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Computational study of saline water film evaporation in a vertical tube

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ABSTRACT

In this present work, a numerical study of conjugated heat and mass transfer along a vertical tube was performed. The effect of the salinity in the water film is investigated. The film is falling along a vertical tube heated by a uniform heat flux. The numerical method applied solves the coupled governing equations together with the boundary and interfacial conditions. Results are presented for pure, brackish and seawater. Parametric computations are performed to evaluate evaporation and salinity progression along the tube. A comparison of operating conditions effects (pressure, film flow rate, tube length and wall heat flux) is made to enhance the effectiveness of desalination.

1. Introduction

Many industrial applications like desalination, air conditioning and cooling systems, include evaporation processes that are characterised by simultaneous heat and mass transfer with convection. In fact, many studies have been conducted to understand the science behind such complicated phenomenon and have permitted the designing and optimisation of multiple applications based on liquid film evaporation or condensation. Whereas an important part of those studies have been done experimentally [1–5] many numerical simulations were also realised [6–9].

Computational studies of combined heat and mass transfer in natural convection between two parallel plates with film evaporation where made by Yan and Lin [10]. The results indicate that the heat transfer is predominated by latent heat transport conjugated with film evaporation. Later Yan [11] extended the previous work to consider mixed convection instead of natural convection. The study revealed the main characteristics of heat and mass transfer in laminar mixed convection channel flow with liquid film vaporization. Comparisons are made between zero film thickness and finite liquid film, and also between water and ethanol films. His results confirm that the liquid film can not be assumed extremely thin except for a small liquid mass flowrate. He et al. [12], have conducted a study about combined heat and mass transfer in a uniformly heated vertical tube with water film cooling. The simulations have permitted the understanding of the fluids dynamics and thermal physics involved in the problem. Comparisons are made with experiments to validate the numerical results. A study of the evaporative cooling of liquid film in laminar mixed convection tube flow was realized by Feddaoui et al. [13]. This study was extended later to investigate the liquid film evaporation along an insulated vertical channel by Feddaoui et al. [14]. In the two studies it was found that heat transfer by latent mode is the main mechanism for heat removal from the interface and a significant liquid cooling results for the system with a high gas flow Reynolds number, a low liquid flow rate or a high inlet liquid temperature. Feddaoui and his co-workers have reported also many works on liquid film evaporation considering turbulent flows [15–17].

Most of the previous studies find their utilities in air conditioning, distillation, cooling devices and heat exchangers applications. Indeed, liquid films evaporation processes are widely encountered in desalination systems. Many works in the literature exist in relation to film evaporation for desalination. Examples include the study realised by Orfi et al. [18] about air humidification by evaporating a thin liquid film flowing down a vertical channel. Results show that heat transfer at the interface may be higher than the heat flux imposed at the wall. A similar investigation was made by Belhadj et al. [19] by considering liquid film condensation instead of evaporation. The study reported the best conditions to enhance condensation. An important experimental study on solar desalination with horizontal tube falling film evaporation is conducted by Ziqian et al. [20]. In the developed unit, it was approved that thermal

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Nomenclature

C_P	specific heat $(\mathrm{J}\cdot\mathrm{kg}^{-1}\cdot K^{-1})$
$C_{P,a}$	specific heat of air $(\mathrm{J}\cdot\mathrm{kg}^{-1}\cdot K^{-1})$
$C_{P,v}$	specific heat of vapour $(\mathrm{J}\cdot\mathrm{kg}^{-1}\cdot K^{-1})$
D	mass diffusivity $(m^2\cdot s^{-1})$
D_h	hydraulic diameter (m)
g	gravitational acceleration $(\mathrm{m}\cdot s^{-2})$
h_{fg}	latent heat of vaporisation $(\mathrm{J}\cdot\mathrm{kg}^{-1})$
h_M	mass transfer coefficient $(\mathrm{m}\cdot s^{-1})$
h_T	heat transfer coefficient $(\mathrm{W}\cdot m^{-2}\cdot K^{-1})$
$\dot{m}_I$	evaporating mass flux $(\mathrm{kg}\cdot m^{-2}\cdot s^{-1})$
Mr	dimensionless film evaporation rate
M_a	molar mass of air $(\mathrm{kg}\cdot\mathrm{mo}l^{-1})$
M_v	molar mass of vapour $(\mathrm{kg}\cdot\mathrm{mo}l^{-1})$
Nu_x	overall Nusselt number
P	mixture pressure (Pa)
P_d	dynamic pressure (Pa)
$Q_{S,I}$	sensible heat flux $(\mathrm{W}\cdot m^{-2})$
$Q_{L,I}$	latent heat flux $(\mathrm{W}\cdot m^{-2})$
Q_I	total heat flux $(\mathrm{W}\cdot m^{-2})$
r	radial coordinate (m)
Re	Reynolds number of the gas stream
Re_L	liquid film Reynolds number
S_x	local salinity $(\mathrm{g}\cdot\mathrm{kg}^{-1})$
Sh_x	local Sherwood number
T	temperature (°C)
u	axial velocity $(\mathrm{m}\cdot s^{-1})$
v	radial velocity $(\mathrm{m}\cdot s^{-1})$
w	mass fraction of vapour
x	coordinate in the flow direction (m)

Greek symbols

δ_x	local liquid film thickness (m)
μ	dynamic viscosity (Pa·s)
ν	kinematic viscosity $(m^2\cdot s^{-1})$
η	dimensionless coordinate in the flow direction
ρ	density $(\mathrm{kg}\cdot m^{-3})$
Γ_0	inlet liquid mass flow rate $(\mathrm{kg}\cdot s^{-1})$
λ	thermal conductivity $(\mathrm{W}\cdot m^{-1}\cdot K^{-1})$

Subscripts

0	at inlet condition
b	bulk quantity
g	mixture (gas + vapour)
I	gas-liquid interface
l	liquid
v	vapour
w	at the wall

performance of the system is improved by the evaporation of falling liquid film. The film evaporation enhancement in vertical annulus with preheated air flow was examined by Ben Radhia et al. [21]. The effect of geometrical and inlet conditions parameters was investigated to determine the important factors for enhancing the film evaporation. Abraham et al. [22] investigated numerically heat transfer characteristics of a falling liquid film evaporation outside a tube. Their results show that convective evaporation heat transfer performance increases with feed rate, whereas it decreases with tube diameter.

Through this literature review, there is no doubt that the problem of liquid films evaporation is largely investigated. Despite this, to the best knowledge of the authors, the evaporation of saline water film along a vertical channel has not been studied yet. This motivates the present work to understand the evaporation of saline water film and how the salinity affects heat and mass transfers.

2. Problem formulation

The present study is a numerical analysis of saline water film evaporation by mixed convection along a tube. The investigated geometry (Fig. 1) is a vertical tube with radius R, where the wall is heated with constant heat flux Q_w and covered on the inner face with a falling water film. The liquid film flows down with inlet temperature T_{l0}, inlet mass flow rate Γ_0 and inlet salinity S_0, while the gas enters with inlet velocity u_0, inlet temperature T_0, and inlet relative humidity Hr.

To mathematically formulate this problem, many simplifying assumptions have been made:

- The flow in the two phases is considered to be laminar, incompressible and axisymmetric. The maximum value of the imposed liquid film flow was less then $Re_L = 1500$ (the critical value quoted by Ueda and Tanaka [23]). The liquid film Reynolds number was calculated using the standard definition: $Re_L = \frac{4\Gamma_0}{\mu 2\pi R}$.
- The problem is two dimensional and steady,
- The film surface is in thermodynamic equilibrium, smooth and semipermeable [24,25]. The solubility of air in the liquid film is negligible, so the air does not move radially at the interface.
- The diffusion-thermo (Dufour) and thermo-diffusion (Soret) effects can be neglected because the species diffusion processes are done in a very low level of concentration. Heat and mass transfer are mainly due to evaporation.

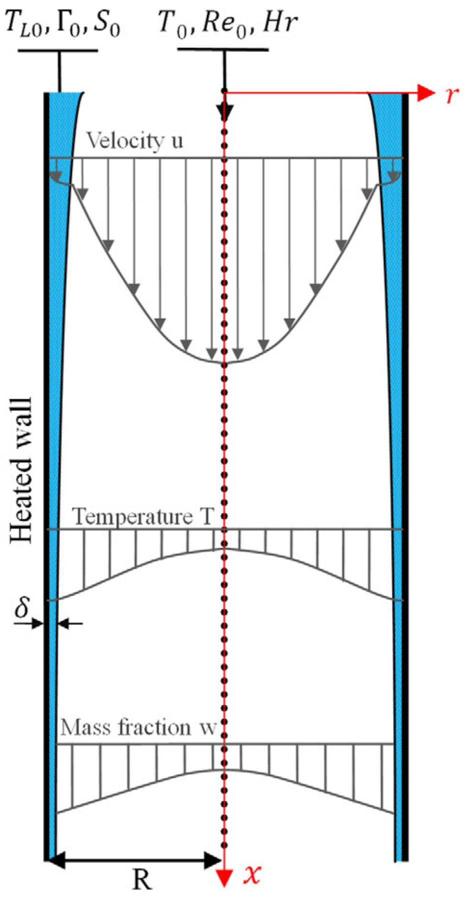

Fig. 1. Physical model.