inlet water temperature of 50°C and water flow rate of 0.058 kg/s, maximum cooling efficiencies of 63%, 58.5% and 44% were obtained at air flow rates of 0.0795, 0.0568 and 0.034 kg/s respectively.

From figures 5 and 6, it could be observed that the cooling power and cooling efficiency of the cooling tower are influenced by both the cooling water flow rate and the air flow rate. It is therefore necessary to obtain an optimum water to air flow ratio that will achieve maximum cooling power as well as enable the cooling tower operate with high cooling efficiency. Water to air flow ratio resulting from the water flow rates and air flow rates used in figures 5 and 6 were used to study variation of cooling power and cooling efficiency with flow ratio. Figure 7 shows the variation of cooling power with flow ratio. For all the flow ratios, cooling power is observed to increase with inlet cooling water temperature. Flow ratio of 0.729 produced a cooling power of 3.7 kW at 50°C inlet water temperature. Flow ratio of 1.6 can be observed to have produced the highest cooling power of 5.3 kW at 50°C inlet water temperature. When the flow ratio increased above 1.6, the cooling power can be observed to decrease below 5.3 kW. This is because increasing flow ratio implies the air flow rate becomes much lower compared to the water flow rate. Lower air flow rate results in lower cooling power.

Figure 8 shows the variation of cooling efficiency with flow ratio. From the figure, it is observed that the cooling efficiency increases with increasing inlet water temperature for all the flow ratios. Also, the cooling efficiency can be observed to decreases with increasing flow ratio. Flow ratio of 0.729 produces a cooling efficiency of 62.9% at inlet water temperature of 50°C. While flow ratio of 1.6 produces a cooling efficiency of 43.2% at inlet water temperature of 50°C. However, for flow ratios above 1.6, the cooling efficiencies become lower than 40%.

From the foregoing, flow ratio of 0.729 gives maximum cooling efficiency, while flow ratio of 1.6 gives maximum cooling power. Flow ratio above 1.6 diminishes cooling power and leads to cooling efficiency lower than 40%. This implies the cooling tower should be operated with flow ratio between 0.729 and 1.6. However, cooling powers obtained with flow ratio of 0.729 is low. Since higher cooling power directly relates to higher difference in temperature between the inlet hot water and outlet cooled water streams, then a higher cooling power is preferred. Therefore flow ratio of 1.6 could be considered an optimum water to air flow ratio.
Fig. 5: Variation of cooling power with water flow rate at varying air flow rates

Fig. 6: Variation of cooling efficiency with water flow rate at varying air flow rates

Fig. 7: Variation of cooling power with flow ratio
4 Conclusion
Experimental tests have been carried out on a spray type induced draft wet cooling tower of 6 kW capacity, operating without packings. Results showed that the cooling power increased with increasing water flow rate, while cooling efficiency decreased with increasing water flow rate. Cooling power and cooling efficiency were observed to decrease with decreasing air flow rate. The highest cooling power of 5.33 kW was obtained with inlet water temperature of 50°C at water flow rate of 0.13 kg/s and air flow rate of 0.0795 kg/s. The highest cooling efficiency of 63% was obtained with inlet water temperature of 50°C, water flow rate of 0.058 kg/s and air flow rate of 0.0795 kg/s. Flow ratio of 0.729 and 1.6 were observed to give highest cooling efficiency and cooling power respectively, while flow ratio above 1.6 caused decreasing cooling power and reduced the cooling efficiency below 40%. Moreover, flow ratio of 1.6 could be considered the optimum flow ratio since it gives highest cooling power. The foregoing shows the cooling tower developed without packings operated satisfactorily within the inlet water temperature range expected from an absorption cooling system of the studied capacity. A cooling tower developed in this form is easier to fabricate, has lower production cost and has less maintenance requirements.

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