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Effects of mass transfer on heat and mass transfer characteristics between water surface and airstream

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ABSTRACT

A numerical study has been conducted to simulate the convective heat and mass transfer between water surface and air fluid flowing over it. The airflow is laminar and steady, and has a temperature much higher than the water, causing a combined heat and mass transfer accompanied with water evaporation into the airstream. Calculations are performed to investigate the effects of mass flux on heat and mass transfer coefficients and the applicability of the Chilton-Colburn analogy for 200 °C air temperature, 1–10 m/s air velocities, and 10–90 °C water temperatures. Calculations are implemented with and without consideration of the air property variations caused by the air temperature and humidity changes near the water surface and in the airflow direction. The results show that the heat and mass transfer coefficients both decrease with increasing water surface temperature, i.e. increasing mass flux. The Chilton-Colburn analogy holds only for low water temperature case, the deviation of the heat to mass transfer coefficient ratio given by the Chilton-Colburn analogy relative to that by the numerical simulation is less than 5% when the water surface temperature is below 60 °C. The air property variability has a notable and complex effect on heat transfer coefficient but an inconspicuous effect on mass transfer coefficient.

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1. Introduction

Water evaporation into air fluid is a process often seen in many areas such as drying, concentration, and water desalination [1,2]. In such a process, the heat and mass transfer coexist, they affect each other, making it difficult to accurately predict the heat and mass transfer coefficients. When the mass flux is low, the mass transfer coefficient can be obtained from the heat transfer coefficient based on the Colburn-Chilton analogy [3–5]. When the mass flux is larger, however, the analogy may become inapplicable because of the significant influence of mass transfer on heat transfer. Also, the properties of moist air, which were often treated as constant in most previous investigations, may vary significantly when the air temperature and humidity change considerably.

Many previous studies involved the problem of simultaneous heat and mass transfer between water surface or wetted solid surface and air fluid. Chow and Chung [6] numerically investigated the vaporization rate of water evaporation between water surface and humid air or superheated steam in a laminar boundary layer flow. They reported that the fluid property variability had little influence on the vaporization rate, but they gave no information on the effects of property variability on heat transfer. Yuan et al. [7] numerically studied the heat and mass transfer characteristics of water evaporation in a laminar boundary layer flow and found that the sensible heat transfer at the interface degraded obviously due to the evaporation: it degraded 11% over the parameter range of their study. Tang and Etzion [8] experimentally investigated the water evaporation rates from a wetted surface and from a free water surface. Boukadida and Nasrallah [9] numerically analyzed the mechanism of heat and mass transfer during water evaporation into a two-dimensional steady laminar flow of dry or humid air in a horizontal channel, they found that the Chilton-Colburn analogy was valid only at low free stream temperatures and vapor concentrations, but they provided no range for which the Chilton-Colburn analogy applies. Stegou-Sagia [10] performed numerical and experimental studies of air humidification process involving simultaneous heat and mass transport in a nearly horizontal tube, and gave the profiles of air velocity, temperature and humidity along the tube. Talukdar et al. [11] conducted CFD simulations for convective heat and mass transfer between water surface and humid air flowing in a horizontal 3D rectangular duct, they found that introducing a heat source/sink at the water surface could cause negative Nusselt and Sherwood numbers. Raimundo et al. [12] investigated the relationship between evaporation from heated water surfaces and mean aerothermal properties of a forced airflow. Their results showed that the rate of evaporation was affected by the air velocity, humidity, and water-air temperature difference.

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Nomenclature

C_p	specific heat, J/kg·K
D	diffusivity, m^2/s
h	heat transfer coefficient, $kg/m^2·K$
h_m	mass transfer coefficient, $kg/m^2·s$
i	enthalpy, J/kg
J	mass flux, $kg/m^2·s$
Le	Lewis number ($=Sc/Pr$)
l	length of water surface, m
M	molar mass
Nu	Nusselt number ($=hl/\lambda$)
P	pressure, Pa or atm
P_c	critical pressure, atm
Pr	Prandtl number ($=\mu C_p/\lambda$)
q	heat flux, W/m^2
Re	Reynolds number ($=\rho ul/\mu$)
Rg	gas constant, J/(kg·K)
Sc	Schmidt number ($=\mu/\rho D$)
Sh	Sherwood number ($=h_m l/\rho D$)
T	temperature, °C
T_c	critical temperature, K
u, v	velocity, m/s
w	specific humidity, kg/kg

Greek symbol

θ	correction factor
ρ	density, kg/m^3
μ	viscosity, Pa·s
λ	thermal conductivity, W/m·K

Subscript

∞	free airstream
a	air
h	heat transfer
h_m	mass transfer
v	water vapor
s	saturation state or water-air interface
x	local

Poós and Varju [13] experimentally examined the rate of evaporation from free water surface to a tubular artificial flow and purposed correlations for calculating the Sherwood numbers at different Reynolds numbers. However, the mass transfer rate in their investigations was low. Iskra and Simonson [14] performed experiments to determine the convective mass transfer coefficient for evaporation in a horizontal rectangular duct. Wei et al. [15] proposed a simplified CFD-based model to analyze the heat and mass transfer in air-water direct contact through the water surface in a rectangular duct. Kumar et al. [16] investigated the effect of roughness on evaporation rates under varying conditions of air velocities and water temperatures and reported that the increase in the roughness caused an increase in the evaporation rate. Schwartze and Brocker [17] and Volchkov et al. [18] theoretically studied the evaporation of water into air-steam mixture and pure superheated steam, they paid a special attention on the phenomena of inversion temperature, above which the rate of evaporation into pure superheated steam became higher than that into dry air.

There are also many investigations on simultaneous heat and mass transfer characteristics for falling film evaporation or condensation in vertical channels or inclined planes [19–32]. Jang et al. [19] numerically investigated the mixed convective heat and mass transfer with film evaporation in inclined square ducts, while Huang et al. [20] numerically simulated the mixed convective heat and mass transfer with film evaporation and condensation in vertical ducts, they both reported that the latent heat transport with film evaporation tremendously augmented the heat transfer rate and claimed better heat and mass transfer rates related with film evaporation for the case with a higher wetted wall temperature. Yan and Lin [21] numerically studied the natural convective heat and mass transfer with film evaporation and condensation in vertical concentric annular ducts, they also found the tremendous enhancement in heat transfer due to the exchange of latent heat associated with film evaporation and condensation. The extent of augmentation of heat transfer due to mass transfer was more significant for a system with a higher wetted wall temperature. Nasr [22,23] and Terzi et al. [24,25] studied the heat and mass transfer of evaporation and condensation of falling film with porous layer inside, their results supported that use of the porous layer could promote the heat and mass transfer. Cherif et al. [26] experimentally and numerically investigated the effects of film evaporation on mixed convective heat and mass transfer in a vertical rectangular channel as well as those of liquid film temperature, evaporated flow rate, and upward airflow rate on the heat and mass transfer. Charef et al. [27] numerically studied the liquid film condensation from vapor-gas mixture in a vertical tube with constant temperature or uniform heat flux, and reported that the increases of relative humidity and inlet-to-wall temperature difference acted to enhance the condensation process. For a fixed heat flux, increasing the inlet temperature substantially increased the accumulated condensation rate. Wan et al. [28,29] numerically analyzed the combined heat and mass transfer characteristics in vertical plate channels with falling film evaporation, and proposed correlations for predicting the heat and mass transfer coefficients. Tang and Min [30] theoretically studied the transient evaporation characteristics of water film attaching to an adiabatic solid wall, they [31] also analyzed the evaporation characteristics of water film on a thermally conductive spherical solid particle and found that the water film transient evaporation characteristics were affected more by the heat capacity than by the thermal conductivity of the solid particle.

Although there are many investigations on heat and mass transfer associated with water evaporation and simultaneous heat and mass transfer, few studies focused on the effects of mass flux and fluid property variability on the heat and mass transfer characteristics. In this research, a numerical study is carried out to analyze the coupled heat and mass transfer between water surface and laminar airflow. The specific objectives of this research are to investigate the effects of mass flux and air property variability on heat and mass transfer coefficients and discuss the applicability of the Chilton-Colburn analogy principle.

2. Computational details

2.1. Physical model

Fig. 1 illustrates the convective heat and mass transfer between water surface and air fluid flowing over it. The free airstream has a zero specific humidity and a temperature much higher than that of the water surface, leading to a combined heat and mass transfer accompanied with water evaporation into the airstream. To simplify the problem and stress the focal point, the following assumptions are adopted:

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