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The analogy between heat and mass transfer in low temperature crossflow evaporation

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ABSTRACT

This study experimentally determines the relationship between the heat and mass transfer, in a crossflow configuration in which a ducted airflow passes through a planar water jet. An initial exploration using the Chilton-Colburn analogy resulted in a coefficient of determination of 0.72. On this basis, a re-examination of the heat and mass transfer processes by Buckingham's-π theorem and a least square analysis led to the proposal of a new dimensionless number referred to as the Lewis Number of Evaporation. A modified version of the Chilton-Colburn analogy incorporating the Lewis Number of Evaporation was developed leading to a coefficient of determination of 0.96.

1. Introduction

Heat and mass transfer devices involving a liquid interacting with a gas flow have a wide range of applications including distillation plants, cooling towers and aeration processes and desiccant drying [1–5]. Many studies have gone through characterising the heat and mass transfer in such configurations [6–9]. The mechanisms of heat and mass transfer are similar and analogical. Therefore, in some special cases where, either the heat or mass transfer data are not reliable or may not be available, the heat and mass transfer analogy can be used to determine the missing or unreliable set of data. In this regards, the Reynolds analogy is the simplest correlation and is applicable only for the special case where the Prandtl and Schmidt numbers are both equal to unity. Chilton and Colburn in 1934 [10] introduced a correlation to predict the coefficient of mass transfer from the experimental data of heat transfer and fluid friction, which is applicable for fully developed flow inside the tubes or between parallel plates with; $0.6 < \text{Prandtl} < 60$ and $0.6 < \text{Schmidt} < 3000$.

However, both of these analogies characterise the "convectional" transport phenomena and may not be applicable for some special cases and geometries. Therefore, a number of studies have examined the applicability of these analogies to other configurations [11–13]. Steeman et al. [12] employed CFD to investigate the validity of the heat and mass transfer analogy for a particular case of indoor airflows and when the analogy conditions are not met. Similarly, Tsilingiris [14] experimentally developed a heat and mass transfer analogy model in solar distillation systems based on the Chilton-Colburn analogy.

This study investigates the analogy between the intensities of heat and mass transfer in low temperature evaporation processes with crossflow configuration, in which a ducted stream of air passes through a falling sheet of water. The interaction in such a configuration has the potential to significantly improve the transfer phenomenon.

2. Experimental setup

In this experiment, a planar jet of water was directed perpendicular to a ducted air crossflow, as shown in Fig. 1. A water tank with adjustable height was used to provide a constant pressure head to drive the water flow at different flow rates and a variable speed axial flow fan with a maximum capacity of 280 m^3/h was employed to drive airflow at various steady flow rates. The flow rates of water were determined by measuring the time taken for a known volume of water to pass through the nozzle, and the exact airflow rate was determined from measurements made using a pitot static probe traversed across the duct and differential manometer.

In order to measure the humidity and temperature, a set of three humidity/temperature sensors, (Sensirion SHT71) with an accuracy of $\pm$ 3% for humidity and $\pm$ 0.3 K temperature at standard room condition were used. Sensors were placed on either side of the side the sheet to measure the change in humidity and temperature of the air stream as it crossed the water sheet, as seen in Fig. 1. A third sensor was placed outside the experiment to monitor the room conditions. A set of two thermocouples (type T) with an accuracy of $\pm$ 0.3 K were used to record the water temperature before and after contact with the air stream. An auxiliary water heater was used to maintain the inlet water temperature at a constant temperature and thereby reduce the relative

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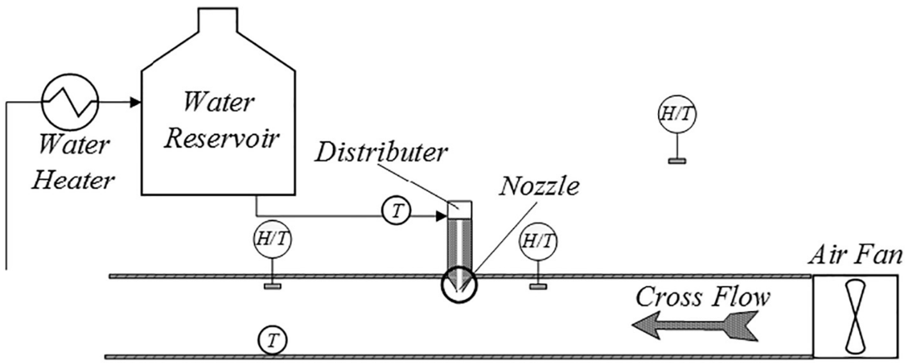

Fig. 1. Experimental apparatus.

error of measurements.

3. Testing the Chilton-Colburn analogy

In considering the heat transfer, the total rate of heat transfer ($\dot{Q}_t$) is the sum of convective, evaporative and radiative rates of heat transfer. Assuming that the radiation heat transfer is negligible, this can be determined from Eq. (1).

$$\dot{Q}_t = \dot{Q}_{cv} + \dot{Q}_{ev} = \dot{m}_a(\hbar_{a,o} - \hbar_{a,i}) \tag{1}$$

where $\dot{Q}_{cv}$ is the convective rate of heat transfer and $\dot{Q}_{ev}$ is the rate of heat transfer through evaporation. $\dot{m}_a$ is the mass flow rate of air and $\hbar_{a,i}$ and $\hbar_{a,o}$ are the enthalpies of the air at the inlet and outlet conditions, respectively. The rate of evaporation can be determined from Eq. (2).

$$\dot{Q}_{ev} = \dot{m}_{ev}\hbar_{fg} \tag{2}$$

where $\hbar_{fg}$ is the enthalpy of vaporization and $\dot{m}_{ev}$ is the rate of evaporation, which can be calculated by measuring the specific humidity (ω) of air at inlet and outlet conditions and the mass flow rate of the air stream as given in Eq. (3).

$$\dot{m}_{ev} = \dot{m}_a(\omega_{a,out} - \omega_{a,in}) \tag{3}$$

On the mass transfer side the experimental value of the coefficient of mass transfer can be determined from Eq. (4).

$$j = \frac{\dot{m}_{ev}}{A_{c,a}(\rho_{v,f} - \rho_{v,b})} \tag{4}$$

where, $\rho_{v,\infty}$ is the density of vapour at the free stream conditions and $\rho_{v,f}$ is the vapour density at film condition, which is considered to be saturated air at the average temperature of the two phases.

The experimental value of the coefficient of convective heat transfer can be calculated from Eq. (5).

$$h = \frac{\dot{Q}_{cv}}{A_{c,a}(T_f - T_\infty)} \tag{5}$$

where $A_{c,a}$ is the cross sectional area of air stream, T_∞ is the bulk stream temperature and T_f is the film temperature. The convective heat transfer rate can be determined from Eq. (1).

The existence of an analogy was first assessed by examining the relationship between the heat transfer coefficient determined from Eq. (5) and the mass transfer coefficient calculated by Eq. (4), as shown in Fig. 2.

As seen in Fig. 2, the experimental values of the heat and mass transfer coefficients are correlated with a reasonable accuracy, with a coefficient of determination (R^2) of 0.72. The heat and mass transfer are analogues, in circumstances where the thermal and concentration boundary layers are of the same type [15]. For the conditions tested by Chilton and Colburn, the empirical correlations of Nusselt and Sherwood numbers were determined as given in Eqs. (6) and (7) [16].

$$Nu = a\ Re^m\ Pr^{1/3} \tag{6}$$

$$Sh = a\ Re^m\ Sc^{1/3} \tag{7}$$

Based on the Reynolds analogy the heat transfer Stanton number is equivalent to the mass transfer Stanton number. Where the heat transfer Stanton number is the ratio of the Nusselt number to the product of the Reynolds and Prandtl numbers, and the mass transfer Stanton number is the ratio of the Sherwood number to the product of the Reynolds and Schmidt numbers, as given in Eqs. (8) and (9) [15].

$$St_{\text{heat}} = \frac{h}{\rho V c_p} = \frac{Nu}{Re\ Pr} \tag{8}$$

$$St_{\text{mass}} = \frac{j}{V} = \frac{Nu}{Re\ Pr} \tag{9}$$

Now, substituting the empirical correlation for the Nusselt and Sherwood numbers, results in Eqs. (10) and (11).

$$St_{\text{heat}} = \frac{h}{\rho V c_p} = \frac{a\ Re^m\ Pr^{1/3}}{Re\ Pr} \tag{10}$$

$$St_{\text{mass}} = \frac{j}{V} = \frac{a\ Re^m\ Sc^{1/3}}{Re\ Sc} \tag{11}$$

From these, Chilton and Colburn had derived a "J" factor for heat and mass transfer as given in Eqs. (12) and (13) [10].

$$J_{\text{heat}} = a\ Re^{m-1} = \frac{h}{\rho V c_p}\ Pr^{2/3} \tag{12}$$

$$J_{\text{mass}} = a\ Re^{m-1} = \frac{j}{V}\ Sc^{2/3} \tag{13}$$

Since the "J" factor is equal for both heat and mass transfer, the Chilton-Colburn analogy was determined as given in Eq. (14) [10].

$$\frac{h}{\rho V c_p} Pr^{\frac{2}{3}} = \frac{j}{V} Sc^{\frac{2}{3}}$$

r

$$\frac{h}{j} = \rho c_p\left(\frac{Sc}{Pr}\right)^{2/3} = \rho c_p Le^{2/3} \tag{14}$$

As mentioned earlier the Chilton-Colburn analogy, seen in Eq. (14), is valid for a fully developed flow inside a pipe, and for flow parallel to plane surfaces, when 0.6 < Prandtl < 60 and 0.6 < Schmidt < 3000.

The applicability of the Chilton-Colburn analogy to other configurations and conditions may be validated for the particular geometry and conditions of the experiment.

Fig. 3 shows the experimental values of the convection heat transfer coefficient from Eq. (5) compared to the calculated value from the Chilton-Colburn analogy, given in Eq. (14) using the experimental mass transfer data. This figure shows some correlation for predicting the heat transfer coefficient from the mass transfer data, but with quite a large scatter.

From this, it could be considered that, the Chilton-Colburn analogy is reasonably valid for these geometries and conditions. However,