

Optimal Water Conservation in a Mechanical Cooling Tower Operations

M. Boumaza, Y. Bakhbakhi

Abstract—Water recycling represents an important challenge for many countries, in particular in countries where this natural resource is rare. On the other hand, in many operations, water is used as a cooling medium, as a high proportion of water consumed in industry is used for cooling purposes. Generally this water is rejected directly to the nature. This reject will cause serious environment damages as well as an important waste of this precious element. On way to solve these problems is to reuse and recycle this warm water, through the use of natural cooling medium, such as air in a heat exchanger unit, known as a cooling tower. A poor performance, design or reliability of cooling towers will result in lower flow rate of cooling water an increase in the evaporation of water, an hence losses of water and energy.

This paper which presents an experimental investigate of thermal and hydraulic performances of a mechanical cooling tower, enables to show that the water evaporation rate, M_{ev} , increases with an increase in the air and water flow rates, as well as inlet water temperature and for fixed air flow rates, the pressure drop ($\Delta P_w/Z$) increases with increasing L , due to the hydrodynamic behavior of the air/water flow.

Keywords—water- recycle- performance - cooling tower

Nomenclature

C_{pw}	specific heat of water at constant pressure, kJ/kg°C
G	air mass flow rate, kg/h
G'	air mass flux, kg/h.m ²
L	water mass flow rate, kg/h
L'	water mass flux, kg/h.m ²
T_1	inlet water temperature, °C
T_2	outlet water temperature, °C
V	volume of the exchange core, m ³

I. INTRODUCTION

MANY manufacturing processes and most industrial chemical reactions generate tremendous amounts of heat that must be continuously removed if these processes are to continue to operate efficiently. Cooling towers filled with packing are commonly used to release excess heat loads from these processes, such as electric generating plants, thermal and nuclear power plants, chemical and petroleum industries and refrigeration and air-conditioning systems, into the atmosphere.

M. Boumaza is a Professor at King Saud University in the Dept of Chemical Engineering, College of Engineering, Riyadh, Saudi Arabia (corresponding author: 0096614679151, email: boumaza_m@hotmail.com)

Y. Bakhbakhi is an Assistant Professor at King Saud University in the Dept of Chemical Engineering, College of Engineering (email: ybakhbak@ksu.edu.sa)

Their principle is based on heat and mass transfer using direct contact between water and air through some types of packing. Several investigators have studied through some experimental analysis of the heat and mass transfer phenomena in cooling towers as these equipment constitute an important water conservation devices.

Milosavljevic and Heikkila [1] carried out experimental measurements on two pilot-scale cooling towers in order to analyze the performance of different cooling tower filling materials. Kloppers and Kröger [2] studied experimentally the transfer characteristics of wet cooling tower fills. They tested trickle, splash and film type fills in a counter flow wet cooling tower with a cross sectional test area of 2.25 m². Elsarrag [3] presented an experimental study and predictions of an induced draft ceramic tile packing cooling tower. Gharagheizi et al. [4] presented an experimental and comparative study on the performance of mechanical cooling tower with two types of film packing. They [4] used vertical corrugated packing (VCP) and horizontal corrugated packing (HCP) having 0.64 m in high and 0.25 m² cross section area. There exist several other mathematical models which can correlate simultaneous heat and mass transfer phenomena occurring within direct-contact cooling towers, such as the models discussed in Braun [5], Kloppers [6] and Qureshi and Zubair [7].

The purpose of this paper is to carry out an experimental investigation of the heat and mass transfer phenomena observed inside a direct-contact cooling tower filled with a vertical grids apparatus 'VGA.' type packing. This type of packing which has been initially been developed and used in mass transfer equipment [8] has not been used in cooling water systems using direct contact between water and air. Some researchers [9–11] used this type of packing in an evaporative cooling system to study its thermal and hydraulic performances. This packing consists of vertical grids disposed between walls in the form of zigzag. The ambient air enters at the bottom of the tower and flows upwards to the top of the tower, crossing several times the vertical grids, whereas the water is introduced at the top of the tower and flows downward along the vertical grids. Indeed, the change of the air flow direction several times within the tower creates better conditions that can improve the heat and mass transfer phenomena between water and air inside the cooling tower.

The results obtained relating mainly the global heat and mass transfer coefficient as well as the pressure drop across the cooling tower for various air and water flow rates seem to be in complete agreement with results published in the literature, suggesting the validation of these results.

II. EXPERIMENTAL RIG

Fig. 1 illustrates the experimental rig used in this investigation. It consists mainly of a packed of a packed

cooling tower which represents the main device used in this test, a cold water basin, a storage tank (3) which contains two electric heaters (12), a water pump (4), a flow meter device (5), a by-pass pipe (6), a water distributor (7), a fan (8), air distribution chamber (9), a separator of water drops (10), a thermostat (11). Auxiliaries items are also used such as temperatures and pressures measuring devices (13) (14) as well as system for the regulation of the water level (15) in the feed basin. The tower has dimensions 206 mm × 148 mm × 550 mm, and is fabricated from Plexiglas. It is filled with the "VGA." type packing having a cross-sectional test area of 150 mm × 148 mm, and consists of four (04) galvanised zigzag form sheets, between which are disposed three (03) metallic vertical grids in parallel. The distance between each two grids is 50 mm (width of the cell). The water distributor [9] is fabricated from copper tubes of 10/12 and 6/8 mm diameters, respectively. Fine droplets sweeping the width of the zigzag starting from the top of the tower are introduced through this distributor. The considered measurements which were taken consist of the temperatures (dry and wet) of the air at the entry and exit of the tower, as well as the inlet and outlet water temperatures.

The experimental procedure is as follows:

- Initiating the circulation of a water flow, and lighting the electrical heaters at the same time.
- As soon as the temperature of feed water exceeds few degrees the desired temperature, air is injected by switching on the fan.
- After a few moments, the temperature of water decreases and passes again by its initial value (set point) which corresponding to the measurements values of the dry and wet temperatures of the air at the entry (t_{d1} and t_{w1}) and the exit (t_{d2} and t_{w2}) of the tower and the inlet and outlet water temperature.

III. THEORETICAL ANALYSIS

A. Heat and Mass Transfer Calculation

General correlations for heat and mass transfer within cooling towers in terms of the physical tower characteristics do not exist [5]. It is usually necessary to correlate the tower performance data for specific tower design. The heat and mass transfer data are typically correlated with the following form:

$$KaV/L = c (L/G)^n \quad (1)$$

where c and n are empirical constants specific to a particular tower design. The left hand side of Eq. (1) is called the Merkel number and may be evaluated (according to the Merkel method) as follows [6, 12]:

$$\frac{KaV}{L} = \int_{T_2}^{T_1} \frac{C_{pw} dT}{H_w - H} \quad (2)$$

from which it results the global heat and mass transfer coefficient defined as Eq. (3)

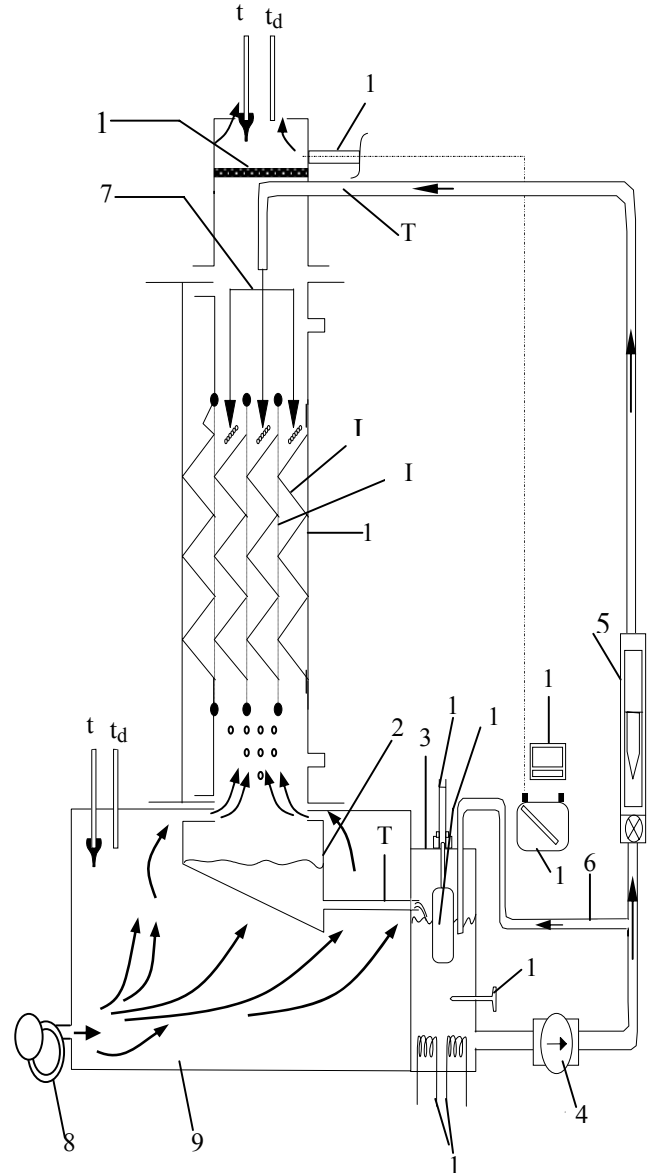


Fig. 1. Schematic diagram of the experimental rig. (1) the cooling tower filled with the "VGA." type packing, (2) load tank, (3) water basin, (4) water circulation pump, (5) flow meter, (6) by-pass pipe, (7) water distributor, (8) fan, (9) air distribution chamber, (10) drift eliminator, (11) thermostat, (12) heaters, (13) digital temperature indicator, (14) manometer, (15) float valve, (16) make-up tank, (17) connection for orifice differential pressure, (I).

$$Ka = \frac{L}{V} \times \int_{T_2}^{T_1} \frac{C_{pw} dT}{H_w - H} \quad (3)$$

The integration of Eq. (3) is solved numerically to obtain the values of the global heat and mass transfer coefficient, Ka , reported to the volume of the exchange core, for different experimental operating conditions for water and air. For integrating Eq. (3), the following equations were used [9], [11]:

$$H_w = \alpha e^{\lambda T} \quad (4)$$

H_w is the enthalpy of saturated air, in kJ/kg, where α and λ are given by:
 $\alpha = 20.900$, $\lambda = 0.05200$ for $17^\circ\text{C} \leq T \leq 51^\circ\text{C}$, with $r^2 = 0.9995$.

where r^2 is the correlation coefficient, which is very close to one.

$$H = H_1 + C_{pw} (L/G) (T_1 - T) \quad (5)$$

where H_1 is the enthalpy of moist air at the entry of the tower, and is given by the following equation [13]:

$$H_1 = (1.005 + 1.884w_1) t_{d1} + 2502.3w_1 \quad (6)$$

w_1 is the specific humidity of moist air at the entry of the tower, in kg/kg.

Eq. (4) was obtained by approximating the enthalpy of the air in saturation, H_w , using the values tabulated in the literature [13, 14].

B. Pressure Drop

According to Kloppers et al [2003] ΔP is calculated as

$$\Delta p_{fi} = K_{fi} \rho v^2 / 2 \quad (7)$$

- Δp_{fi} = measured static pressure drop across the fill.
- Δp_{fi} :due to viscous drag, form drag resistance and the acceleration of the air due to heating and mass transfer.
- Buoyancy effects will tend to counteract these effects in cases of counter flow,

$$K_{fi} = 2\Delta p_{fi} / \rho v^2 \quad (8)$$

- K_{fi} : Loss coefficient of a cooling tower packing
- Literature shows that ΔP is

$$\Delta P_{fi} = C_1 L^2 G^{C_3} \quad (9)$$

- C_1, C_2, C_3 = Constants for particular packing.

IV. RESULT AND DISCUSSIONS

A. Heat and Mass Transfers Coefficients

Two main operating hydrodynamic regimes were observed during the air and water contact, through the "VGA." type packing inside the cooling tower, as reported by Lemouari et al. [10]-[11]:

A first regime, called Pellicular Regime (PR), exists with low water flow rates, and a second regime, called Bubble and Dispersion Regime (BDR), appears with relatively larger water flow rates. Consequently, two different states of heat and mass transfer phenomena were identified, as illustrated in Fig. 2.

Figure 2 shows the variation of the global heat and mass transfer coefficient, Ka , with respect to the air flow rate, G , for different values of the water flow rate, L , carried out at an inlet water temperature of 50°C . It appears from this figure that the global heat and mass transfer coefficient increases gradually with an increase of G . This increase becomes more pronounced

as G increases, for the case of the Bubble and Dispersion Regime (BDR) where higher values of, Ka are observed, compared to those obtained in Pellicular Regime (PR). The effect of G on the global heat and mass transfer coefficient can be mainly attributed to the increase in the fraction of water that evaporates per unit mass of inlet air stream. It has also been observed during the experiments, that an increase in water flow rate is accompanied by an increase in the water hold-up in the cells of the packing, and this might increase considerably the actual contact area between water and air which leads to higher values of Ka particularly in the case of Bubble and Dispersion Regime. This figure shows also a linear variation of Ka with the water flow rate (in log-log scale), but with certain irregularities in the evolution in Pellicular Regime as in Bubble and Dispersion Regime. This could be partially attributed to the incomplete wetting of the vertical grids and imperfect water distribution on the packing material which induces irregular variations of the actual air-water contact area, leading to such irregular variations of, Ka . Similar behavior was also noticed by Hutchison and Spivey [15], particularly for low water flow rates which are therefore, insufficient to ensure complete wetting of the surface of the packing. Thus, in Bubble and Dispersion Regime, the increase of the global heat and mass transfer coefficient becomes less sensitive to the increase in the water flow rate, which can be attributed to the hydrodynamic behavior of the air/water flow which becomes gradually more or less reproducible presenting a better distribution of water on the vertical grids, starting from the water flow rate for which this regime is reached, and which corresponds to the appearance of relatively higher values of, Ka in such case. Indeed, London et al. [16] reported that the global heat and mass transfer coefficient of air/water increases with the increase of water flow rate, and becomes roughly independent of this one if this last is sufficient to completely wet the surface of the packing. Thus, it is observed that the effect of increasing water flow rate on the global heat and mass transfer coefficient becomes weaker compared to that of the air as soon as the bubble and dispersion regime is reached.

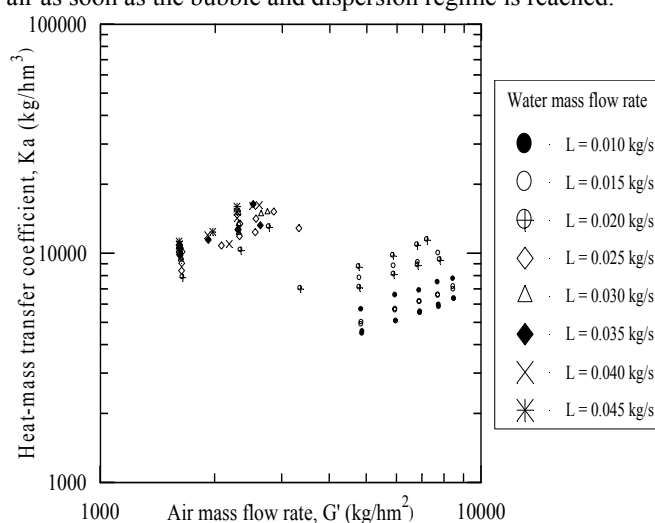


Fig. 2. Global heat and mass transfer coefficient vs. air mass flow rate for different values of water flow rate at an inlet water temperature of 50°C .

B. Correlation of the Global Coefficient

As mentioned earlier, the global heat and mass transfer coefficient, Ka , between the water and the air inside the cooling tower is influenced by the air and water flow rates. As shown earlier (Eq. (1)), this coefficient is often correlated into the form:

$$Ka = c_1 (L')^{c_2} (G')^{c_3} \quad (7)$$

where c_1 , c_2 and c_3 are constants specific to a particular cooling tower design which are to be determined experimentally. Therefore, in order to derive the heat and mass transfer characteristic equations for the type of the packed cooling tower under investigation, results of three tests are gathered, and the data were correlated into the following form, for each operating regime of the tower.

- *Pellicular Regime (PR):*

$$Ka = 1.998(L')^{0.60}(G')^{0.40} \quad (8)$$

within a standard deviation of 20.4%.

- *Bubble and Dispersion Regime (BDR):*

$$Ka = 4.428567(L')^{0.29}(G')^{0.71} \quad (9)$$

within a standard deviation of 9.10%.

The empirical correlations developed in this work (Eqs. (8) and (9)) were then compared with some published correlations in the literature for other types of packing as illustrated in Fig. 3. These correlations are as follows,

Kloppers and Kröger's correlation (for the trickle fill) [2]:

$$Ka = 0.857913777(L')^{0.43177}(G')^{0.641400}Z^{-0.352377}T_1^{-0.178670} \quad (10)$$

with a correlation coefficient (r^2) of 0.9862 where $L' = 2.75-6.72 \text{ kg/s.m}^2$ and $G' = 1.20-4.25 \text{ kg/s.m}^2$, Z is the packing high, in (m).

Gharagheizi et al.'s correlations [4]:

Vertical Corrugated Packing (VCP):

$$Ka = 0.534375(L')^{0.747}(G')^{0.253} \quad (11)$$

Horizontal Corrugated Packing (HCP):

$$Ka = 0.350000(L')^{0.705}(G')^{0.295} \quad (12)$$

where $(L/G) = 0.2-4$; packing high: 0.64 m.

It should be noted that the choice of the correlations for comparison is justified by the operating conditions at which the experiments were carried out, such as the air and water flow rates ranges and the inlet water temperature. The height of the packing has not been considered in the comparison with Kloppers and Kröger's correlation [2] as its effect was included

in this correlation (Eq. (10)) and therefore, it is assumed to be 0.42 m as in this work.

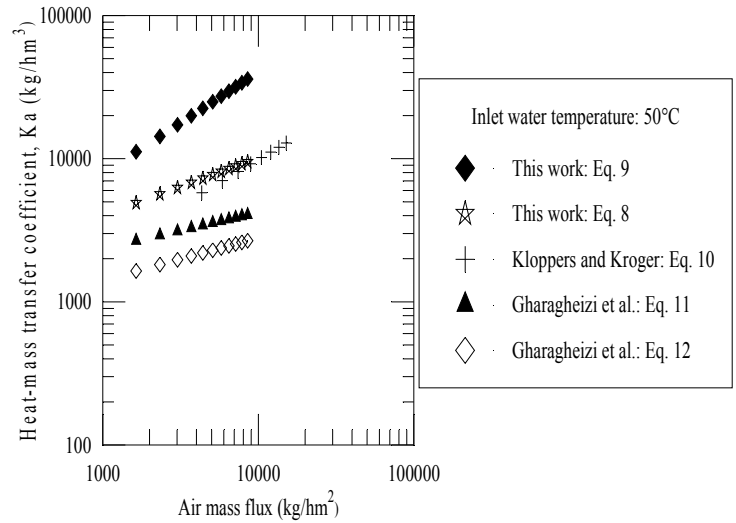


Fig. 3. Comparison of the results with Kloppers and Kröger [2] and Gharagheizi et al.'s correlations [4].

As can be seen from Fig. 3, the correlations developed in this work (Eqs. (8) and (9)) are higher than those used for comparison (Eqs. (10)–(12)). This indicates clearly that the heat and mass transfer coefficients of the packed cooling tower used in this investigation are much higher than the values in the cooling towers used for comparison which results in a higher heat and mass transfer effectiveness between water and air through the “VGA.” type packing in the cooling tower used in this work and therefore leads to higher values of water cooling capacity for the VGA type of cooling tower, than other types [11] of cooling towers.

This suggests that cooling tower filled with the “VGA.” type packing possesses better heat and mass transfer characteristics, and can contribute significantly to the saving of energy.

C. Pressure Drop

Figure 4 shows the variation of the wet pressure drop per unit height of packing, $\Delta P_w/Z$, with the air flow rate, G , for several values of the water flow rate, L , at different inlet water temperatures: 35°C, and 50°C, respectively. For each value of L , ΔP across the cooling tower packing increases with the increase in G for all inlet water temperatures. This evolution is slow in Pellicular Regime so that it appears nearly similar to that for dry packing, then it becomes more significant as the Bubble and Dispersion Regime is reached. The abrupt increase of the pressure drop could be partially explained by the wetting of a great fraction of the surface of the vertical grids whose opening are covered by the water film in flow, and primarily by the existence of stagnant water layers in certain cells of contact between air and water, which in turn constitute a barrier to the passing air, thus representing a great resistance to the air flow through the packing in such case, and therefore affect severely the pressure drop. It can be seen through these figures that, at fixed air flow rates, $\Delta P_w/Z$ increases with increasing the water flow rate, L , which is due

principally, as explained in reference [200], to the reduced free cross section offered for air flow resulting from the presence of the water. This increase is in certain cases irregular that is due probably to the hydrodynamic behavior of the air/water flow which changes from one test to another because of the difficulty of being controlled, particularly that of water, of which the distribution on the vertical grids is not made with the same manner for different tests. Thus, the pressure drop reach higher values in the Bubble and Dispersion Regime compared to those obtained in the Pellicular regime. This can be mainly attributed to the stagnation of water layers in certain cells of the packing particularly in the zone near the top of the tower.

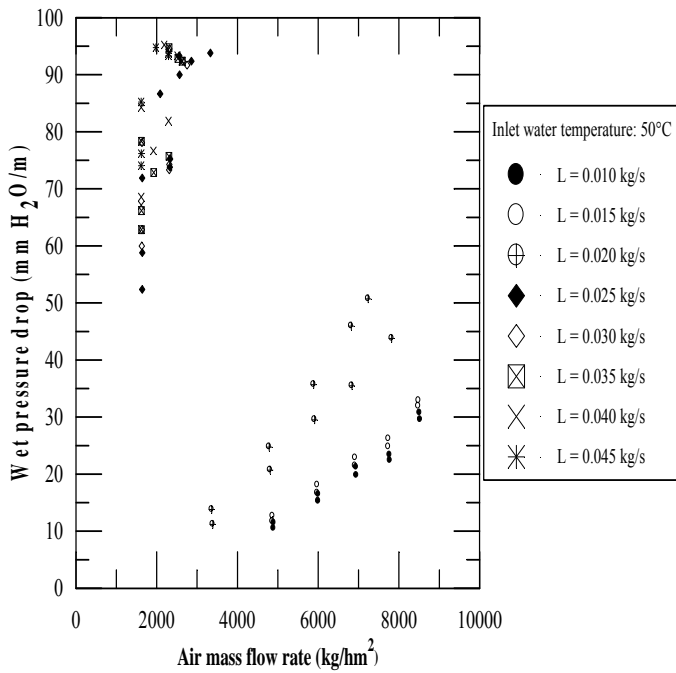


Fig. 4 Wet Pressure drop Vs Air Mass flow rate

D. Wet Bulb Temperature approach

Figure 5 shows the variation of the wet bulb approach, T_{ap} , with the air flow rate, G , for several values of the water flow rate, L , carried out at different inlet water temperatures of 50°C. For each value of, L , the wet bulb approach decreases progressively with an increase of the air flow rate, in Pellicular Regime as well as in Bubble and Dispersion Regime. This evolution is more pronounced in the Bubble and Dispersion Regime compared to that observed in the Pellicular Regime, particularly for the inlet water temperature of 50°C. This can be attributed to the increase in the actual contact area between air and water with an increase in the air flow rate in such case, which involves a progressive decrease in the outlet water temperature, which in turn would have a direct effect on the wet bulb approach. It should be noted in this case that the differences observed between the results of the various tests could be partially attributed to the variation in the wet bulb temperature of the cooling air which depends on the atmospheric conditions. Thus, it can be shown through these figures that the wet bulb temperature approach varies proportionally with the inlet water temperature. In this respect,

similar tendency was noticed by Kloppers [6]. (20020 and could be partially explained by the increase in the outlet water temperature with the increase in the inlet water temperature and, as mentioned above, with the water mass flow rate for fixed air flow rate

V. CONCLUSIONS

This study is concerned with water conservation during the recycling of water in a direct contact cooling tower, as it covers evaporative heat and mass transfer inside a tower filled with a vertical grids apparatus "VGA." type. The investigation enabled to obtain the following conclusions:

i) During the air and water contact through the packing within the tower, two operating hydrodynamic regimes of the cooling tower were observed: a pellicular regime: existing with low water flow rates, and a bubble and dispersion regime: appearing for relatively larger water flow rates. These two regimes have enabled to identify two different states of heat and mass transfer and therefore can determine the best way to promote the evaporative heat and mass transfer phenomena in such equipment

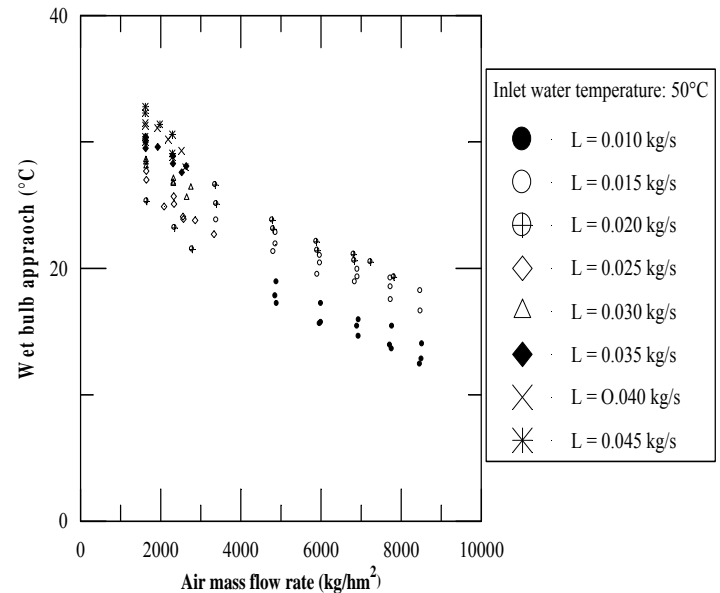


Fig. 5 Variation of wet bulb temperature with air mass flow rates

(ii) The global heat and mass transfer coefficient, Ka , increases in power with the water and air mass flow rates. This increase is more pronounced for the Bubble and Dispersion Regime which appear at higher values of, Ka . Consequently, better heat and mass transfer phenomena within the cooling tower is obtained in the Bubble and Dispersion Regime.

(iii) ΔP_w reaches higher values in the BDR, due to the stagnation of water layers in certain cells of the packing particularly at the top of the tower

(iv) Despite of its low height, compared to systems filled with other types of packing, the cooling tower filled with the "VGA." type packing, leads to very interesting heat and mass transfer characteristics and therefore a great water cooling

capacity. This can contribute significantly to the energy saving and economics.

It is recommended to extend the range of variation of the air and water flow rates for relatively higher inlet water temperatures, using higher towers.

ACKNOWLEDGMENT

The authors are grateful to the research centre of the college of Engineering, King Saud University, Riyadh, Saudi Arabia for their financial support.

REFERENCES

- [1] N. Milosavljevic, P. Heikkila, A comprehensive approach to cooling tower design, *Applied Thermal Engineering* 21 (2001) 899–915.
- [2] J. C. Kloppers, D. G. Kröger, Refinement of the transfer characteristic correlation of wet cooling tower fills, *Heat Transfer Engineering* 26 (4) (2005) 35–41.
- [3] E. Elsarag, Experimental study and predictions of an inclined draft ceramic tile packing cooling tower, *Energy Conversion and Management* 47 (2006) 2034–2043.
- [4] F. Gharagheizi, R. Hayati, S. Fatemi, Experimental study on the performance of mechanical cooling tower with two types of film packing, *Energy Conversion and Management* 48 (2007) 277–280.
- [5] J. E. Braun, Methodologies for the design and control of central cooling plants, PhD Thesis, Mechanical engineering, University of Wisconsin–Madison, USA, 1988.
- [6] J. C. Kloppers, A critical evaluation and refinement of the performance prediction of wet cooling towers, PhD Thesis, Mechanical engineering, University of Stellenbosch, South Africa, 2003.
- [7] B. A. Qureshi, S. M. Zubair, A complete model of wet cooling towers with fouling in fills, *Applied Thermal Engineering* 26 (2006) 1982–1989.
- [8] Y. I. Ignatenkov, Study and elaboration of a method for calculating optimum parameters of mass exchange apparatuses with vertical grids, Doctorate Thesis, Institute of Leningrad, 1979.
- [9] M. Lemouari, M. Boumaza: An experimental investigation of thermal characteristics of a draft wet cooling tower, in: *Proceedings 13th IAHR Symposium in cooling towers*, Poitiers, France, 2005.
- [10] M. Lemouari, M. Boumaza, M. Mujtaba: Thermal performances investigation of a wet cooling tower, *Applied Thermal Engineering* 27 (2007) 902–909.
- [11] M. Lemouari, M. Boumaza, A. Kaabi: Experimental analysis of heat and mass transfer phenomena in a direct contact evaporative cooling tower, *Energy conversion management*, 50, 2009.
- [12] F. Merkel, *Verdunstungskuehlung*, VDI Forschungsarbeiten, no. 275, Berlin, 1925.
- [13] R. E. Treybal, *Mass Transfer operations*, Third ed., McGraw-Hill, 1980. Instruction manual: Basic water cooling tower, Engineering Teaching and Research Equipment, Armfield, England, 1993.
- [14] W. K. Hutchison, E. Spivey, Design and performance of cooling towers, *Trans. Inst. Chem. Eng.* 20 (1942) 14–29.
- [15] A. M. London, W. E. Mason, L. M. K. Boelter, Performance characteristics of a mechanically induced draft counterflow packed cooling tower, *Trans. A. S. M. E.* 62 (1940) 41–50.