International Journal of Heat and Mass Transfer 111 (2017) 94–104

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Characterising the heat and mass transfer coefficients for a crossflow interaction of air and water

Reza Enayatollahi [*], Roy Jonathan Nates, Timothy Anderson

Department of Mechanical Engineering, Auckland University of Technology, Auckland, New Zealand

ARTICLE INFO

Article history:
Received 8 February 2017
Received in revised form 19 March 2017
Accepted 21 March 2017

Keywords:
Heat and mass transfer
Flow regimes
Crossflow
Liquid sheet
Gas stream

ABSTRACT

An experimental study was performed in order to characterise the heat and mass transfer processes, where an air stream passes through a sheet of falling water in a crossflow configuration. To achieve this, the hydrodynamics of a vertical liquid sheet in a ducted gaseous crossflow were studied. Four distinct flow regimes were identified (a stable sheet, a broken sheet, a flapping sheet and a lifted sheet) and mapped using Reynolds and Weber numbers. Subsequently, the Buckingham π theorem and a least squares analyses were employed leading to the proposal of two new dimensionless numbers referred to as the Prandtl Number of Evaporation and the Schmidt Number of Evaporation. These describe the heat and mass transfer in low temperature evaporation processes with crossflow interaction. Using these dimensionless numbers, empirical correlations for Sherwood and Nusselt numbers for the identified flow regimes were experimentally determined. These correlations were in a good agreement with their corresponding experimental values. It was found that flapping sheets have the strongest heat and mass transfer intensities whereas the weakest intensities were seen for the "stable" sheets.

1. Introduction

Heat and mass transfer devices involving liquid and gas streams interacting have a wide range of applications including distillation plants, cooling towers, aeration processes and desiccant drying [1–5]. Enhancing the heat and mass transfer processes in these systems could improve the overall performance, and reduce the size and cost of these devices.

In this respect, the nature of the flow and the interaction of the phases has a significant influence on the heat and mass transfer processes. In order to be able to design a simultaneous heat and mass exchanger, a developed non-dimensional understanding of heat and mass transfer processes for the possible modes of interaction is required. A number of investigations have sought to characterise the heat and mass transfer processes for different applications, in different geometries and conditions of interactions [6–10]. For example, Wee et al. [11], performed an investigation on simultaneous natural convection heat and mass transfer in a vertical and horizontal cavity. It was reported that the Nusselt and Sherwood numbers were functions of the Rayleigh number only for both the horizontal and vertical cavities. Iskra et al. [12], determined the convective mass transfer coefficient for evaporation in a horizontal rectangular duct. The experimental Sherwood number for both laminar and turbulent flows was reported as a function of the Rayleigh and Graetz numbers and the Nusselt number was derived from the Chilton-Colburn analogy.

Extending this to forced convection, Sun et al. [13], theoretically and experimentally examined the heat and mass transfer processes for drying a short porous cylinder. It was reported that both the Nusselt and Sherwood numbers are functions of the Reynolds and Gukhman numbers, in which Gukhman number expresses the ratio of the outer mass transfer intensity to the outer heat transfer intensity. Chuck et al. [14] studied the evaporative mass and heat transfer from a partially filled pan of water situated in the floor of a rectangular duct with turbulent air flow. It was reported that the Sherwood number was a function of the Reynolds number of the air stream and the aspect ratio of the unfilled portion of the water pan. It was also shown that the Nusselt number could be determined using the analogy between heat and mass transfer.

Now for this work the aim was to develop an understanding of a crossflow interaction, where gas stream flows horizontally through falling sheets of liquid, and how this influences the intensities of heat and mass transfer, with particular reference to improving the performance of a solar desalination system [1]. Although there has been extensive work on characterising the heat and mass

---

[*] Corresponding author at: WD308, 19 St Paul Street, Auckland CBD, Auckland, New Zealand.

E-mail address: renayato@aut.ac.nz (R. Enayatollahi).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.03.098
0017-9310/

Nomenclature

A	area (m^2)
c_p	specific heat (J/kg·K)
$\hbar$	enthalpy (J/kg)
h	heat transfer coefficient ($W/m^2 \cdot K$)
j	mass transfer coefficient (m/s)
k	thermal conductivity (W/m·K)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
Q	flow rate per unit length (m^2/s)
$\dot{Q}$	rate of heat transfer (W)
R	specific gas constant (J/kg·K)
T	temperature (K)
V	velocity (m/s)
μ	viscosity (kg/m·s)
λ	mass diffusivity (m^2/s)
ρ	density (kg/m^3)
σ	surface tension(N/m)
ω	specific humidity ($kg_{water}/kg_{dry\ air}$)

Subscripts

∞	bulk fluid
a	air
ch	characteristic
$Conv$	convection
ev	evaporation
f	film
fg	vaporization
in	inlet
loc	local
m	mean
noz	nozzle
out	outlet
R	resultant
t	total
v	vapour
w	water

transfer in different configurations, there are no studies that characterise the intensities of heat and mass transfer when falling sheets are exposed to a gas crossflow.

Now, given the complexity of such an interaction, and the absence of simple analytical solutions, it is necessary to provide a flow regime map to aid the design of heat and mass transfer devices involving falling liquids in gaseous crossflows. Numerous studies have examined the behaviour of sheets of falling liquid, in quiescent gas [15–21], and similarly a number of studies have examined the behaviour of liquid sheets with gas co-flow and around jets in crossflow [22–24]. Bolanos-Jimenez et al. [25] performed a theoretical and experimental study on the behaviour of air and water sheets in a parallel flow condition. They observed a “bubbling” regime that lead to the periodic breakup of the air sheet, and a “jetting” regime, where both sheets evolved slowly downstream without breaking. They suggested the formation of either of these regimes was dependent on two factors, namely; the Weber number of the water and the velocity ratio between the air and the water.

Ng et al. [26] performed an experimental investigation on what they termed “bag breakup” of a circular, non-turbulent liquid jet with a gaseous crossflow. They found that as a result of gaseous crossflow a series of column waves would be formed in the jet flow and that the variable wave frequency caused instability. Based on their findings it is apparent that the primary breakup processes are due to the aerodynamic effects of the crossflow, regardless of initial disturbances within a liquid jet.

Extending this to liquid sheet flows, Brown [27] investigated the behaviour of a thin sheet of liquid exiting a slot and impinging on a moving solid surface. In this study it was reported that the liquid sheet would be unstable in the region close to the slot unless the liquid velocity outside the slot was greater than 2T/Q, where T is the surface tension of the liquid and Q is the mass flow rate. Using the Weber number, it was found that the sheet was stable for Weber numbers greater than unity. Becerra et al. [28] also performed an experimental study on the stability of a viscoelastic liquid sheet and reported that the liquid sheet would be unstable for Weber numbers below 0.94. They also noted that liquids with high extensional viscosity were able to create a more stable sheet.

Despite the work that has been undertaken on understanding falling liquid sheet flows and circular liquid jets in crossflow, there are no studies that examine the behaviour of falling liquid sheets when exposed to a gas crossflow and none that characterise the heat and mass transfer coefficients for such a process. Therefore, this work aims to experimentally characterise and map the flow regimes in such interactions and from this develop correlations to describe the heat and mass transfer.

2. Experimental method

In order to develop an understanding of the behaviour of liquid sheets with a gas crossflow, an experiment was developed where a thin sheet of water was injected into a rectangular air channel, as shown in Fig. 1. The sheet was generated by passing water through a slotted nozzle, formed by two finely grounded stainless steel plates. An elevated water reservoir was used to provide a constant head to the jet, where the height of this reservoir was adjustable in order to deliver a range of steady flow rates. The water flow rate was determined by measuring the time taken for a known mass of water to pass through the nozzle.

To provide the crossflow, air was directed through the duct by a variable speed axial flow fan with a maximum capacity of 280 m^3/h. The dimensions of the duct were a width of 100 mm and a height adjustable between 30 and 100 mm. For each test the airflow rate was determined from measurements made using a pitot static probe traversed across the duct and a differential manometer. Two cameras (*Nikon D300* and *Nikon D3300*) were used to capture images of the air and water interaction. The first of these (Camera

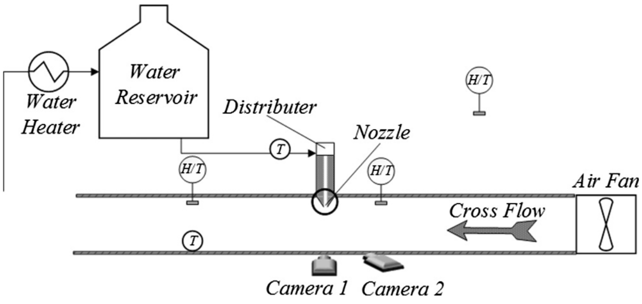

Fig. 1. Experimental apparatus.