Numerical simulation of wall thermal protection by the evaporation of binary liquid film

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Abstract

The purpose of this study is to investigate the thermal protection of a channel wall by evaporating a portion of binary water-ethanol liquid film. To achieve the goals, an implicit finite difference method is used to solve the coupled governing equations in both liquid and gas phases. The influence of the composition of binary liquid film is studied. The results revealed the efficient liquid and water mass fraction to have low wall temperature. It was found that both latent and sensible heat are important in this process.

Keywords: *binary liquid film; evaporation; heat and mass transfer*

1. Introduction

Most of the industrial applications need heat exchanging liquid for cooling devices and protecting wall against high temperature. Many solutions are based on water as a cooling fluid, but it has been replaced or mixed with other fluids to reduce its freezing point or to increase the cooling by exploiting the evaporation. The ethanol fluid is known by its high volatility comparing to water and is been employed frequently in the electronic devices cooling by heat pipes.

A simple review of the literature, reveals the efficiency of liquid films in wall protection against high temperature [1–3]. Feddaoui et al. [4] have shown in their numerical investigation that rising the liquid flow rate and gas Reynolds number both decrease the wall temperature. Jang and Yan [5] have conducted a similar study confirming the previous results. Moreover, they showed that effective thermal protection occurs with high inlet gas flow temperature. An important study of ethanol film evaporation is realised by Nait alla et al. [6]. Effects of many parameters were analysed and detailed in their study.

The previous studies have been realised considering only pure liquid film components, and the major part considers water film evaporation. However, cooling fluids are commonly a mixture of water and other fluids. In present study, the thermal protection of a channel wall, using a mixture of ethanol and water is investigated.

2. Analysis

2.1 Physical model and assumptions

For running the simulations, a vertical channel with height L and width b and with insulated walls is considered. The channel walls are protected by a binary flowing liquid film (Figure 1) containing a mixture of ethanol and water.

We assume in this study that the fluids are Newtonian and incompressible. The simulation is done for bi-dimensional laminar steady flow, and considering a smooth interface between liquid film and airflow. The thermophysical properties are variables with temperature and mass fraction and the correlations used for calculating the properties of mixture are extracted from [7].

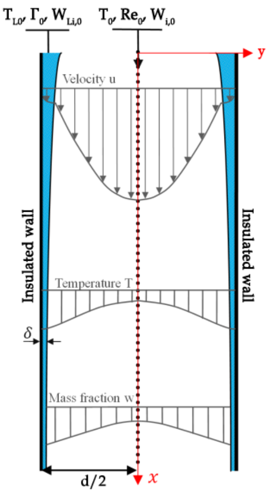

Figure 1: Geometry of the studied problem

2.2 Mathematical formulation

The liquid film flow is expressed by continuity, momentum, energy, and species equations as follows:

$$\frac{\partial}{\partial x}(\rho_L u_L)+\frac{\partial}{\partial y}(\rho_L v_L)=0 \tag{1}$$

$$\frac{\partial}{\partial x}(\rho_L u_L u_L)+\frac{\partial}{\partial y}(\rho_L v_L u_L)=-\frac{\partial P}{\partial x}+\frac{\partial}{\partial y}\left(\mu_L\frac{\partial u_L}{\partial y}\right)+\rho_L g \tag{2}$$

$$\frac{\partial(\rho_L C_L u_L T_L)}{\partial x}+\frac{\partial(\rho_L C_L v_L T_L)}{\partial y}=\frac{\partial}{\partial y}\left(\lambda_L\frac{\partial T_L}{\partial y}\right)+\frac{\partial}{\partial y}\left[\rho_L D_L\left(C_{pL,1}-C_{PL,2}\right)T_L\right]\frac{\partial w_{L,1}}{\partial y} \tag{3}$$

- Species concentration equations:

$$\frac{\partial\left(\rho_L u_L w_{L,i}\right)}{\partial z}+\frac{\partial\left(\rho_L v_L w_{L,i}\right)}{\partial y}=\frac{\partial}{\partial y}\left[\rho_L D_L \frac{\partial w_{L,i}}{\partial y}\right];$$
$$i=1,2 \quad (4)$$

Similarly for the gas flow:

$$\frac{\partial}{\partial x}\left(\rho_G u_G\right)+\frac{\partial}{\partial y}\left(\rho_G v_G\right)=0 \quad (5)$$

$$\frac{\partial(\rho_G u_G u_G)}{\partial x}+\frac{\partial(\rho_G v_G u_G)}{\partial y}=-\frac{dP}{dx}+\frac{\partial}{\partial y}\left[\mu_G \frac{\partial u_G}{\partial y}\right]+\rho_G g \quad (6)$$

$$\frac{\partial(\rho_G C_{PG} u_G T_G)}{\partial x}+\frac{\partial\left(\rho_G C_{PG} v_G T_G\right)}{\partial y}=\frac{\partial}{\partial y}\left(\lambda_G \frac{\partial T_G}{\partial y}\right) \quad (7)$$
$$+\sum_{i=1}^{2}\frac{\partial}{\partial y}\left[\rho_G\left(C_{pi} D_{G,im}-C_{pa} D_{G,am}\right) T_G \frac{\partial w_{G,i}}{\partial y}\right]$$

$$\frac{\partial\left(\rho_G u_G w_{G,i}\right)}{\partial z}+\frac{\partial\left(\rho_G v_G w_{G,i}\right)}{\partial y}=\frac{\partial}{\partial y}\left[\rho_G D_{G,im} \frac{\partial w_{G,i}}{\partial y}\right]$$
$$;i=1,2,a \quad (8)$$

2.3 Boundary and interface conditions

The inlet conditions (x=0) are as follows:

$$\Gamma=\Gamma_0;\ \ T_L=T_{L0};\ \ w_{Li}=w_{Li,0} \quad (9)$$

$$u=u_0;\ \ T_G=T_{G0};\ \ w_G=w_{G0}\ \ i=1,2 \quad (10)$$

At the wet wall y=b

$$\frac{\partial T_L}{\partial y}=0;\ \ u_L=v_L=0;\ \ \frac{\partial w_{L,i}}{\partial y}=0;\ i=1,2 \quad (11)$$

At the dry wall y=0

$$\frac{\partial T_G}{\partial y}=0;\ \ u_G=v_G=0;\ \ \frac{\partial w_{G,i}}{\partial y}=0;\ i=1,2,a \quad (12)$$

The matching conditions at the interface are:

$$u_I(x)=u_{G,I}=u_{L,I};T_I(x)=T_G=T_{L,I}; \quad (13)$$

$$\tau_I=\left[\mu\frac{\partial u}{\partial y}\right]_{nf,I}=\left[\mu\frac{\partial u}{\partial y}\right]_{G,I} \quad (14)$$

$$\left[\lambda\frac{\partial T}{\partial y}\right]_{nf,I}=\left[\lambda\frac{\partial T}{\partial y}\right]_{G,I}+\dot{m}h_{fg} \quad (15)$$

$$\dot{m}_i=\dot{m}w_{L,i}-\rho_L D_{L,12}\frac{\partial w_{L,i}}{\partial y}=\dot{m}w_{G,i}-\rho_G D_{G,im}\frac{\partial w_{G,i}}{\partial y} \quad (16)$$

Where h_{fg} is the latent heat of vaporisation and $i=1,2$.

2.4 Numerical solution method

To solve the parabolic equations (1 to 8), a fully implicit scheme is employed. The numerical solution is realised using finite difference method. Each finite-difference equation's system forms a tridiagonal matrix, which can be solved using the TDMA method [8]. It is still necessary to satisfy the global mass flow constraint. This is done by correcting the pressure gradient and axial velocity profile at each axial step, according to Raithby and Schneider method [9]. Moreover, the generated grid is non-uniform, in order to enhance numerical solutions accuracy.

3. Results and discussion

All the simulations in this study are established considering a channel dimension d x L =0.02 x 2m with the following conditions:

Table 1 : Simulations parameters

$T_{L0}=300K;\ T_0=393K;\ \Gamma_0=0.02\frac{kg}{m.s};\ Re=2000$		
Liquid film composition: Water + Ethanol		
Run	**Mass fraction of water**	**$w_{L1,0}$**
1	$w_{L1,0}$ (Pure water)	1.00
2	$w_{L1,0}$	0.75
3	$w_{L1,0}$	0.50
4	$w_{L1,0}$	0.25
5	$w_{L1,0}$ (Pure ethanol)	0.00

Figure 2 shows the axial variation of liquid film convective heat Q_{fc} along the channel. It can be seen that as the water quantity increases in the liquid mixture, the convective heat transported by the liquid film increases. It is important to note that the case of pure ethanol is special since it shows negative values. Negative values of Q_{fc} indicates that the liquid film is releasing heat to the gas flow instead of absorbing it. Those findings mean that the wall temperature will be low whenever Q_{fc} is low. By decreasing the water mass fraction, the Q_{fc} drop is transformed gradually from hyperbolic to exponential form, except for ethanol where it decreases to a peak value (-33.5 W/m² for d/L=7) and then rises up slightly.

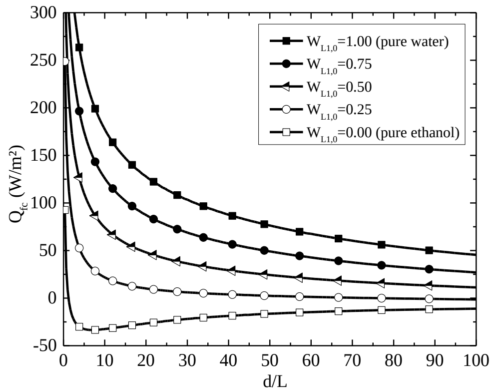

Figure 2: Axial variation of liquid film convective heat along the channel

Figure 3 shows the axial evolution of wall temperature T_W. The temperature increases along the channel for all mixtures containing water. Furthermore, incrementing the amount of ethanol in the mixture decreases the wall temperature. Consequently, pure ethanol provides the best wall protection from temperature rising. More than that, it permits to reduce the wall temperature continuously along the channel. The pure ethanol is more effective in the protection of wall from hot gas owing to its high volatility comparing to water. In fact, having a volatile fluid allows the heat transfer enhancement by phase change.

To give a detailed analysis of heat transfer characteristics, we present the variations of latent and sensible heat fluxes at the interface as depicted in figure 4. We observe that the latent heat Q_L decreases as the liquid film downstream the channel for all liquids. A quick analyse of the figures reveals that both sensible and latent heat fluxes are in the same range.

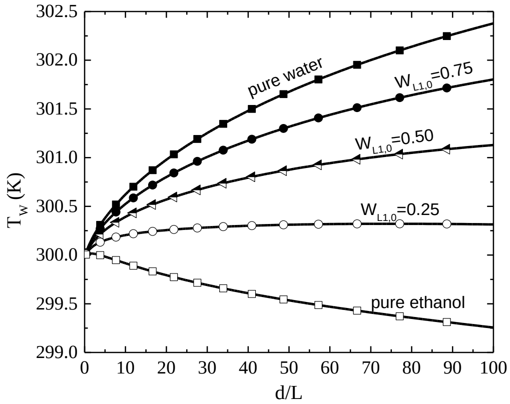

Figure 3: Axial variation of wall temperature

The sensible heat fluxes take negative values since the heat transfer is done from the gaseous phase to the liquid film. As predicted in the interpretation of wall temperatures along the channel, pure ethanol has the highest latent heat flux. For the mixture of water and ethanol, decreasing the mass fraction of water causes the increase of the mixture latent heat flux. However, the sensible heat flux is not affected by the mixture composition. This proves that the decrease of wall temperature caused by increasing the quantity of ethanol is mainly due to the phase change. Hence, the heat flow released by pure ethanol to the gas flow is surely done by evaporation.

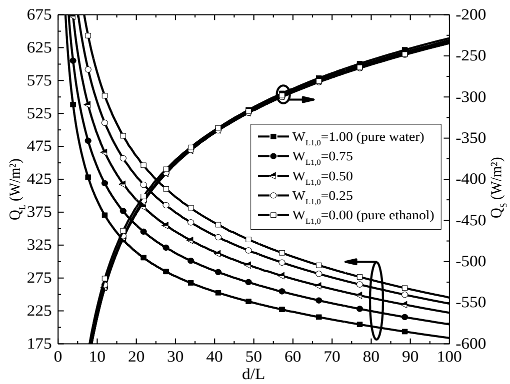

Figure 4: Axial variations of latent and sensible heat fluxes

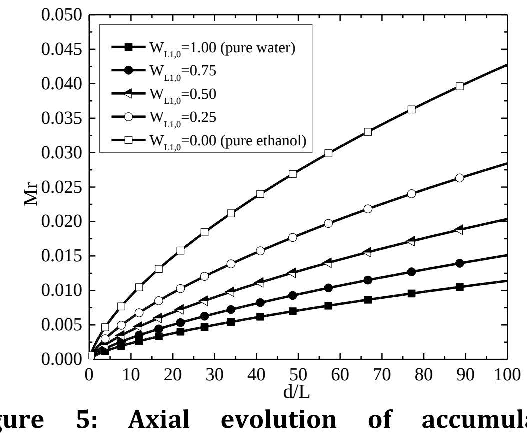

Figure 5: Axial evolution of accumulated evaporation rate

Attention is now turned to investigate the mass transfer process. Figure 5 shows the axial variation of the accumulated evaporation rate Mr. A better evaporation rate is found for the case of pure ethanol film. Mr increases by increasing the mass fraction of ethanol. It's worth noticing that Mr is higher for pure ethanol. This is surely due to the high volatility of ethanol. From above findings, the evaporation of liquid films mixtures is restrained by increasing the amount of water.

4. Conclusion

In this work, the heat and mass transfer in wall protection process is analysed. Comparisons have been made between pure water and water-ethanol mixtures. The main outcomes of this study are:

1- Pure ethanol presents the highest evaporating mass flux and the best solution for the thermal protection of wall from hot gas flow,
2- Mixing ethanol with water restraint the evaporation process, especially with high mass fractions of water.
3- In studied conditions, both latent and sensible heat transfer are important and the best heat removal is provided by the latent mode.

References

[1] T.R. Shembharkar, B.R. Pai, *Prediction of film cooling with a liquid coolant*, Int. J. Heat Mass Transf. 29 (1986) 899–908.

[2] W.-M. Yan, T.F. Lin, *Evaporative cooling of liquid film through interfacial heat and mass transfer in a vertical Numerical study*, Int. J. Heat Mass Transf. 34 (1991) 1113–1124.

[3] M. Feddaoui, E.M. Belahmidi, A. Mir, A. Bendou, *Numerical study of the evaporative cooling of liquid film in laminar mixed convection tube flows*, Int. J. Therm. Sci. 40 (2001) 1011–1020.

[4] M. Feddaoui, a Mir, E. Belahmidi, *Numerical simulation of mixed convection heat and mass transfer with liquid film cooling along an insulated vertical channel*, Heat Mass Transf. 39 (2003) 445–453.

[5] J.H. Jang, W.M. Yan, *Thermal protection with liquid film in turbulent mixed convection channel flows*, Int. J. Heat Mass Transf. 49 (2006) 3645–3654.

[6] A. Nait Alla, M. Feddaoui, H. Meftah, *Numerical study of the evaporation by mixed convection of ethanol in partially heated plate along a vertical channel*, Int. J. Heat Mass Transf. 89 (2015) 206-215.

[7] J.P.O. Bruce E. Poling, John M.Prausnitz, *The Properties of Gases and Liquids*, Fifth Edit, McGRAW-HILL, New York, 2001.

[8] S. V.PATANKAR, *Numerical heat transfer and fluid flow*, 1978.

[9] G.D. Raithby, G.E. Schneider, *Numerical solution of problems in incompressible fluid flow: treatement of the velocity-pressure coupling*, Numer. Heat Transf. 2 (1979) 417–440.