International Journal of Thermal Sciences 109 (2016) 136–147

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Liquid film evaporation inside an inclined channel: Effect of the presence of a porous layer

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ARTICLE INFO

Article history:
Received 12 July 2015
Received in revised form
13 May 2016
Accepted 17 May 2016
Available online 9 June 2016

Keywords:
Evaporation
Porous layer
Liquid film
Heat and mass transfer

ABSTRACT

In this paper, we numerically investigate the improvement of the heat and mass transfer during the evaporation of a liquid film by introducing a liquid saturated porous layer inside an inclined channel. To achieve this, we solved the non linear partial differential equations that describe the physical system using the finite volume method in both phases (liquid saturated porous layer and gas). Compared to the liquid case, the use of the porous layer promotes the heat and mass transfer. This improvement is greater when we increase the air inlet velocity and we decrease the porosity and the thickness of the porous medium. We also propose correlations that allows us to relate the Nusselt and Sherwood numbers to the Reynolds and Biot numbers.

1. Introduction

The phenomena of heat and mass transfer during the flow of a liquid film on a heated wall has a considerable interest in the engineering field, which was translated into many applications, such as in desalination, distillation, drying, and the cooling of electronic components. In order to understand the heat and mass transfer better, different geometries were studied. Firstly, the flow of a liquid was examined on a horizontal flat plate [1]. We cite Siow et al. [2], who studied the evaporation of a laminar model within a horizontal channel. Yuan et al. [3] conducted a study on the coupled transfer of heat and mass from a thin film of water subjected to a flow of moist air.

Thereafter, several studies addressed the case of a vertical plate in order to improve the flow of the liquid. Ben Jabrallah et al. [4] studied the coupled heat and mass transfer in a rectangular cavity that acts as a distillation cell. Cherif et al. [5] experimentally studied the natural and forced convection evaporation of a thin liquid film that flows on the inner faces of the plates of a vertical channel. Fahem et al. [6] numerically analyzed the heat and mass transfer within a distillation cell. Debbissi et al. [7] studied the evaporation of water by free and mixed convection into humid air and superheated steam. Jingchun and Yicm [8] conducted a theoretical study to analyze the transient evaporation characteristics of a water film attaching to an adiabatic solid wall.

Later on, other researchers have studied evaporation on an inclined plane [9–11], which affects gravitational forces and decreases the rate of fluid flow. We cite Zeghmati and Daguenet [12] who realised a study of transient laminar free convection over an inclined wet flat plate. Agunaoun and Daif [13] studied the evaporation of a thin film of water flowing on an inclined plane surface at a constant temperature that is higher than the air temperature.

From the discussions above, it is clear that researchers have studied different geometries and conducted parametric studies on almost all input parameters that may influence the heat and mass transfers.

On the other hand, alternative solutions, such as the use of binary fluids, have also been proposed to improve transfer. Cherif and Daif [14] numerically studied the heat and mass transfer between two vertical flat plates in the presence of a binary liquid film that flows on one heated plate. Debbissi et al. [15] studied the evaporation of a binary liquid film in a vertical channel.

However, obtaining a homogenous liquid film over the entire

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http://dx.doi.org/10.1016/j.ijthermalsci.2016.05.018
1290-0729/

Nomenclature

Bi	Biot number [−]
c	mass fraction [−]
C	inertia coefficient [−]
C_p	heat capacity at constant pressure [J Kg^{-1} K^{-1}]
d	thickness of porous layer [m]
D	mass diffusivity [m^2 s^{-1}]
Da	Darcy number [−]
Fr	Froude number [−]
g	gravity acceleration [m s^{-2}]
H	channel width [m]
h	heat transfer coefficient [W m^{-2} K^{-1}]
k	thermal conductivity of the fluid [W m^{-1} K^{-1}]
K	permeability [m^2]
L	length of the channel [m]
Le	Lewis number [−]
L_v	latent heat of water [J Kg^{-1}]
m_{ev}	evaporated flow rate [Kg s^{-1} m^{-2}]
Nu_L	Latent Nusselt number [−]
p	pressure [Pa]
P^*	dimensionless pressure [−]
Pr	Prandlt number [−]
Re_g	Reynolds number [−]
Sc	Schmidt number [−]
Sh	Sherwood number [−]
T	Temperature [K]
u,v	velocity components [m s^{-1}]
U,V	dimensionless velocity components [−]
W	dimensionless mass fraction [−]
(x,y)	cartesian coordinates [m]
(X,Y)	dimensionless cartesian coordinates

Greek symbols

θ	dimensionless temperature [−]
ε	porosity [−]
μ	dynamic viscosity [Pa s]
ν	kinematic viscosity [m^2 s^{-1}]
ν^*	kinematic viscosity ratio of liquid to air [−]
ρ	density [Kg m^{-3}]
α	thermal diffusivity [m^2 s^{-1}]
δ	dimensionless thickness of porous layer [−]
φ	relative humidity at inlet [−]
ϕ	inclined angle [−]
τ	dimensionless inertia coefficient of porous medium [−]

Subscripts

l	liquid phase
g	gas phase
e	effective
i	liquid gas interface
s	solid
w	wall

plate constitutes a major discrepancy between the theoretical and experimental studies. Despite efforts in the field of modeling and numerical simulation, we still see a difference between calculation and experiment. In a previous work, Cherif et al. [16], have studied the two aspects of evaporation film: experiment and simulation. A difference was reported. They believe that this difference is caused by the difficulty of making a falling film on a vertical plate. In fact, the film cannot be controlled if it is directly adhered to the plate. To analyze the effect of dry zones on the plate, Mammou et al. [17] numerically studied the evaporation along an inclined plate. This plate consists of two wet zones separated by dry zone. The results of this study showed that the length of the dry zone plays an important role.

More recent studies have explored various techniques to solve this problem. For example, several researchers utilized rough surfaces, or interposed obstacles [18]. For example, Zheng and Worek [19] numerically and experimentally studied the evaporation of a liquid film inside an inclined channel. They fixed glass rods on the plate to disrupt the flow of liquid, thus improving the heat and mass transfer.

We believe that the best way to achieve a falling film on a flat plate and control its characteristics is the application of a porous layer that serves as a support for the liquid film. Few studies have theoretically examined the effect of the presence of a porous medium during evaporation [20,21]. Part of the reason for this is that the coupled heat and mass transfer process in the presence of such medium becomes more complicated.

As a result, this work focuses on the study of the evaporation of a saturated porous layer inside an inclined airflow channel. The main objective of this study is to evaluate the effect of introducing a liquid saturated porous layer on the heat and mass transfer. Specifically, this study examines the influence of parameters such as the air inlet velocity and the structural properties of the porous material (thickness, porosity), on the performance of the evaporation. We also propose correlations that allows as to define the Nusselt and Sherwood numbers based on the Reynolds and Biot numbers.

2. Mathematical formulation

We studied the evaporation of a liquid film in an inclined channel that consisted of two flat plates separated by a distance H. The liquid flows onto the plate from below, which is maintained at a constant temperature T_w and covered with a porous layer of thickness d. The second plate is adiabatic. A laminar descending flow of humid air flowed through the channel. At the entrance, the temperature of the gas was $T_{0g} = T_{0\,l} = T_{amb}$, the humidity was φ_0 and the velocity was uniform at V_0 (Fig. 1).

To simplify the problem, we will consider the following assumptions [22]:

- The liquid and gas flows are laminar, stationary and two-dimensional.
- There is no slip between the liquid and gas flows.
- Moist air is an ideal mixture of water vapor and dry air, which is considered an ideal gas.
- The effect of surface tension is negligible.
- The liquid-vapor interface is free of waves, in local thermodynamic equilibrium and impermeable to air-drying.
- The mass transfer induced by heat diffusion (Soret effect) and the heat transfer induced by a concentration gradient (Dufour effect) are negligible.