International Journal of Thermal Sciences 126 (2018) 194–204

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Comparison of two configurations to improve heat and mass transfer in evaporating two-component liquid film flow

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A R T I C L E I N F O

Keywords:
Evaporation
Mixed convection
Binary mixture
Heat and mass transfer vertical channel

A B S T R A C T

This paper deals with a numerical analysis of comparison of two configurations to improve heat and mass transfer by the evaporation of two-component liquid film in a vertical channel under mixed convection. The liquid mixture falling down on one plate of the channel consists of water and ethanol. Two configurations are considered in this study, the first one consists in applying a uniform heat flux density to the wetted wall while in the second case, the same quantity of heat, was used for preheating the liquid mixture at inlet. The model solves the coupled governing equations in both phases together with the boundary and interfacial conditions. The systems of equations obtained by using an implicit finite difference method are solved by Tridiagonal Matrix Algorithm. The main purpose of this study is to compare the heat and mass transfer in two studied configurations. The result shows that the configuration with preheated film at the inlet of channel is the best technique to obtain a significant average evaporated mass flux density.

1. Introduction

The evaporation of a liquid mixture containing volatile liquids in air occurs in a wide variety of processes such as boiling, distillation, cooling towers, thermal protection of heated walls and combustion premixing. Since the number of independent variables influencing the hydrodynamic, thermal and concentration fields is important, their control in experimental installations is difficult, that is why major studies are treated numerically. The literature reviews show that a large number of studies have been made concerning the evaporation of pure substances, the theoretical treatment of flows with multicomponent evaporation has not received much attention even though the phases involved in technical processes are nearly always mixtures of several components. Evaporation of pure liquid film of water has been extensively investigated [1–12]. Computational studies of liquid film evaporation for other pure substances than water have been carried out by a number of investigators [13–17]. The case of the evaporation of binary liquid film knows an increasing number of both experimental and theoretical researches dealing with the study of this process [18–27].

The evaporative cooling of liquid film in mixed convection channel flows was explored by Yan et al. [1]. Their results show that the liquid film cooling is mainly caused by latent heat transfer associated with its evaporation. The evaporation of the pure liquid film by mixed convection of a humid air in a vertical channel has been studied by Yan et al. [2]. Their study has shown that the assumption of an extremely thin film thickness is valid only for a low mass flow rate. The detailed analysis, including transport process in the gas flow and liquid film was performed by Yan [3]. He investigates the effect of finite film evaporation on the mixed convection heat and mass transfer in a vertical pipe. He et al. [4] were interested in water film cooling of a uniformly heated wall in a vertical tube. Turbulent flow is considered in the gas flow and laminar flow in the liquid film. Two different modes of heat transfer are identified. When water is supplied at relatively high temperature, the system operates in evaporating mode. When the temperature is low the system operates in the direct film cooling mode. An et al. [5] reported an experimental study of the cooling of a heated vertical tube by an upward airflow with a thin falling water film, produced by spraying jets onto the inner surface of the tube at the top. Both naturally induced and forced convection were considered. Feddaoui et al. [6,7] studied the thermal transfer taking place in the case of film evaporation in the presence of a gas flow inside a vertical heated tube. They reported that the evaporation is higher for a smaller inlet liquid flow and a larger heat flux through the wall. They also treated the case of insulated wall for both cylindrical configuration and vertical channel [8,9] for examining the effectiveness of evaporative cooling process. Cherif et al. [10] presented an experimental and numerical study of mixed convection heat and mass transfer in a vertical channel with film evaporation. The results show that evaporation takes place on the majority of the surface of the two walls and, in some cases, evaporative

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https://doi.org/10.1016/j.ijthermalsci.2017.12.031
Received 29 August 2016; Received in revised form 25 December 2017; Accepted 27 December 2017

Nomenclature

B_0	Inlet liquid mass flow rate per unit periphery length at inlet [kg.m^{-1}.s^{-1}]
C_{pi}	specific heat for species i vapour [J.kg^{-1}.K^{-1}]
C_{pa}	specific heat of air [J.kg^{-1}.K^{-1}]
C_{pL}	specific heat of liquid film [J.kg^{-1}.K^{-1}]
d	channel width [m]
$D_{G,i}$	mass diffusivity of species i in the gas mixture [m^2.s^{-1}]
$D_{G,a}$	mass diffusivity of dry air in the gas mixture [m^2.s^{-1}]
D_L	mass diffusivity in the liquid film mixture [m^2.s^{-1}]
$D_{L,ij}$	diffusion coefficient of solute i in solvent j in the liquid film mixture [m^2.s^{-1}]
F	Heat flux per unit height in the liquid film [W.m^{-1}]
g	gravitational acceleration [m.s^{-2}]
h_{fg}	latent heat of vaporization [J.kg^{-1}]
H	channel height [m]
J''	evaporating mass flux [kg.m^{-2}.s^{-1}]
J''_i	evaporating mass flux of species i [kg.m^{-2}.s^{-1}]
k	thermal conductivity [W.m^{-1}.K^{-1}]
M_a	molar mass of air [g.mol^{-1}]
M_i	molar mass of species i [g.mol^{-1}]
M_r	total accumulated evaporation rate [kg.m^{-1}.s^{-1}]
p	mixture pressure [Pa]
p_0	ambient pressure [Pa]
p_d	dynamic pressure [Pa]
$p_{v,i}$	pressure of saturated vapour of species i [Pa]
$p^*_{v,i}$	partial pressure of species i at the interface gas-liquid [Pa]
Q_{ev}	Heat flux used in evaporation from the binary liquid film [W.m^{-2}]
Q_S	sensible heat flux [W.m^{-2}]
Q_w	heat flux density at the wall [W.m^{-2}]
Q_f	heat flux per unit height at the wall or to preheat liquid film [W.m^{-1}]
Re	Reynolds number of the gas stream [−]
T	Temperature [K]
T_w	dry wall Temperature [K]
u	axial velocity [m.s^{-1}]
v	transversal velocity [m.s^{-1}]
$W_{G,i}$	mass concentration of species i vapour [−]
$W_{GI,i}$	mass concentration of species i vapour [−]
$W_{L,i}$	mass fraction for species i in the liquid film [−]
$Y_{L,i}$	molar fraction for species i in the liquid film [−]
y	coordinate in the transverse direction [m]
z	coordinate in the flow direction [m]

Greek symbols

δ_z	local liquid film thickness [m]
μ	dynamic viscosity [kg.m^{-1}.s^{-1}]
ρ	density [kg.m^{-3}]

Subscripts

a	dry air
am	dry air in the mixture
G	mixture (gas + vapour)
I	condition at the gas-liquid interface
i	species i (1 for water, 2 for ethanol)
im	species i in the mixture
L	mixture liquid film (water + ethanol)
m	mixture
0	condition at inlet

cooling occurs especially for small heating flux and large air velocities. Mixed convection during evaporation of a water falling film in a vertical concentric annulus was studied numerically by Ben Radhia et al. [11]. Their results are analyzed to emphasize and evaluate the influence of the previous operating parameters and the annulus curvature on the effective evaporation surface and on the mass flux density of evaporated water. The falling film evaporation in a large scale rectangular channel is experimentally studied by Huang et al. [12] for the design and improvement of passive containment cooling system. The evaporation mass transfer coefficient h_D is obtained by the evaporation rate and vapour partial pressure difference of film surface and air bulk. The experimental results indicate that increasing the air flow rate appears to enhance h_D, while the film temperature and film flow rate have little effect on h_D. Since the wave effect on evaporation is noticed in experiment, the evaporation mass transfer correlation including the wave effect is developed on the basis of heat and mass transfer analogy and experimental data.

Regarding other pure substances than water on heat and mass transfer in channels, Tsay et al. [13] undertook a numerical and experimental study of cooling wall by using an ethanol film on a vertical plate in the presence of a co-current gas flow. It was observed that the interfacial heat flux is predominantly determined by latent heat transfer connected with film evaporation, and significant results are obtained for the system with a high inlet liquid temperature or a low inlet liquid film. Yan et al. [14] carried out an experimental study on the evaporative cooling of the falling water or ethanol liquid films through interfacial heat and mass transfer in a vertical channel. Senhaji et al. [15] conducted a numerical study of evaporating liquid film of pure alcohols by mixed convection. They considered turbulent liquid film falling on the inner face of a vertical tube with a laminar flow of dry air entering the tube with a constant temperature. Recently, Nait Alla et al. [16] studied the effectiveness of ethanol liquid film evaporation along the channel by analyzing the effect of the number of heating zones and their positions on combined heat and mass transfers and flow characteristics. Their study shows that the evaporation is enhanced in the case where the insulated zone is situated at the channel exit. They also treated the case of heated vertical channel [17] by analysing the coupled heat and mass transfers during the evaporation of ethylene glycol and propylene glycol with comparison to water film.

As far as the evaporation of multicomponent liquid film is concerned, Baumann and Thiele [18] performed a detailed analysis including transport process in the gas flow and liquid film for turbulent multi-component gas flow with evaporation from a two component liquid film. Their study demonstrates that even small portions of a second component in the liquid film can create significant changes in the temperature levels as well as in the heat and mass transfer.

Hoke et al. [19] presented a numerical study of the evaporation of a binary liquid film on a vertical plate. They presented the evolution of Sherwood and Nusselt numbers. Palen et al. [20] conducted an experimental study in the case of mixtures of water - ethylene glycol and water - propylene glycol in a vertical tube. They observed that for some experimental conditions, the local heat transfer coefficient between the partition and the liquid mixture can fall by 80% in relation to the relative value of the pure water, a value that is as low as the one got with pure ethylene glycol in the same conditions. Mhetar et al. [21] studied the isothermal evaporation of a binary liquid film. They measured the diffusion coefficient during the evaporation of a binary liquid in a Stefan tube while observing the position of the liquid gas interface. Agunaoun et al. [22] presented a numerical analysis of the heat and mass transfer in a binary liquid film flowing on an inclined plate. The most interesting results are obtained in mixed convection, particularly in the case of ethylene glycol-water mixture. Ali Cherif and Daif [23]