International Journal of Heat and Mass Transfer 110 (2017) 783–788

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Technical Note

Study on average Nusselt and Sherwood numbers in vertical plate channels with falling water film evaporation

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ARTICLE INFO

Article history:
Received 19 January 2017
Received in revised form 24 March 2017
Accepted 24 March 2017

Keywords:
Falling water film evaporation
Average Nusselt and Sherwood numbers
Correlations
Heat and mass transfer

ABSTRACT

In this paper, the effects of variable parameters on the average Nusselt and Sherwood numbers between moist air and liquid water film in vertical plate channels are investigated using an approach proposed by previous work. The validity of data is also investigated. Traditional correlations for the average Nusselt and Sherwood numbers are not comprehensive enough as they cannot indicate the effects of inlet parameters on heat and mass transfer process. In this research, correlations for the average Nusselt and Sherwood numbers are developed in terms of moist air inlet Reynolds number, ratio of water to moist air inlet mass flow rate, ratio of channel length to half channel width and moist air inlet dimensionless temperature. The definition of the moist air inlet dimensionless temperature takes into account the effects of moist air inlet dry-bulb and wet-bulb temperatures and water film inlet temperature. The correlations show that the moist air inlet dimensionless temperature has the greatest influence on the average Nusselt number compared with that of the other dimensionless parameters, but it has the lowest influence on the average Sherwood number. The results would be helpful to understand the heat and mass transfer behavior between moist air and liquid water film.

1. Introduction

Falling film evaporation is widely used for effective cooling [1–3]. The application of falling film evaporation for air conditioning can bring environmentally friendly products and reduce energy consumption. Therefore falling film evaporation devices are drawing more and more attention in recent years.

Xuan et al. [4,5] presented research and application of evaporative cooling for air conditioning in China. Experimental and theoretical research works on feasibility studies, performance test and optimization as well as heat and mass transfer analysis were reviewed in detail. The energy saving potential and environmental impacts of typical evaporative cooling air conditioning systems were illustrated. Camargo et al. [6,7] developed a mathematical model for evaporative cooling air conditioning system, allowing the determination of the effectiveness of saturation. The experimental results are used to determine the heat transfer coefficient and to compare with the mathematical model. Dowdy and Karabash [8] proposed the correlation for determination of the heat transfer coefficient in a rigid cellulose evaporative medium based on the assumption that air flow is turbulent. The correlation has been used in literature [9–12]. Wu et al. [11] proposed a simplified cooling efficiency correlation based on material properties and configuration of wetted medium used in the cooler. The models that implement this correlation were presented in literature [13,14].

Considering that heat and mass transfer process are also affected not only by material, but also by operation conditions, such as the inlet parameters of moist air and liquid water, traditional correlations are not comprehensive enough as they cannot indicate the effects of the inlet parameters on heat and mass transfer process. Heat and mass transfer coefficients correlations developed by many studies were calculated by the logarithmic mean temperature difference or arithmetical mean temperature difference. Little study was concerned on the method of measuring coupled heat and mass transfer coefficients during falling water film evaporation process. In a previous article [15], we have developed a new approach to analyze the heat and mass transfer characteristic in vertical plate channels with falling water film evaporation. The objective of the present paper is to extend the previous work [15] to develop general correlations for heat and mass transfer coefficients. In dimensionless terms, this means developing correlations for the average Nusselt and Sherwood numbers in terms of their dependence on the influence parameters. A temperature dimensionless parameter $\theta_{g,i}$ takes into account the effects of moist

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.03.087
0017-9310/

Nomenclature

A	heat and mass transfer area [m^2]
c_p	specific heat capacity [$kJ\,kg^{-1}\,°C^{-1}$]
C_w^{ast}	water to air heat capacity rate ratio
D, L	half width and length of the channel respectively [m]
D_s	diffusion coefficient of water vapor in air [$m^2\,s^{-1}$]
$\check{E}$	dimensionless ratio of water film heat transfer coefficient to air mass transfer coefficient defined as $h_{c,w}/h_D c_{p,dg}$
h_{fg}	evaporation heat of water [$kJ\,kg^{-1}$]
$h_{fg,0}$	evaporation heat of water at reference temperature (0 °C) [$kJ\,kg^{-1}$]
h_c	moist air side heat transfer coefficient [$kW\,m^{-2}\,°C^{-1}$]
$h_{c,w}$	water film side heat transfer coefficient [$kW\,m^{-2}\,°C^{-1}$]
h_D	moist air side mass transfer coefficient [$kg\,m^{-2}\,s^{-1}$]
$\overline{h_{fg,0}}$	normalized evaporation heat of water at reference temperature condition [°C]
i	specific enthalpy [$kJ\,kg^{-1}$]
Le_f	Lewis factor defined as $h_c/h_D c_{p,dg}$
m	mass flow rate [$kg\,m^{-1}\,s^{-1}$]
NTU_m	number of mass transfer units
Nu_M, Sh_M	average Nusselt and Sherwood numbers respectively
Re	Reynolds number
R_{wg}	ratio of water to moist air mass flow rate
T	temperature [°C]
u, v	velocity components in x, y coordinate directions, respectively [$m\,s^{-1}$]
W	humidity ratio of moist air [$kg\,kg^{-1}$]
x, y	space coordinate as shown in (Fig. 1) [m]

Greek letters

α_L	ratio of channel length to half channel width
δ	water film thickness [m]
θ	dimensionless temperature
λ	thermal conductivity [$W\,m^{-1}\,°C^{-1}$]
υ	kinematic viscosity [$m^2\,s^{-1}$]
ρ	density [$kg\,m^{-3}$]
Φ	relative humidity [%]

Subscripts

g, dg	moist air, dry air respectively
i, o	inlet, outlet respectively
I	condition at the gas-liquid interface
w, v	water film, water vapor respectively
wg	moist air wet bulb temperature

air inlet dry-bulb and wet-bulb temperatures and water film inlet temperature. The results would be helpful to understand the heat and mass transfer behavior between moist air and liquid water film.

2. Methodology

2.1. 2-D model

The model investigated is a vertical plate channel with the length L and half channel width D as shown schematically in Fig. 1. The moist air flows upward and the liquid water film flows along the surface of the channel. The channel walls are thermally insulated in order to investigate the evaporative cooling process associated with many engineering applications such as direct evaporative cooler, cooling tower, etc. It is assumed that the flow is incompressible and the air-vapor mixture is an ideal gas mixture. The thermo-physical properties of the dry air, water and water vapor are assumed to be constant. Dufour and Soret effects are neglected. The interface between the water film and the moist air is at thermodynamic equilibrium state [16–18].

The governing equations for the 2-D CFD model have been described in our previous study [15]. In view of the large number of parameters, a similarity analysis was performed to deduce the 2-D model equations into dimensionless forms to find the dimensionless factors affecting the average Nusselt and Sherwood num-

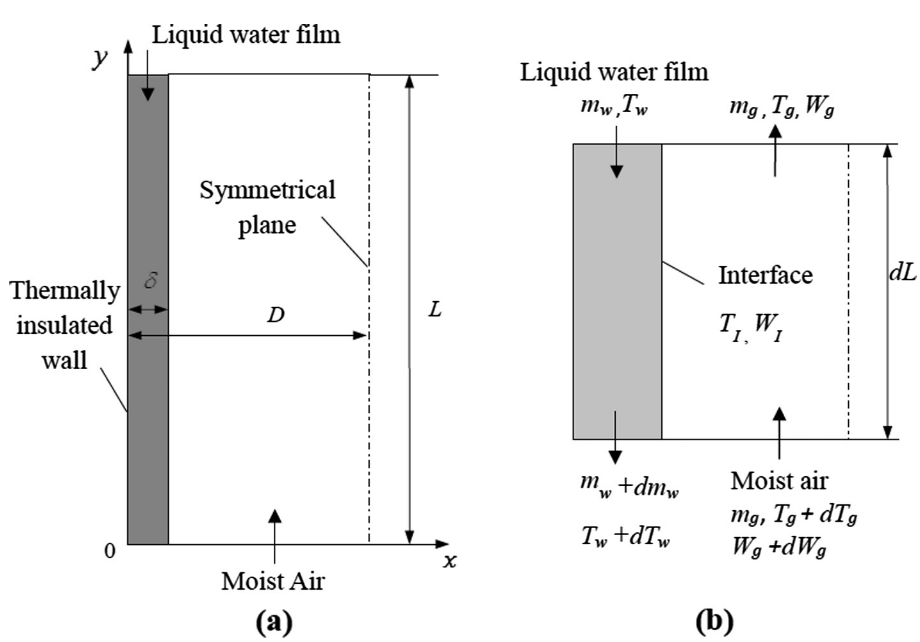

Fig. 1. (a) Schematic diagram of the physical. (b) Differential element of channel.