

Evaporation of the Nanofilm Liquid Inside a Vertical Channel by Mixed Convection

Husni Marwan Sharaf², Abdullah Manea Al-Batati², Achraf Noor Shafie², Abdelaziz Nasr^{1,2}, Mowffaq Oreijah²

¹Laboratory of Thermal and Energy Systems Studies, Monastir University, Ibn Eljazzar Street, 5019 Monastir, Tunisia

²Mechanical Engineering Department, College of Engineering, Umm Al-Qura University, Makkah P.O. BOX 5555, Kingdom of Saudi Arabia

Abstract: *In the present work, a numerical study of evaporation of liquid film with a low nanoparticles volume fraction of copper flowing on one plate of a vertical channel under mixed convection is investigated. The wetted plate is externally subjected to a uniform heated flux or adiabatic while the second one is dry and isothermal. The results concern the effect of nanoparticles volume fraction of added in the water film on the heat and mass transfer and on the water film evaporation. The results show that, the presence of the nanoparticles enhances the performances of the heat and mass transfer and the liquid film evaporation.*

Keywords: Brownian motion, Thermophoresis., nanoparticles, evaporation, liquid film

1. Introduction

The coupled heat and mass transfer with liquid film evaporation is widely encountered in industrial fields such as desalination, drying technology, cooling towers, distillation and air conditioning. Sethumadhavan et al. [1] investigated the effects of colloidal particles concentration and size on liquid film stability. The experimental study conditions were adjusted to avoid the evaporation phenomenon. Mahanthesh et al. [2,3], Gireesha et al. [4] presented a series of studies on the radiative flow of dusty nanofluids and observed the enhancement of heat transfer thanks to the Marangoni flow impact, magnetic parameter and nanoparticle volume fraction. Warner et al. [5] studied the dewetting dynamics of ultrathin film containing nanoparticles in the presence of evaporation. They exploited fluid model takes into account the effects of multiple forces like intermolecular, surface and Marangoni forces. Zheng Hongfei [6] presented an experimental study on enhanced falling film evaporation–air flow absorption and closed circulation solar still. Yan and Soong [7] studied numerically the evaporation of water along an inclined heated plate. The influences of the inclined angle, the wall heating flux, the inlet film thickness and the free stream velocity on the momentum, heat and mass transfer in the system are clarified. Tsay et al. [8] and Chang et al. [9] have treated the evaporation of liquids by free convection driven by thermal and mass buoyancy forces into air. Yan and Lin [10] presented a numerical analysis to investigate the effects of the latent heat transfer, in association with the evaporation into air of a liquid film on the channel wall, on the free convective heat and mass transfer. Ben Jabrallah et al. [11] conducted a numerical study of convective heat and mass transfer with evaporation of a falling film in a cavity. Nasr et al. [12] reported a numerical analysis of binary film evaporation. The results concern the effects of the inlet parameters in the gas and in the liquid film on the interfacial pressure, temperature and concentration profiles. The evolutions of the heat fluxes and of the water and mixture evaporation rates have been analysed. They showed, in particular, that it is possible to

increase the accumulated evaporation rate of water and of the liquid mixture when the inlet liquid concentration of ethylene glycol is less than 40%. Debbissi et al. [13, 14] analyzed the evaporation of water by free into humid air and superheated steam. In their work, particular attention is paid to study the effect of the ambient conditions on the water evaporation rate and on the inversion temperature in the condition of free and mixed convection. The effect of ambient conditions, channel width and walls radiation are analysed in this study. Ali Cherif and Daif [15] analysed numerically the binary liquid film evaporation by mixed convection flowing on the internal face of one of the two parallel plates. They demonstrated the film thickness importance and mixture composition in the mass and thermal transfers. They showed, for example, that for a particular ethylene glycol-water mixture concentration at the channel entry, it is possible to evaporate in the same conditions more water than if the film at the entry was pure water only.

Many works have shown that nanofluid have higher thermal conductivities and higher convective heat transfer coefficients than conventional pure fluids. Thus, studies of liquid film based on nanofluid still need to be addressed. The objective of this work is therefore to study the effect of the introduction of nanoparticles into water on the heat and mass transfer performance. Particular attention was paid to the effect of nanoparticles on the water film evaporation.

2. Analysis

This work presents a numerical study of evaporation by mixed convection of a liquid film following on one of two vertical parallel plates (Fig.1). The film is a water-based nanofluid liquid, containing nanoparticles of aluminium. The wetted plate is externally subjected to a uniform heated flux or adiabatic while the second one is dry and isothermal. The nanofluid film flows down with an inlet temperature T_{0L} , an inlet mass flow rate m_{L0} and a volume fraction of nanoparticles ϕ_0 . The air enters the channel with a

temperature T_0 , a water vapour concentration c_0 , a constant velocity u_0 and an ambient pressure p_0 .

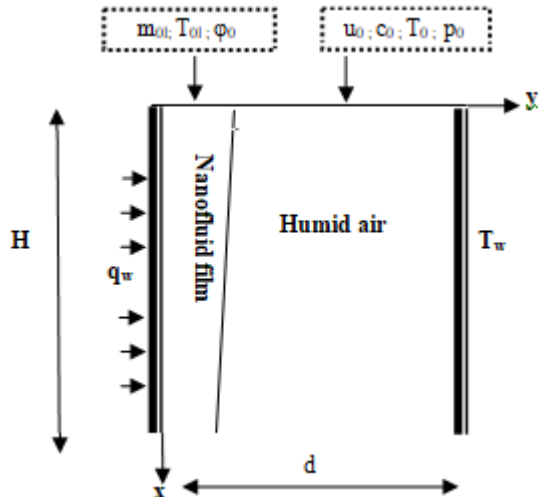


Figure 1: Physical System

2.1 Assumptions

For mathematical formulation of the problem, the following simplifying assumptions are introduced:

- Vapour mixture is ideal gas.
- The base fluid and the nanoparticles are in thermal equilibrium and no slip occurring between them.
- The liquid-gas interface is assumed impermeable to nanoparticles since the axial dynamic forces are much bigger than transversal forces
- The boundary layer approximations are used.
- Dufour and Soret effects are negligible.
- Flows and transfers in the two phases are steady, laminar and two dimensional.
- The effect of the superficial tension is negligible. The gas-liquid interface is in thermodynamic equilibrium.

2.2. Governing equations

Under the assumptions presented above, the equations governing the flow and the combined heat and mass transfers during water film evaporation in the liquid and in the gas phases are [7, 12, 16, 27, 28] as will be shown in the following subsections.

2.2.1. For the liquid phase

Continuity equation

$$\frac{\partial \rho_{nf} u_{nf}}{\partial x_L} + \frac{\partial \rho_{nf} v_{nf}}{\partial y_L} = 0$$

x-momentum equation

$$\rho_{nf} \left(u_{nf} \frac{\partial u_{nf}}{\partial x_L} + v_{nf} \frac{\partial u_{nf}}{\partial y_L} \right) = \rho_{nf} g - \frac{dp_{nf}}{dx_L} + \frac{\partial}{\partial y_L} \left(\mu_{nf} \frac{\partial u_{nf}}{\partial y_L} \right)$$

Energy equation

$$\rho_{nf} c_{p, nf} \left(u_{nf} \frac{\partial T_{nf}}{\partial x} + v_{nf} \frac{\partial T_{nf}}{\partial y} \right) = \frac{\partial}{\partial y} \left(\lambda_{nf} \frac{\partial T_{nf}}{\partial y} \right) + \rho_p c_{p, p} \frac{\partial}{\partial y} \left(D_B \frac{\partial \phi}{\partial y} \frac{\partial T_{nf}}{\partial y} + \frac{D_T}{T_{nf}} \left(\frac{\partial T_{nf}}{\partial y} \right)^2 \right)$$

Nanoparticles concentration equation

$$\frac{\partial u_{nf} \phi}{\partial x} + \frac{\partial v_{nf} \phi}{\partial y} = \frac{\partial}{\partial y} \left(D_B \frac{\partial \phi}{\partial y} + \frac{D_T}{T_{nf}} \frac{\partial T_{nf}}{\partial y} \right)$$

2.2.2. For the gaseous phase

Continuity equation

$$\frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} = 0$$

x-momentum equation

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{dP}{dx} - \beta g (T - T_0) - \beta^* g (c - c_0) + \frac{1}{\rho} \frac{\partial}{\partial y} \left(\mu \frac{\partial u}{\partial y} \right)$$

Energy equation

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{1}{\rho c_p} \left(\frac{\partial}{\partial y} \left(\lambda \frac{\partial T}{\partial y} \right) + \rho D (c_{pv} - c_{pa}) \frac{\partial T}{\partial y} \frac{\partial c}{\partial y} \right)$$

Species diffusion equation

$$u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} = \frac{1}{\rho} \frac{\partial}{\partial y} \left(\rho D \frac{\partial c}{\partial y} \right)$$

The overall mass balance described by the following equation should be satisfied at every axial location:

$$\int_{\delta}^d \rho u dy = (d - \delta) \rho_0 u_0 - \int_0^x \rho v(x, 0) dx$$

2.3. Boundary conditions

- For inlet conditions (at $x=0$): $T(0, y)=T_0$; $c(0, y)=c_0$; $u=u_0$ and $P=P_0$
 $T_L(0, y_L)=T_{0L}$; $m(0, y_L) = m_{0L}$; $\phi = \phi_0$

• For dry plate (at $x=d$):

$$u(d, y) = 0; v(d, y) = 0; \left. \frac{\partial \phi_i}{\partial y} \right|_{x=d} = 0; T(d, y) = T_w$$

For wet plate (at $y_L = 0$):

$$u_L(x, 0) = v_L(x, 0) = 0; q_w = -\lambda_{nf} \left. \frac{\partial T_{nf}}{\partial y_L} \right|_{y_L=0};$$

$$D_B \left. \frac{\partial \phi}{\partial y} \right|_{y_L=0} + \frac{D_T}{T_{nf}} \left. \frac{\partial T_{nf}}{\partial y} \right|_{y_L=0} = 0$$

- For gas-liquid interface (at $y=0$ and $y_L = \delta$):

The continuities of the velocities and temperatures give:

$$u_{nf}(x, y_L = \delta) = u(x, y = 0) ; T_{nf}(x, y_L = 0) = T(x, y = 0)$$

The transverse velocity component of the mixture at the interface is obtained by assuming the interface to be semi-permeable:

$$v(x, 0) = -\frac{D}{1-c(x, 0)} \frac{\partial c}{\partial y} \Big|_{y=0} \quad \text{where } c(x, 0) = c_{sat}(T(x, 0))$$

$$c_{sat}(T(x, 0)) = \frac{M_v P_{v,i}}{M_g P_g} \quad \text{where } p_{v,i} \text{ is the partial pressure of}$$

saturated vapour at the gas-liquid interface.

The continuities of shear stress give:

$$\mu_{nf} \left(\frac{\partial u_{nf}}{\partial y_L} \right)_{y_L=\delta} = \mu \left(\frac{\partial u}{\partial y} \right)_{y=0}$$

The heat balance at the interface implies:

$$-\lambda_{nf} \left(\frac{\partial T_{nf}}{\partial y_L} \right)_{y_L=\delta} = -\lambda \left(\frac{\partial T}{\partial y} \right)_{y=0} - \frac{\rho L_v D}{1-c(x, 0)} \frac{\partial c}{\partial y} \Big|_{y=0}$$

where L_v is the latent heat of water evaporation

In order to evaluate the importance of the different processes of energy transfer, the following quantities are introduced:

The local evaporation rate of water at the interface is given by:

$$\dot{m}(x) = -\frac{\rho D}{1-c(x, 0)} \frac{\partial c}{\partial y} \Big|_{y=0}$$

The cumulated evaporation rate of water at the interface is given by:

$$Mr(x) = \int_0^x \dot{m}(x) dx$$

Table 1: Thermo-physical properties of used nanoparticles at $T=300$ K.

Thermo-physical properties	Copper (Cu)
ρ (kg.m ⁻³)	8933
C_p (J.kg ⁻¹ .K ⁻¹)	385
λ (W.m ⁻² .K ⁻¹)	401

3. Solution Method

The system of equations in the liquid and in the gaseous phases and their boundary conditions are solved numerically using a finite difference method. The flow area is divided into a regular mesh placed in axial and transverse direction and a 51x21x31 grid is retained in actual computations. A fully implicit marching scheme where the axial convection terms were approximated by the upstream difference and the transverse convection and diffusion terms by the central difference is employed to transform the governing equations into finite difference equations.

4. Results and Discussion

In this case, we turn our attention to study the impact of the volume fraction of copper nanoparticles ϕ_0 on the heat and mass transfer when the film plate is heated by uniform heat flux q_1 . Fig.2.a shows that the temperature at the channel exit in the gas region increases with an increase of the volume fraction of copper nanoparticles ϕ_0 . The same behaviour has been founded for the evolution of the temperature at the interface liquid-gas (Fig. 3a). In fact, it is shown from figure 4.a that an increase of the volume fraction of copper nanoparticles ϕ_0 induces an increase of the temperature at the interface liquid-gas. It is observed from figures 2b and 3b that the increasing of the volume fraction of copper nanoparticles ϕ_0 leads to an increase of the vapour concentration at the channel exit in the gas region and at the interface liquid-gas.

Figure 4 gives the profiles of the evaporation rate of liquid water at various values of volume fraction of copper nanoparticles ϕ_0 . A careful examination of figure 4 shows that the film evaporation is important for larger value of volume fraction ϕ_0 . This is owing to the fact that the increase of volume fraction of copper nanoparticles ϕ_0 enhances the heating of the film plate (Figs. 2a and 3a) induces an increase of the water film evaporation (Fig. 4). To evaluate the heat transfer along the nanofluid-gas interface, we present in figures 5a and 5b the latent and sensible heat flux for different volume fraction of copper nanoparticles ϕ_0 . Obviously, heat transfer is enhanced with nanoparticles introduction into water. This is due to the high thermal conductivity value of copper nanoparticles. Figures 6a and 6b show that the latent and sensible heat fluxes are increased with an increase of ϕ_0 .

5. Conclusion

A numerical study is carried out to improve our understanding of heat and mass transfer during film evaporation with nanoparticles introduced in a liquid film flow. The effect of nanoparticles volume fraction on heat and mass transfer and on the liquid film evaporation is studied. The following conclusions are demonstrated:

- 1) Heat and mass transfer enhancement is a strong function of thermal conductivity and heat capacity nanoparticles.
- 2) The copper-water nanofluid used in this study enhances the heat and mass transfer along the channel.
- 3) Increasing nanoparticles volume fraction allows us to improve evaporation rate in the channel.

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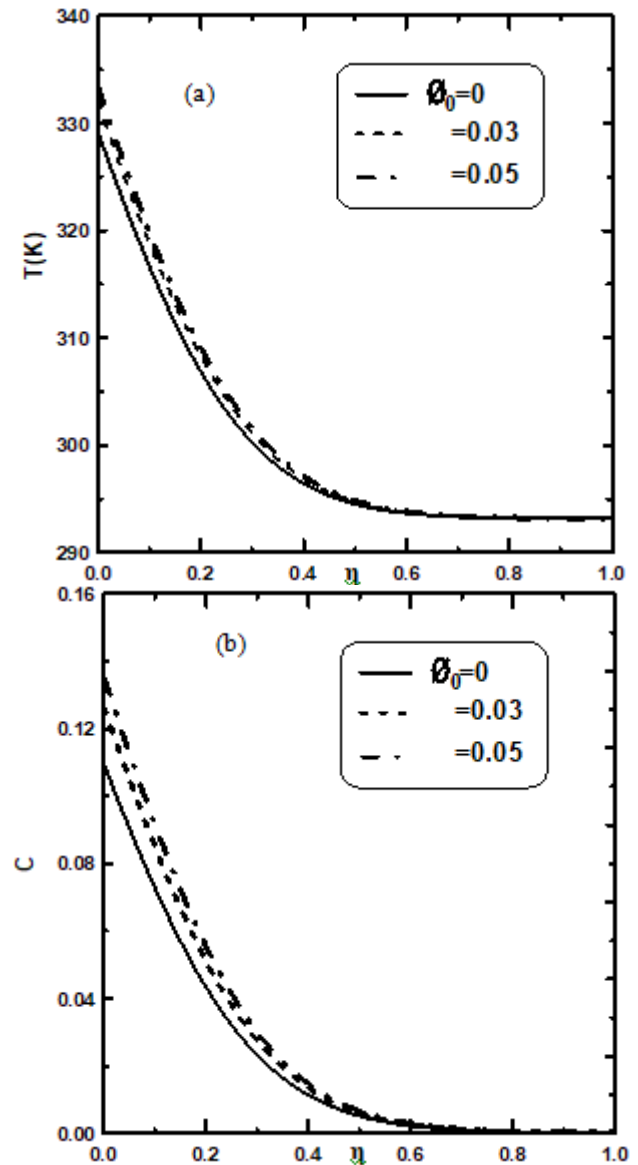
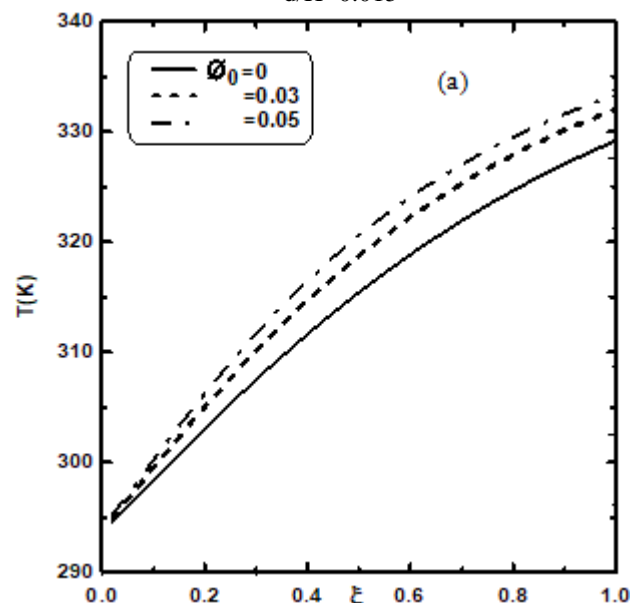


Figure 2: Effect of nanoparticles volume fraction on the temperature and the vapor mass fraction at the channel exit (case of heated plate) : $T_0=20^\circ\text{C}$, $T_{0L}=20^\circ\text{C}$, $q_1=3000\text{ W/m}^2$, $T_w=20^\circ\text{C}$, $c_0=0$, $u_0=1\text{ m/s}$, $m_{0L}=0.0015\text{ Kg/m.s}$, $p_0=1\text{ atm}$, $d/H=0.015$



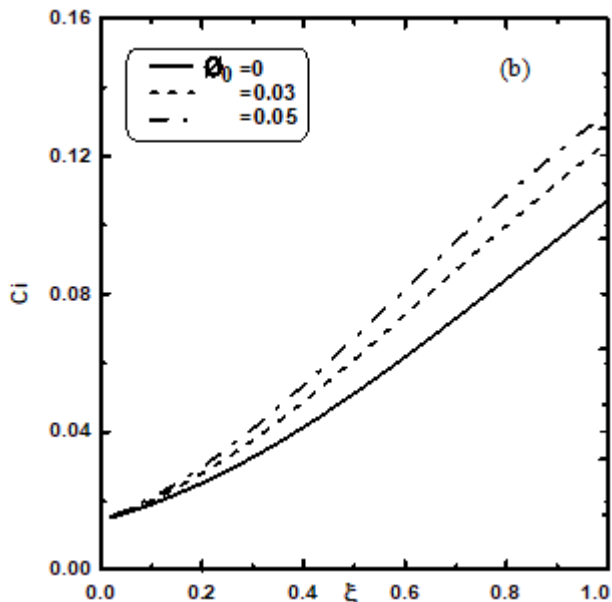


Figure 3: Effect of nanoparticles volume fraction on the temperature and the vapor mass fraction at the interface liquid-gas (case of heated plate) : $T_0=20^{\circ}\text{C}$, $T_{0L}=20^{\circ}\text{C}$, $q_1=3000\text{ W/m}^2$, $T_w=20^{\circ}\text{C}$, $c_0=0$, $u_0=1\text{ m/s}$, $m_{0L}=0.0015\text{ Kg/m.s}$, $p_0=1\text{ atm}$, $d/H=0.015$

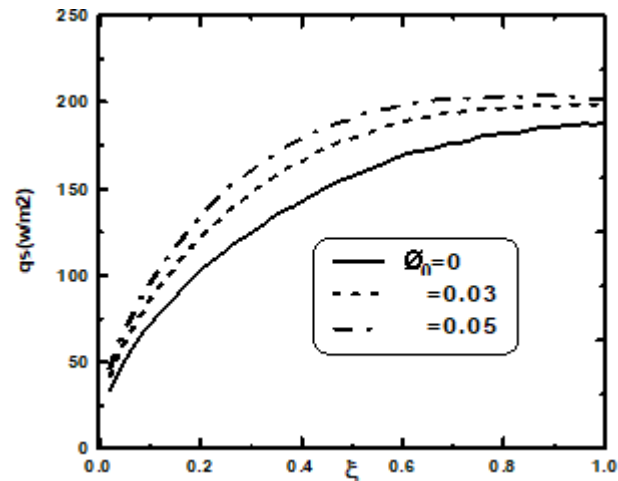


Figure 5: Effect of nanoparticles volume fraction on the latent q_l and sensible q_s heat fluxes (case of heated plate) : $T_0=20^{\circ}\text{C}$, $T_{0L}=20^{\circ}\text{C}$, $q_1=3000\text{ W/m}^2$, $T_w=20^{\circ}\text{C}$, $c_0=0$, $u_0=1\text{ m/s}$, $m_{0L}=0.0015\text{ Kg/m.s}$, $p_0=1\text{ atm}$, $d/H=0.015$

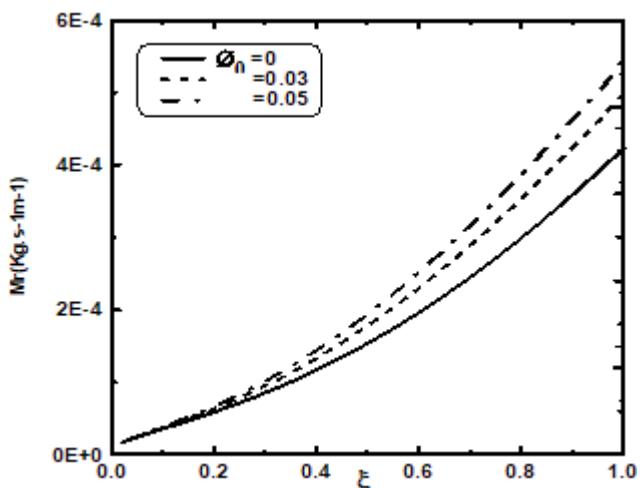


Figure 4: Effect of nanoparticles volume fraction on the cumulated evaporation rate (case of heated plate) : $T_0=20^{\circ}\text{C}$, $T_{0L}=20^{\circ}\text{C}$, $q_1=3000\text{ W/m}^2$, $T_w=20^{\circ}\text{C}$, $c_0=0$, $u_0=1\text{ m/s}$, $m_{0L}=0.0015\text{ Kg/m.s}$, $p_0=1\text{ atm}$, $d/H=0.015$

