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Numerical study of evaporation of falling liquid film on one of two vertical plates covered with a thin porous layer by free convection

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ABSTRACT

The numerical study of coupled heat and mass transfer during the evaporation of flowing liquid film has been analysed. The film falls down on one plate of a vertical channel under free convection. The wetted plate is covered with a thin porous layer and externally subjected to a uniform heated flux while the second one is dry and isothermal. The liquid consists of pure water film while the gas mixture has two components: dry air and water vapour. The results concern the influence of porosity and porous layer thickness of the porous media on the coupled heat and mass transfer performance and on the film evaporation. The results show that, in the free convection, the presence of the porous layer enhances the heat and mass transfer performance at the liquid-gas interface during the liquid film evaporation.

1. Introduction

The combined heat and mass transfer with liquid film evaporation in the presence of the porous medium is one effective heat and mass transfer mechanism widely utilized in industrial fields such as drying technology, desalination, distillation, cooling towers and air conditioning. An accurate evaluation of heat and mass transfer coefficients is an important task because the high transfer coefficients facilitate a compact design of the condenser and evaporator of such applications. Leu et al. [1] presented a numerical study of the heat and mass transfer for liquid film evaporation along a vertical plate covered with a thin porous layer. They showed that the heat transfer by latent mode is more important than the heat transfer by sensible mode. The cases for lower porosity and layer thickness would produce higher interfacial temperature and mass concentration, and thus enhance the heat and mass transfer performances across the film interface. Beg et al. [2] studied the transient hydromagnetic flow and the heat and mass transfer of a conducting nanofluid in a Darcian porous medium. They analysed the effect of the Richardson number, buoyancy ratio parameter, nanoparticle solid volume fraction, magneto-hydrodynamic body force parameter, Darcy number, unsteadiness parameter, wall transpiration, velocity slip parameter, thermal slip parameter, mass slip parameter, space and temperature dependent heat source/sink parameter on velocity, temperature, and concentration distributions. Christmann et al. [3] compared typical values of metallic falling film heat exchangers. They modeled and compared the heat transfer within the prototype heat exchanger with the obtained experimental results. They showed that correlations valid for falling film heat transfer on a vertical wall are not applicable for a spacer stabilized polymeric heat transfer surface, but that they can be used after modifications. Ming-Hsyan et al. [4] presented a study of the liquid evaporation with Darcian resistance effect on mixed convection in porous media. They showed that the evaporation of liquid on the wall increases when the buoyancy force is gradually increased and the overall heat transfer rate will be pronounced when the Darcian resistance is very small. Yiotis et al. [5] presented a study of the effect of liquid films on the drying of porous media. They showed that film flow is a major transport mechanism in the drying of porous materials, its effect being dominant when capillarity controls the process, which is the case in typical applications. By contrast, viscous flow in the bulk contributes negligibly. The results are then generalized to drying under an applied temperature gradient. Rees and Vafai [6] studied the free convection boundary layer flow of a Darcy–Brinkman fluid induced by a horizontal surface embedded in a fluid-saturated porous layer. They described in detail how boundary friction affects the free

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Nomenclature

c	mass fraction for water vapour
c_0	mass fraction for water vapour in the inlet condition
c_p	specific heat at constant pressure[J kg^{-1} K^{-1}]
c_{pa}	specific heat for air [J kg^{-1} K^{-1}]
c_{pv}	specific heat of water vapour [J kg^{-1} K^{-1}]
C	flow inertia parameter
d	channel width [m]
D	mass diffusivity [m^2 s^{-1}]
K	permeability of the porous layer [m^2]
H	channel length [m]
I	grid point index number in the flow direction
J	grid point index number in transverse direction
L_v	latent heat of water evaporation [J kg^{-1}]
$\dot{m}$	local evaporation rate of water [kg s^{-1} m^{-2}]
m_{0L}	inlet liquid flow rate [kg s^{-1}]
M_a	molecular weight of air [kg mol^{-1}]
M_v	molecular weight of water vapour [kg mol^{-1}]
Mr	total evaporation rate of mixture [kg s^{-1} m^{-1}]
p	pressure in the channel [N m^{-2}]
P	dynamic pressure in the channel [N m^{-2}]
p_{vs}	pressure of saturated water vapour [N m^{-2}]
p_0	ambient pressure [N m^{-2}]
T	absolute temperature [K]
T_w	dry wall temperature [K]
q_1	external heat flux of wetted wall [W m^{-2}]
q_L	latent heat flux of water
q_S	sensible heat flux
g	gravitational acceleration (m s^{-2})
R_e	Reynolds number ($R_e = u_0.d/\nu_0$)
u	axial velocity [m s^{-1}]
v	transverse velocity [m s^{-1}]
x	coordinate in the axial direction [m]
x^*	dimensionless axial coordinate
y	coordinate in the transverse direction [m]

Greek symbols

ε	porosity
α_e	effective thermal diffusivity [m^2 s^{-1}]
δ	thickness of porous layer [m]
λ	thermal conductivity of the fluid [W m^{-1} K^{-1}]
μ	dynamic viscosity of the fluid [kg m^{-1} s^{-1}]
ν	kinematic viscosity of the fluid [m^2 s^{-1}]
ρ	density of the gas [kg m^{-3}]
η	dimensionless coordinate in the transverse direction
ξ	dimensionless coordinate in the flow direction
β	thermal expansion coefficient $-1/\rho(\partial\rho/\partial T)_{p,c}$ [K^{-1}]
β^*	mass expansion coefficient $-1/\rho(\partial\rho/\partial c)_{p,T}$

Subscripts

0	inlet condition
L	liquid phase
a	dry air
m	mixture
am	dry air in the mixture

convective flow pattern in a porous medium. Haddad et al. [7] investigated the validity of the local thermal equilibrium assumption in the case of free convection flow over an isothermal flat plate embedded in a porous medium. Alazmi and Vafai [8] analysed in detail the fluid flow and heat transfer interfacial conditions between a porous medium and a fluid layer. They proposed a set of correlations for interchanging the interface velocity and temperature as well as the average Nusselt number among various models. Diky et al. [9] carried out an experiment for liquid film evaporation in heated gas flow in a contact apparatus with a porous packing. Maclaine-Cross and Bank [10,11] analysed the heat and mass transfer characteristics in a wet surface heat exchanger. Their results are 20% higher than the experimental data. Wassel and Mills [12] illustrated a 1-D design methodology for a counter-current falling film evaporative cooler. The narrow flow passages were found to be more effective than conventional designs for the thermal performance of the evaporative condenser. Freitas et al. [13] presented a study of evaporation of a Binary liquid from a capillary porous medium. They developed a model of evaporation of a binary liquid mixture into a ternary gas phase. The model is applied to study the influence of surface tension gradients induced by composition variations of the liquid on the phase distribution within a capillary porous medium. They showed that the surface tension gradients lead to the accumulation of liquid near the open edge of the network. Zhao [14] presented an analytical solution for the study of coupled heat and mass transfer in a stagnation point flow of air through a heated porous bed with thin liquid film evaporation. They showed that the analysis indicates that the coupled heat and mass transfer process in the air stream induced by the evaporation of a thin liquid water film embedded in the porous medium of a given porous material is governed by the Peclet number *Pe*, the Lewis number *Le*, the porosity of the porous bed ε, as well as the ambient temperature $T\infty$ and relative humidity φ of air. They showed that the heat transfer between the heated plate and the air stream is predominated by the transport of the latent heat associated with the thin liquid film evaporation. They also showed that the air stream with a lower relative humidity, a higher temperature, and a higher Peclet number lead to an increase of heat transfer rate. For the case when $Le > 1$, the mass transfer rate is enhanced while the heat transfer rate is reduced. Laurindo and Prat [15,16] presented an experimental and numerical study of evaporation in capillary porous media. Three basic cases are investigated: in the absence of gravity forces, in a stabilizing gravity field and in a destabilizing gravity field. The drying rates are measured and compared to the results of numerical pore network simulations. The poor quantitative agreement between the simulations and the experiments is explained by the existence of roughness and corner flows within the micromodel during drying.

To the author's knowledge, these previous studies concerned with a numerical study of the water film evaporation along a heated vertical channel covered with a thin liquid-saturated porous layer by free convection, despite their practical importance such as drying technology, desalination, cooling towers and air conditioning, require further investigation. The objective of this work is therefore to study the influence of the presence of the porous layer on the heat and mass transfer during water film evaporation. Particular attention was paid to the effect of porosity and porous layer thickness of the porous media on the heat and mass transfer and on the water evaporation.

2. Analysis

The present work deals with a numerical analysis of the evaporation of a flowing liquid film by free convection induced by the