Effect of Different Type of Nanoparticles of the Liquid Film Evaporation by Mixed Convection

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Abstract: In this paper, we numerically investigate the improvement of the heat and mass transfer during the evaporation of a liquid film by introducing nanoparticles inside a liquid film. Compared to the liquid case, the use of the nanoparticles added in the liquid film promotes the heat and mass transfer. This improvement is greater when we increase the nanoparticle volume fraction in the liquid film. We also showed that the Cu nanoparticles present the best choice in term of heat and mass exchange compared to Al nanoparticles.

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

1. Introduction

The simultaneous heat and mass transfer between a thin liquid film and gas stream are widely encountered in industrial fields such as desalination, drying technology, cooling systems and air conditioning. Feddaoui et al. [1] presented a combined buoyancy effects of thermal and mass diffusion on the turbulent mixed convection tube flows. Ben Jabrallah et al. [2] presented a numerical study of convective heat and mass transfer with evaporation of a falling film in a cavity. El Armouzi et al. [3] numerically studied the binary liquid film evaporation by mixed convection flowing down of two coaxial cylinders. They showed that the latent heat flux is the dominant mode for the present study. They also showed that the mass and heat transfers are more important near the inlet of the channel and increase with the wall heat flux density. Zheng Hongfei [4] presented an experimental study the enhanced falling film evaporation-air flow absorption and closed circulation solar still. Nasr et al. [5] numerically investigated the evaporation by free convection of flowing liquid film in the presence of porous layer. They showed that the presence of the porous layer enhances the heat and mass transfer performance at the liquid-gas interface during the liquid film evaporation. Yan and Lin [6] numerically studied 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. Yan and Soong [7] treated numerically the evaporation of water along an inclined heated plate. They analysed 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. Lazarus et al. [8] experimentally studied the steady state convective heat transfer of de-ionized water with a low volume fraction of copper oxide nanoparticles dispersed to form a nanofluid that flows through a copper tube. Debissi et al. [9] presented a numerical investigation of the evaporation of binary liquid film falling down on one plate of a vertical channel under mixed convection. They showed that from a definite distance and from a certain value of the inlet liquid

mass fraction of ethylene glycol, it is possible to evaporate in the same conditions more water than if the film at the entry was pure water only. They showed that the existence and the value of the inversion distance depend on the value of the heat flux density. Agunaoun et al. [10] presented a numerical analysis of the heat and mass transfer in a binary liquid film flowing on an inclined plate. They showed that it is possible to increase the cumulated evaporation rate of water when the inlet liquid concentration of ethylene glycol is less than 40%. Recently, a new generation of coolant called nanofluids is used to improve heat transfer of liquids.

The objective of this work is therefore to study the effect of the addition of different types of nanoparticles into water on the heat and mass transfer performance and 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 .

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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 then 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 gasliquid 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**

$$\frac{\partial \rho_{\rm nf} \mathbf{u}_{\rm nf}}{\partial \mathbf{x}_{\rm I}} + \frac{\partial \rho_{\rm nf} \mathbf{v}_{\rm nf}}{\partial \mathbf{y}_{\rm I}} = 0$$

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

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

Nanoparticles concentration equation

$$\frac{\partial \mathbf{u}_{\mathrm{nf}} \phi}{\partial \mathbf{x}} + \frac{\partial \mathbf{v}_{\mathrm{nf}} \phi}{\partial \mathbf{y}} = \frac{\partial}{\partial \mathbf{y}} \left(D_B \frac{\partial \phi}{\partial \mathbf{y}} + \frac{D_T}{T_{nf}} \frac{\partial T_{nf}}{\partial \mathbf{y}} \right)$$

The thermophoresis and Brownian motion coefficients D_T and D_B are written respectively as follows:

$$D_B = \beta \frac{\mu_L}{\rho_L} \phi$$
, $D_T = \frac{k_b T}{3\pi\mu_L d_p}$ and $\beta = \frac{0.26\lambda_L}{(2\lambda_L + \lambda_p)}$

where k_b is the Boltzmann's constant and d_p the nanoparticles diameter.

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

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

Energy equation

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

Species diffusion equation

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

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)=T₀; c(0, y)=c₀; u=u₀ and P=P₀

$$\mathbf{T}_{L}$$
 (0, \mathbf{y}_{L})= \mathbf{T}_{0L} ; $\mathbf{m}(0, \mathbf{y}_{L}) = \mathbf{m}_{0L}$; $\boldsymbol{\phi} = \boldsymbol{\phi}_{0}$

• For dry plate (at x=d):

$$\mathbf{u}(\mathbf{d}, \mathbf{y}) = \mathbf{0}; \mathbf{v}(\mathbf{d}, \mathbf{y}) = \mathbf{0}; \quad \frac{\partial c_i}{\partial y} \bigg|_{x=d} = 0 \quad ; \mathbf{T}(\mathbf{d}, \mathbf{y}) = \mathbf{T}_{\mathbf{w}}$$

• For wet plate (at $y_L = 0$):

$$u_{L}(x,0) = v_{L}(x,0) = 0; q_{w} = -\lambda_{nf} \frac{\partial T_{nf}}{\partial y_{L}} \bigg|_{y_{L}=0};$$

$$D_{B} \frac{\partial \phi}{\partial y} \bigg|_{y_{L}=0} + \frac{D_{T}}{T_{nf}} \frac{\partial T_{nf}}{\partial y} \bigg|_{y_{L}=0} = 0$$

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

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 semipermeable:

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

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

saturated vapour at the gas-liquid interface.

The continuities of shear stress give:

$$\mu_{nf} \frac{\partial u_{nf}}{\partial y_L} \bigg|_{y_L = \delta} = \mu \frac{\partial u}{\partial y} \bigg|_{y = 0}$$

The heat balance at the interface implies:

$$-\lambda_{\rm nf} \frac{\partial T_{\rm nf}}{\partial y_{\rm L}} \bigg|_{y_{\rm L}=\delta} = -\lambda \frac{\partial T}{\partial y} \bigg|_{y=0} - \frac{\rho L_{\rm v} D}{1 - c(x,0)} \frac{\partial c}{\partial y} \bigg|_{y=0}$$

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:

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

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

$$\mathbf{Mr}(x) = \int_{0}^{x} \mathbf{\dot{m}}(x) \mathrm{d}x$$

Table 1: Thermo-physical properties of used nanoparticles atT=300 K.

Thermo-physical properties	Aluminium (Al)	Copper
		(Cu)
ρ (kg.m ⁻³)	2700	8933
$Cp (J.kg^{-1}.K^{-1})$	900	385
$\lambda (W.m^{-2}.K^{-1})$	240	401

3. Solution method

The system of equations in the liquid and in the gaseous phases (1-8) and their boundary conditions given by Eqs (9-16) 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

Figure 2 shows the evolution of temperature and vapour concentration at the interface for different nanoparticles types added in the liquid film flow (nanofluid). Fig.2 shows that the temperature and concentration at the interface liquid-gas is more important for water-aluminium (H₂O-Al) and water-copper (H₂O-Cu) nanofluids compared to the case of

pure water. It is shown also, that the temperature at the interface liquid-gas for water-copper nanofluid is more important to that of water-aluminium nanofluid. This result can be explained by the high thermal conductivity compared to the basic fluid (pure water) and consequently the high thermal diffusivity. The total evaporation rate evolution for various nanoparticles is illustrated in figure 3. It is observed from this figure that the film evaporation is s higher for nanofluids compared to base fluid (water). This is due to the enhancement of temperature and concentration by using the nanofluids (see figure 2). The best evaporation rate is observed for water-copper nanofluid compared to water-aluminium.

After examining the effects of different nanofluids type, attention is turned now to effect of volume fraction of copper nanoparticles ϕ_0 on the heat and mass transfers and on the evaporation process. Figure 4 presents the effect of nanoparticles volume fraction on the temperature and vapour concentration at the interface nanofluid-gas. Fig.4a shows that the temperature at the interface increases with an increase of the nanoparticles volume fraction ϕ $_{0}.$ The same behaviour has been founded for the distributions of the vapour concentration at the interface liquid-gas (Fig. 4b). In fact, it is observed from fig.4b that the increasing of the nanoparticles volume fraction ϕ o leads to an increase of the vapour concentration at the interface liquid-gas. Figure 5 illustrates the profiles of the evaporation rate of nanofluid film at various values of volume fraction of copper nanoparticles φ o. A careful examination of figure 6 shows that the evaporation rate 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 ϕo induces an increase of the thermal conductivity. Figure 7 presents the impact of gas inlet temperature T_0 on the nanofluid film evaporation. In fact, figure 7 indicate that the total evaporation is enhanced for larger values inlet gas temperature.

5. Conclusion

The film evaporation with low volume fraction of nanoparticles introduced in a liquid film flow has been numerically analysed. The effect of different types of nanoparticles and its volume fraction ϕo on heat and mass transfer and on the liquid film evaporation is studied. The following conclusions are demonstrated:

- The Cu nanoparticles present the best choice in term of heat and mass exchange compared to Al nanoparticles.
- The introduction of nanoparticles in the liquid film enhances the heat and mass transfer compared to the basic fluid.
- The addition of nanoparticles in the liquid film enhances the liquid film evaporation.

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 $d/H=0.015, \varphi_0=0.05$



evaporation rate: $T_0=20^{\circ}C$, $T_{0L}=20^{\circ}C$, $q_1=0$, $T_w=20^{\circ}C$, $c_0=0$, u₀=1m/s, m_{0L}=0.0015Kg/m.s, p₀=1 atm, d/H=0.015,

$\Phi_0 = 0.05$

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Figure 4: Effect of nanoparticles volume fraction on the temperature and the vapor mass fraction at the channel exit (case of heated plate): $T_0=20^{\circ}$ C, $T_{0L}=20^{\circ}$ C, $q_1=3000$ W/m², $T_w=20^{\circ}$ C, $c_0=0$, $u_0=1$ m/s, $m_{0L}=0.0015$ Kg/m.s, $p_0=1$ atm,



Figure 5: Effect of nanoparticles volume fraction on the cumulated evaporation rate: $T_0=20^{\circ}$ C, $T_{0L}=20^{\circ}$ C, $q_1=0$, $T_w=20^{\circ}$ C, $c_0=0$, $u_0=1$ m/s, $m_{0L}=0.0015$ Kg/m.s, $p_0=1$ atm, d/H=0.015



Figure 6: Effect of heat flux on the cumulated evaporation rate: $T_0=20^{\circ}$ C, $T_{0L}=20^{\circ}$ C, $q_1=0$, $T_w=20^{\circ}$ C, $c_0=0$, $u_0=1$ m/s, $m_{0L}=0.0015$ Kg/m.s, $p_0=1$ atm, d/H=0.015



Figure 7: Effect of inlet gas temperature on the cumulated evaporation rate: $T_0=20^{\circ}$ C, $T_{0L}=20^{\circ}$ C, $q_1=0$, $T_w=20^{\circ}$ C, $c_0=0$, $u_0=1$ m/s, $m_{0L}=0.0015$ Kg/m.s, $p_0=1$ atm, d/H=0.015

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