Journal of Trends in the Development of Machinery and Associated Technology
Vol. 18, No. 1, 2014, ISSN 2303-4009 (online), p.p. 143-146

EXPERIMENTAL INVESTIGATION OF HEAT AND MASS TRANSFER FROM A FALLING LIQUID FILM

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ABSTRACT
Simultaneous heat and mass transfer from falling films is investigated experimentally. In this study, water is uniformly spread over a set of five vertically placed plates. Liquid film is formed on both sides of the plates. The experiments were conducted on cement plates containing asbestos fibers (salonite), as a hydrophilic material. The Reynolds number of the air varied from 5170 to 8105. Inlet temperature of the water film varied from 43 to 49°C. Reynolds number of the liquid film had a value of 50. The inlet air temperature in the test section was varied from 26 to 28°C and the relative air humidity varied from 3.33–5.12 %. The coefficients of heat and mass transfer are determined by measuring the inlet and the outlet parameters of the air flow (flow rate, temperature and humidity) and of the falling film (temperature and flow rate).
Keywords: falling film, humid air, heat and mass transfer, cooling tower, Merkel method

1. INTRODUCTION
Simultaneous heat and mass transfer from falling films appear during cooling and heating processes in industry, for example in breweries, dairy factories, chemical industries, drying processes, food technology, falling film chiller, falling film evaporators, cooling tower, air humidification and dehumidification. These technologies usually operate with low Reynolds numbers of liquids.
Evaporative cooling of a liquid film through interfacial heat and mass transfer in vertical ducts was investigated by Yan et al. [1-3]. A liquid film streams along the plates at a temperature higher than that of the downward airflow at the entrance. Results from [1-3] showed that the influence of the evaporative latent heat transfer on the cooling of the liquid film depends largely on the inlet liquid film temperature and the inlet liquid mass flow rate. Influence of various parameters on heat and mass transfer coefficients in a laboratory-scale cooling tower with flat type packing and falling liquid film is experimentally investigated by [4, 5].
A numerical and experimental analysis has been carried out by Tsay et al. [6] to explore the detailed heat transfer characteristics for a falling liquid film along a vertical insulated flat plate. Inlet liquid film temperature of 30°C or 35°C was adopted and the temperature of the free air stream was 30°C. The results show that the latent heat transfer connected with the vaporization is the main cause for cooling of the liquid film. Mezaache & Daguenet [7] conducted a numerical study of the evaporation of a water film falling on an inclined plate in a forced convection flow of humid air. The plate is insulated or heated by a constant heat flux. Volchkov et al. [8] numerically investigated both laminar and turbulent forced convection of humid air over an infinite flat plate. Oubella et al. [9] numerically investigated mixed convection heat and mass transfer with film evaporation in a vertical channel formed by two parallel plates, which are isothermal and wetted by a thin liquid film of water, methanol or acetone. The effects of temperature of the dry air at the inlet and Reynolds number on the heat and mass transfer rates were particularly investigated.
The total heat transfer, sensible and latent heat transfer, the evaporation rate, and heat and mass transfer coefficients are estimated in this study. The humidity content, temperature change and the water evaporation rate in terms of the air Reynolds number are presented as well. The results of the

experiment were then compared with the relation obtained by Merkel method. Experimental results are presented in terms of the inlet temperature of the falling film and the Reynolds numbers. The mass transfer coefficient is compared with those obtained from known correlations. The mass transfer coefficients obtained using the Merkel method and the corresponding Reynolds numbers have similar increasing trend. Relative difference between the mass transfer coefficient obtained experimentally and the one obtained via the Merkel method is between 16 and 33 %. This difference increases as the air Reynolds number increases.

2. EXPERIMENTAL APPARATUS AND METHOD

A schematic diagram of the experimental facility is presented in Figure 1a. A photograph of the set of plates is shown in Figure 1b. The same set-up is used by [4,5]. The water was drawn from an electrical water heater by a gear pump. Water temperature at the inlet of the heater is controlled by a thermostat. The water flow-rate was controlled by a flow regulator and measured using a calibrated rotameter with an accuracy of ±2%. The air was delivered by a compressor and it flows through a filter and a dryer to remove moisture and oil from the air. The air flow-rate was regulated by a valve and measured by an air rotameter with an accuracy of ±2%. The test section consists of five vertically oriented parallel salonite (asbestos-cement) plates which are assembled together to a set. The plates are 0.5 m high and 0.25 m wide. Distance between the plates is 50 mm, so that the liquid spreads over both sides of each of the plates. The set of plates is installed in a rectangular section. Cross area of the channel is 0.3 x 0.3 m^2 with height of 0.61 m. It is constructed from a transparent Plexiglas to permit visual observation of the flow patterns. The Plexiglas section is placed on a stainless chamber, which serves as an air distributor. Water at the inlet of the section flows through a water distributor where spreads uniformly over both side of the plates. The distributor is has many small holes in order to spread water uniformly across the plates. The upper edges of the plate are covered with fine tissue which assists a uniform spreading of the water all over the plates. The water flows downwards as a liquid film along the test section while the air flows in counter-current direction.

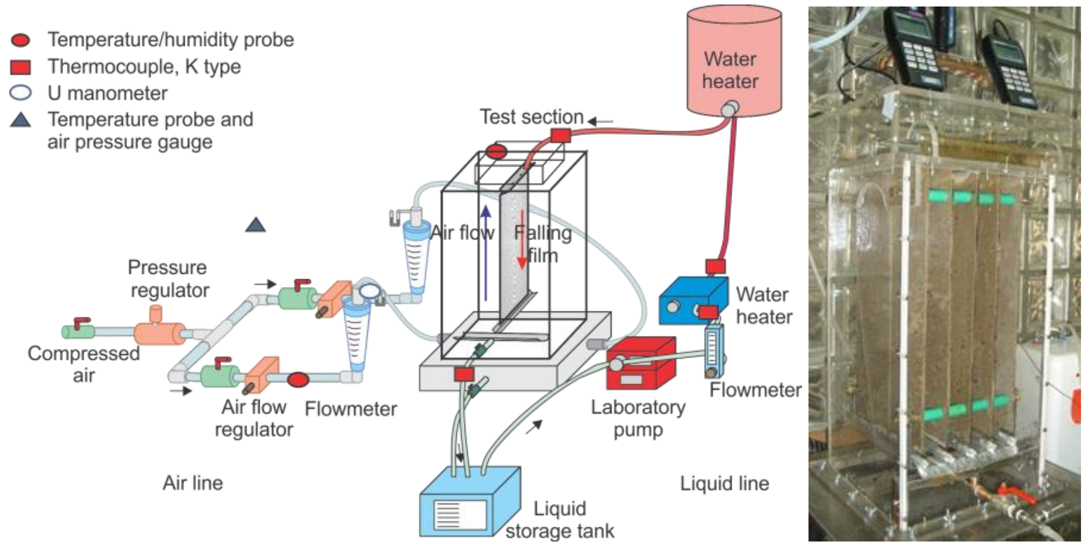

Figure 1. Schematic of the experimental set-up (left) and a photograph view of the test section.

The temperature and the relative air humidity at the inlet and the outlet are measured by digital humidity meters (electrostatic capacitance type). The water temperatures at the inlet and the outlet of the test section are measured by thermocouples. The air flow rate was changed while the flow rate of water and its temperature remained constant. After each change in the inlet air flow rate, both the air and the water flow rates, the relative humidity of the air at the inlet and the outlet of the test section were recorded.

3. RESULTS AND DISCUSSION

A large number of graphs can be drawn from the result of the study. Due to the space limitations, only few representative results of these experiments are show. While the hot water flows down as a film counter currently with air flow, vaporization occurs at the interface and water vapor from this vaporization will be added to the existing water vapor in the air flow. Mass fraction of the water vapor at the outlet of the test section is, therefore, higher than those of the inlet and is also found to be below the saturation line.

Sensible heat rate transferred to the air is defined as

$$Q_{\text{sens}} = \dot{m}_{\text{a}} c_{p,\text{a}} (t_{\text{a,in}} - t_{\text{a,out}}) \tag{1}$$

Latent heat rate transferred to the air is defined as

$$Q_{\text{sens}} = \dot{m}_{\text{a}} (X_{\text{a,in}} - X_{\text{a,out}}) r \tag{2}$$

Heat and mass transfer coefficients (α_a, W/m^{2}K; β_X, kg/m^{2}s) are defined as

$$\alpha_{\text{a}} = \frac{Q_{\text{sens}}}{A \Delta t_{\text{lm}}}; \qquad \beta_X = \frac{Q_{\text{lat}}}{A \Delta X_{\text{ln}} r} \tag{3a,b}$$

where A is the contact area, Δt_{lm} the logarithmic mean temperature difference, ΔX_{lm} the logarithmic mean humidity difference and r is latent heat of water vaporization.

Total heat transfer coefficient on air side, α (W/m^{2}K), is obtained from the total heat rate (Q_{sens}+ Q_{lat})

$$\alpha = \frac{Q}{A \Delta t_{\text{log}}} \tag{4}$$

Total heat rate is calculated from: the heat balance for water, enthalpy balance of air flow and the sum of latent and sensible heat rate absorbed by the air flow.

The experimental results for two inlet temperature of air flow are presented in Figs. 2 and 3. The Reynolds number ($\text{Re}_{\text{a}} = u_{\text{a}} D_{\text{H,a}} / \nu_{\text{a}}$) of the air was in range of 5170 to 8105. Temperature of the falling film at the test section inlet had a range of 43 to 49°C. Mass flow rate of the falling film had a value of 0.0187kg/s.

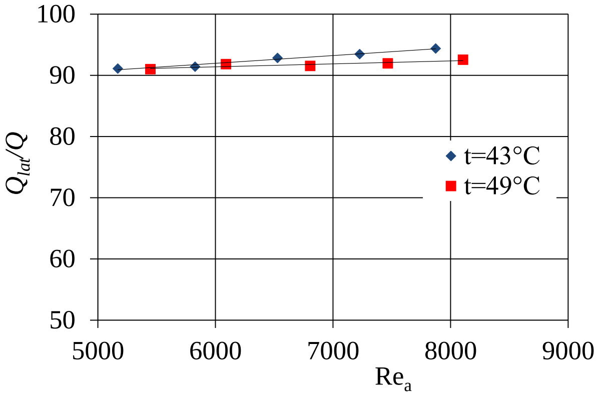

Figure 2. Ratio of latent to total heat transfer rates (for film flow rate of 0.0187 kg/s).

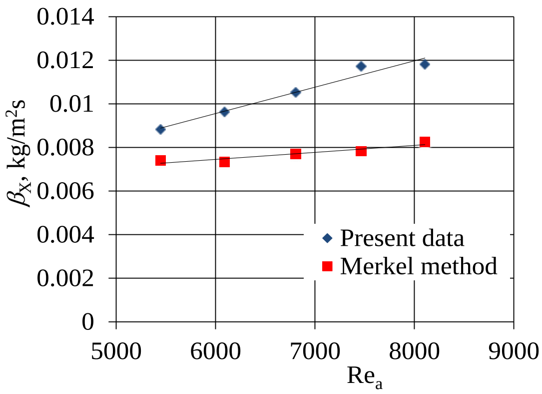

Figure 3. Mass transfer coefficient: the experimental data and the calculated by Merkel method (inlet film temperature 49°C).

The ratio of latent to total heat rate, in terms of the air Reynolds number for two different inlet water temperature is shown in Fig. 2. The ratio of the latent heat rate to total heat rate increases as the air Reynolds number increases. As the water temperature increases the fraction of latent heat rate in the total heat rate decreases. An increase of temperature differences between water and air flow imply increase of the sensible heat rate. The fraction of the latent heat in the total heat transfer was between 90 and 95%. These results coincide with published data [10]. Therefore, heat transfer between the falling film and the humid air is controlled by mass transfer; the latent heat rate is associated with vaporization of liquid film.

Mass transfer coefficient in terms of Reynolds number of the air for the experimental date and the data obtained by the Merkel methods are presented in Figure 3. A numerical integration is used in the

Merkel method. Mass transfer coefficient increases as the air Reynolds number increase. The Merkel method gives lower values for the mass transfer coefficient than that obtained experimentally. The relative difference in the mass transfer coefficient ranges from 16% at Re_a=5446 to 30% at Re_a=8100. These differences are due to the assumption used in the Merkel method. In his model, the water loss of evaporation is neglected and the Lewis number is assumed to be one in order to simplify the analysis. However, as evaporate water cannot be neglected in cooling tower operation, Merkel's model is not accurate enough and not suitable for real applications.

4. CONCLUSIONS

Simultaneous heat mass transfer in direct contact of a liquid film and a humid air flow has been investigated. Reynolds number of the air was in a range from 5170 to 8100. Inlet water temperature was in a range from 43 to 49°C. Latent heat transfer rate are dominated in a comparison to the sensible heat transfer rate. The latent heat rate is up to 12 times higher than the sensible heat transfer rate. Mass transfer coefficient increases as the gas Reynolds number increases. The Merkel method under predicts the mass transfer coefficient in comparison to the experimentally obtained mass transfer coefficient by 30% at the gas Re_a=8100. The change of the gas mass flow rate due to the evaporation is neglected in the Merkel method, which causes the difference in the mass transfer coefficient. This difference increases as the water temperature increases.

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