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Heat and mass transfer for liquid film condensation along a vertical channel covered with a thin porous layer

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ABSTRACT

The problem of heat and mass transfer enhancement of liquid film condensation by covering a porous layer on one of channel vertical plates has been numerically investigated. The liquid film falls down on one plate of a vertical channel under mixed convection. The wetted plate is covered with a thin porous layer and externally subjected to a uniform cooling heat flux while the second plate is dry and isothermal. The effects of porosity, porous layer thickness and the ambient conditions on the heat and mass transfer performance and on the liquid film condensation have been examined in detail. The numerical results show that the heat and mass transfer performance at the liquid-gas interface during the liquid film condensation is enhanced by the presence of the porous layer.

1. Introduction

The heat and mass transfer problems in a porous medium with phase change widely exists in practical applications, such as geothermal energy utilization, desalination, distillation, drying technology, cooling towers, heat exchangers and air conditioning. The liquid film condensation in a porous medium has received considerable attention in many theoretical and experimental investigations [1–20]. Chaynane et al. [1] presented a numerical and analytical study of the film condensation on the wall of an inclined porous plate. They presented a comparison between the Darcy-Brinkman-Forchheimer (DBF) model and the Darcy-Brinkman (DB). They also presented the effects of the effective viscosity, permeability and dimensionless thickness of porous coating on the flow and the heat transfer enhancement. Kibboua and Azzi [2] studied numerically the laminar film condensation of saturated vapor flowing over an isothermal elliptical tube embedded in a porous medium. They showed that the local film thickness and the local Nusselt number depend on practical dimensionless parameters such as Reynolds number, Darcy number, Bond number and eccentricity. Ebinuma and Nakayama [3] analysed the problem of non-Darcy and transient film condensation over a vertical surface in a porous medium. They showed that the time required for the steady state increases, while the surface heat transfer rate decreases, as the non-Darcy porous inertia effects become significant. Masoud et al. [4] introduced a mathematical model of the transient film condensation on a vertical plate imbedded in a porous medium. They presented the effect of the permeability of the porous material on several issues including the velocity profiles, the film thickness and the time required to reach steady state conditions. Merouani et al. [5] presented a numerical investigation of the laminar film condensation on an inclined channel with an insulated upper wall and an isothermal lower wall coated with a thin porous material. They presented the axial evolution of the condensate flow rate and the wall heat flux for different operating conditions. They showed that the inclination angle, the inlet values of relative humidity and the Reynolds number exert an influence on the condensation process much more significant than that coming from a change in the porous layer properties. Renken et al. [6] conducted a theoretical investigation of laminar film condensation along a solid impermeable surface coated with a porous material. They found that a conductive coating may yield a considerable heat transfer enhancement. Renken et al. [7] presented an experimental analysis of the film condensation on vertical isothermal porous metallic coated plates. They presented a comparison of the experiments with a theoretical model based on porous fluid composite condensation. Renken and Raich [8] presented a numerical analysis of the film condensation enhancement by a porous/fluid composite system. They compared the numerical results with Nusselt's theory and preliminary experimental data. Xue-Hu Ma et al. [9] performed an investigation of the influence of the porous layer characteristic parameters on filmwise condensation heat transfer enhancement. The results revealed that the enhancement ratio increased with the increase of the porous layer thickness and permeability. Ma and Wang [10] reported a numerical investigation of the film condensation on a vertical

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Nomenclature

c	mass fraction for water vapor
c_0	mass fraction for water vapor 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 vapor [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 condensation [J kg^{-1}]
$\dot{m}$	local condensation 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 vapor [kg mol^{-1}]
Mr	total condensation 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 vapor [N m^{-2}]
p_0	ambient pressure [N m^{-2}]
T	absolute temperature [K]
T_w	dry wall temperature [K]
q_1	external cooling heat flux of wetted wall [W m^{-2}]
q_L	latent heat flux
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 used by Yan [30]
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 [W m^{-1} K^{-1}]
μ	dynamic viscosity [kg m^{-1} s^{-1}]
ν	kinematic viscosity [m^2 s^{-1}]
ρ	density [kg m^{-3}]
η	dimensionless coordinate in the transverse direction in the gaseous phase (η = (y − δ(/(d − δ))))
η_L	dimensionless coordinate in the transverse direction in the liquid phase (η_L=(y − δ(/(d − δ))))
ξ	dimensionless coordinate in the flow direction (ξ = x/H)
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

porous coated. They illustrate the effects of the porous coating thickness, the effective thermal conductivity and the permeability on condensate film thickness and local Nusselt number. They showed that the predicted average Nusselt number has similar tendencies to experimental results reported in literature. Chiou and Chang [11] investigated the steady-state film condensation on an isothermal horizontal disk with suction at the porous wall. The dimensionless film thickness along the disk is found to be a function of parameter Ja/Pr (Jakob number/Prandtl number) and the suction parameter Sw. They showed that the dimensionless heat transfer coefficient increases as suction parameter Sw increases. Char et al. [12] studied numerically the laminar mixed-convection film condensation along a vertical plate within a saturated vapor porous medium. They showed that the local heat transfer rate increases with a decrease in the Jakob number, the Peclet number, and the inertial parameter or an increase in the conjugate heat transfer parameter. Ping Cheng [13] studied the problems of steady film condensation outside a wedge or a cone embedded in a porous medium filled with a dry saturated vapor. El Hammami et al. [14] presented an analysis of the condensation of steam-gas mixture within a porous layer for different conditions. They examined the effects of porosity, porous layer thickness and non-condensable gas of the heat and mass transfer in condensed liquid film. White and Tien [15] presented a study of the laminar film condensation inside a porous medium. They showed that a simple rescaling of the Nusselt number calculated in each of these cases reduces to a simple function of the rescaled distance from the top of the condenser. Chang [16] reported a study of the laminar film condensation on a horizontal wavy plate embedded in a porous medium. They showed that the inclusion of capillary effects in the liquid film analysis has a significant effect on the computed results for the heat transfer coefficient. They showed also that the wave number and the wave amplitude of the wavy plate both have a significant effect on the mean Nusselt number. Kibboua and Azzi [17] presented a study of the laminar film condensation on an elliptical tube embedded in porous media. They analysed the effect of vapor shear on the condensation. They showed a dependence of the local film thickness and local Nusselt number on practical dimensionless parameters such as Reynolds number, Darcy number, Bond number and eccentricity. Kumari et al. [18] presented an analysis of the steady film condensation along a frustum of a cone in a porous medium. Al-Nimr and AlKam [19] conducted a study of the film condensation on a vertical plate imbedded in a porous medium. They presented closed-form expressions for the condensate's film thickness and flow rate and for the convective heat transfer coefficient. They showed that the liquid film thickness is proportional to $x^{1/4}$ in a thin porous domain and to $x^{1/2}$ in a thick porous domain. Renken et al. [20] analysed the film condensation of a saturated vapor in forced flow on an inclined plate embedded in a porous medium. They analysed the effect of vapor velocity on the film condensation along a surface embedded in a porous medium.

The previous studies reveals that the numerical study of the heat and mass transfer for liquid film condensation along a vertical plate covered with a thin porous layer by mixed convection, despite their practical importance, has not been sufficiently studied. The aim of this work is to evaluate the effect of the presence of the porous layer and the ambient parameters on the coupled heat and mass transfer for liquid film condensation. Particular attention will be addressed to the effect of porosity and porous layer thickness on the performance of liquid film condensation.

2. Analysis

The present work numerically treated the heat and mass transfer for liquid film condensation by mixed convection flowing along one of the channel vertical plates. The studied channel is made up of two vertical and parallel plates (Fig. 1). The film falls down on one plate of a vertical