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Evaporation of water/ammonia binary liquid film by mixed convection inside isothermal vertical plates

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ABSTRACT

An ammonia/water mixture can be used as an efficient working fluid in several industrial applications such as in heat pumps, heat transformers and separation processes. This paper presents a numerical analysis of coupled heat and mass transfer by mixed convection during water/ammonia binary liquid film evaporation inside vertical channels. The two channel walls are isothermal, but maintained at different temperatures. One wall maintained at (T_w) is covered with an extremely thin liquid film, while the other wall which is maintained at (T_p) is dry. The conducted simulations enable the analysis and the description of the evaporation process and the heat and mass transfers for a wide range of parameters including the inlet variables of each liquid and the inlet properties of the gas. The results focused on the effect of the inlet amount of water vapour and that of ammonia vapour on the evaporating rates of these two components as well as on the distribution of the concentration profiles.

Keywords: Ammonia; Water; Binary liquid; Evaporation; Distillation; Mixed convection

1. Introduction

Evaporation of binary liquids is widely encountered in several important natural and industrial applications. Examples of these applications are the distillation used in thermal desalination processes, combustion reactions and refrigeration technology. Ammonia is used as a refrigerant in air conditioning devices. The understanding of the corresponding heat and mass transfer was the main objective of several studies in these fields.

Ali Cherif and Daif [1] studied numerically the evaporation of a binary liquid film flowing on the internal wall of one plate of a channel. The wetted plate is subjected to a uniform heat flux while the other is taken adiabatic. They showed the film thickness importance and mixture composition in the mass and heat transfer process. The presented results concern two types of liquid mixtures namely the ethanol/water and the ethylene glycol/water. It was shown, for example, that for a particular ethylene glycol/water 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. Agunaoun et al. [2] presented a numerical analysis of the heat and mass transfer in a binary liquid film flowing on an inclined plate. The most interesting results are

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obtained in mixed convection, particularly in the case of ethylene glycol/water mixture.

Hoke and Chen [3] in their study on the evaporation of a binary liquid film flowing on a vertical plate analysed the distribution of the Sherwood and Nusselt numbers. Vijay et al. [4] measured the diffusion coefficient during the evaporation of a binary liquid in a Stefan tube.

Other geometrical configurations are also used in addition to two parallel plates channel. The evaporation of a binary liquid film in coaxial cylinders has been studied by El Armouzi et al. [5,6]. It was shown that the volatilities of the mixture influence significantly the heat transferred through the latent mode. Palen et al. [7], in their experimental work on the evaporation of a liquid mixture namely ethylene glycol/water inside circular tubes, observed that for some conditions, the local heat transfer coefficient between the partition and the liquid mixture can fall by 80% compared to the case of pure water. It is also of interest to present the study of Baumann and Thiele [8] who analysed the evaporation in mixed convection of benzene/methanol liquid mixture inside tubes. The effect of the mixture composition on the heat and mass transfer rates was found to be very important.

O'Hare and Spedding [10] conducted an experimental work on the evaporation of the binary water/ethanol mixture on a horizontal plate. Belhadj Mohamed [12] presented a detailed mathematical analysis of the phase change of a multi-component liquid film. Several simulations of binary liquids were conducted for the case where the film thickness was considered.

In this work, the ammonia/water mixture is considered and the boundary layer form of the corresponding conservation equations was solved numerically. The gas entering the channel contains dry air, water vapour and ammonia vapour. The evaporation process is analysed and described.

2. Mathematical formulation

The studied physical model (Fig. 1) shows the flow and transfers in a vertical channel of height (H) and width (L). The plate covered with the liquid film is maintained at the temperature T_w. The second plate is maintained at the temperature T_p, which is different than T_w. The gas mixture enters the channel with a temperature T_0, a water vapour concentration c_{01}, an ammonia vapour concentration c_{02}, a pressure p_0 and an axial velocity u_0.

For the mathematical formulation, the following simplifying assumptions were taking into consideration:

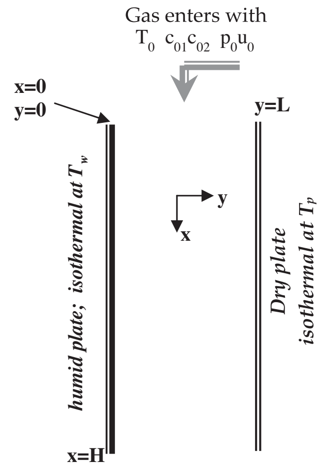

Fig. 1. Physical model.

(i) The liquid and gas flows are laminar, steady and two-dimensional.
(ii) The liquid film is supposed to be extremely thin [13].
(iii) The boundary layer approximations are supposed valuable for the gas stream.
(iv) Air is an ideal mixture of water and ammonia vapours and dry air. It is considered as an ideal gas.
(v) The gas–liquid interface is at the thermodynamic equilibrium.
(vi) The effects of surface tension, Soret and Duffour are neglected.
(vii) Radiation heat transfer, viscous dissipation and pressure work terms are neglected in the energy equation.

The conservation equations of mass, species, energy and momentum corresponding to the gas mixture of air, water vapour and ammonia vapour are expressed as [13,14]:

Continuity equation

$$\frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} = 0 \qquad (1)$$

where u and v are, respectively, the longitudinal and transversal velocity of the gas mixture.

Momentum equation

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\left(\frac{\rho - \rho_0}{\rho}\right)g - \frac{1}{\rho}\frac{dp}{dx} + \frac{1}{\rho}\frac{\partial}{\partial}\left(\mu\frac{\partial u}{\partial y}\right) \qquad (2)$$

where ρ is the mixture mass density; p is the mixture pressure and μ is the mixture dynamic viscosity.

Energy equation

$$\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\rho D_1\left(c_{pv1}-c_{pa}\right)\frac{\partial T}{\partial y}\frac{\partial c_1}{\partial y}+\rho D_2\left(c_{pv2}-c_{pa}\right)\frac{\partial T}{\partial y}\frac{\partial c_2}{\partial y} \tag{3}$$

where λ is the gas mixture thermal conductivity; C_{pa}, C_{pv1} and C_{pv2} are the specific heats at constant pressure for the air, water vapour and ammonia vapour, respectively. D_1 and D_2 refer to the mass diffusivities of the two vapours such as water and ammonia, respectively, inside the gas mixture. T is the gas mixture temperature.

Gas concentration equations

$$u\frac{\partial c_1}{\partial x}+v\frac{\partial c_1}{\partial y}=\frac{1}{\rho}\frac{\partial}{\partial y}\left(\rho D_1\frac{\partial c_1}{\partial y}\right) \tag{4}$$

where c_1 is the mass concentration of water vapour,

$$u\frac{\partial c_2}{\partial x}+v\frac{\partial c_2}{\partial y}=\frac{1}{\rho}\frac{\partial}{\partial y}\left(\rho D_2\frac{\partial c_2}{\partial y}\right) \tag{5}$$

where c_2 is the mass concentration of ammonia vapour.

Global mass balance

$$\int_0^L \rho u(x,y)dy = d\rho_0 u_0 + \int_0^x \rho v(x,0) \tag{6}$$

Boundary conditions

Channel entry

$$T=T_0;\ p=p_0;\ c_1=c_{01};\ c_2=c_{02};\ u=u_0 \tag{7}$$

Dry plate

$$\begin{cases}\left(\frac{\partial c_1}{\partial y}\right)_{y=L}=0\\ \left(\frac{\partial c_2}{\partial y}\right)_{y=L}=0\end{cases};\begin{cases}u=0\\ v=0\end{cases};T(x,L)=T_p \tag{8}$$

Plate covered with the thin film

$$c_1(x,0)=\frac{w_1p_{vs1}}{w_1p_{vs1}+\left[w_2p_{vs2}\frac{M_2}{M_1}\right]+[p-w_1p_{vs1}-w_2p_{vs2}]\frac{M_a}{M_1}} \tag{9a}$$

$$c_2(x,0)=\frac{w_2p_{vs2}}{w_2p_{vs2}+\left[w_1p_{vs1}\frac{M_1}{M_2}\right]+[p-w_1p_{vs1}-w_2p_{vs2}]\frac{M_a}{M_2}} \tag{9b}$$

p_{vs1} and p_{vs2} are obtained from [11].

$$T(x,0)=T_w;\ u(x,0)=0;$$
$$v(x,0)=-\frac{1}{1-c_1(x,0)-c_2(x,0)}\left(D_1\frac{\partial c_1}{\partial y}\right)_{y=0}+\left(D_2\frac{\partial c_2}{\partial y}\right)_{y=0} \tag{10}$$

The local evaporation rate of the species i is

$$m_{evapi}=\rho v(x,0)c_i(x,0)-\rho D_i\left.\frac{\partial c_i}{\partial y}\right|_{y=0}\quad i=1,2 \tag{11}$$

where $i=1$ refers to water vapour, while $i=2$ refers to ammonia vapour.

3. Solution method

The present problem defined by the governing equations and the boundary conditions is solved numerically using a finite difference marching procedure in the downstream direction. A fully implicit scheme, where the axial convection terms are approximated by the upstream difference and the transverse convection and diffusion terms by the central difference, is employed [13].

Because of the lack of results on the evaporation of ammonia–water mixture in the literature, the present numerical model was validated using the results given by Cherif and Daif [9] for the case of laminar

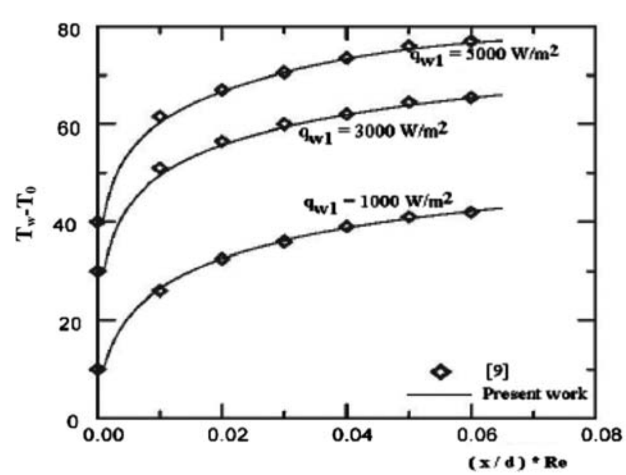

Fig. 2. Validation of the program simulation.

Table 1
Influence of grid size on the evaporation rates of species at the channel exit: ($T_p = T_0 = 20$°C, $T_w = 10$°C, $L = 0.02$ m, $H = 1$, $u_0 = 0.75$ m/s, $c_{01} = c_{02}$ and $c_{l1} = c_{l2} = 0.5$)

$N_x \times N_y$	(71, 51)	(51, 51)	(41, 51)	(51, 71)	(51, 31)
mevap$_1$($\times 10^{-6}$)	7.5462	7.5474	7.5532	7.5512	7.5204
mevap$_2$($\times 10^{-3}$)	5.9481	5.9490	5.9524	5.94522	5.9402

convective heat and mass transfer of an ethylene glycol/water binary liquid flowing inside a heated vertical channel. Fig. 2 shows a very good agreement between our results and those of Cherif and Daif [9].

Table 1 presents the effect of the grid size on the exit evaporating rates for the water and ammonia. These values are practically independent of the chosen grid. We select the grid size of 51×51 for the simulations conducted in this work.

4. Results and discussion

In this theoretical study, we analyse the evaporation phenomenon of a binary liquid film (mixture of water and ammonia) by laminar convection in a vertical channel. The results concern an air-water/ammonia system with $L = 0.02$ m, $H = 1$ m, $T_0 = 30$°C, $c_{01} = 0$, $c_{02} = 0$, $p_0 = 7$ bars, $T_p = 30$°C and $u_0 = 0.75$ m/s.

Referring to the 7 atm binary diagram of the mixture, the liquid film temperature should be in the liquid zone of the diagram (Fig. 3(a)). Figs. 3(b) and 3 (c) compare, respectively, the saturation pressure and the latent heat of evaporation for the two species water and ammonia. The Y-axis values corresponding to the saturation pressure in Fig. 4(b) are those of ln (pvs), where pvs is expressed in Pa. The saturation pressure values as well as the latent heat values shown in Figs. 3(b) and 3(c) correspond to the reported values in the literature.

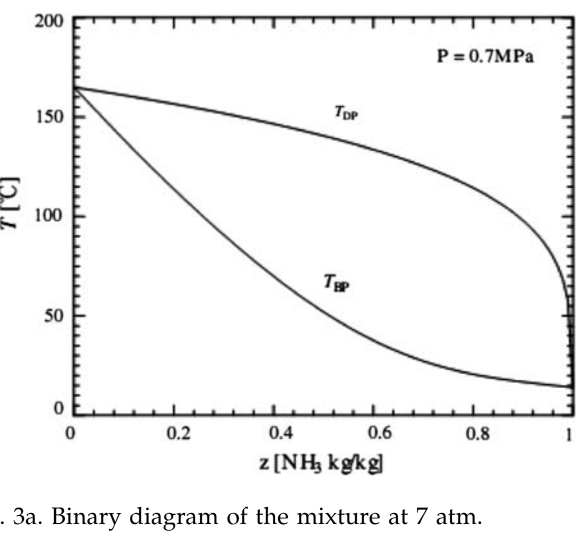

Fig. 3a. Binary diagram of the mixture at 7 atm.

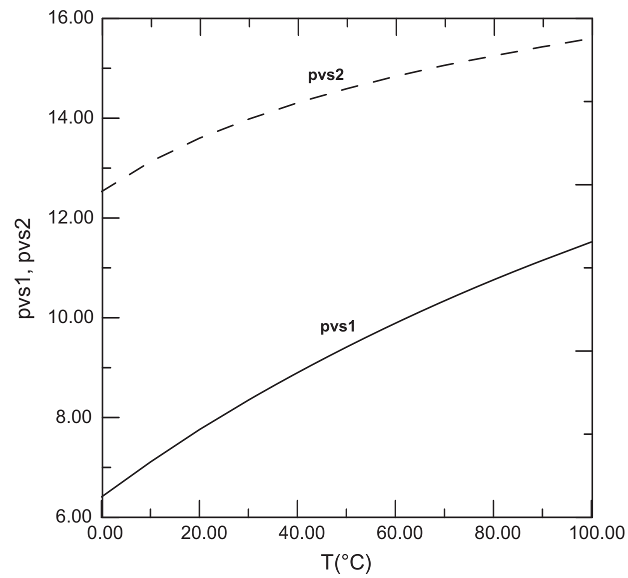

Fig. 3b. Saturation pressure of water and ammonia.

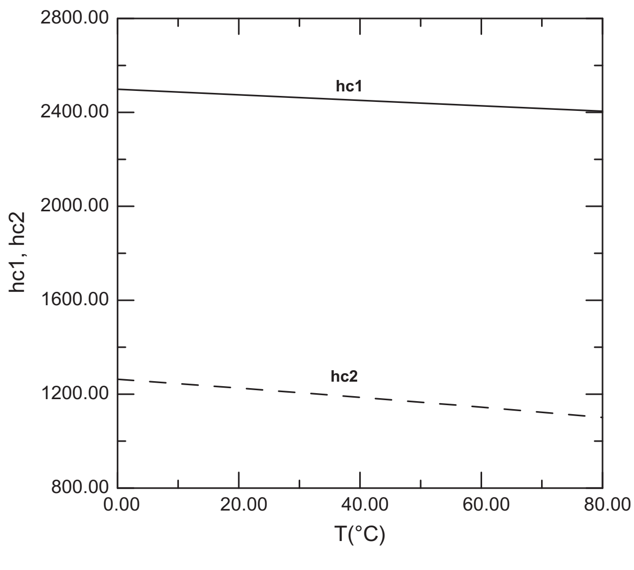

Fig. 3c. Latent heat for evaporation of water and ammonia.

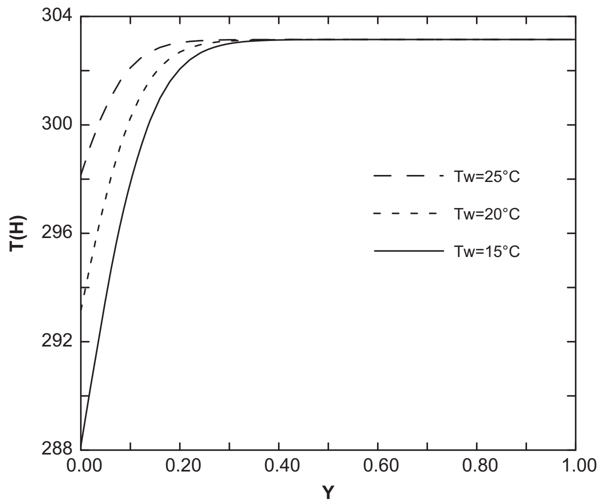

Fig. 4. Effect of the humid plate temperature T_w on the outlet gas temperature.

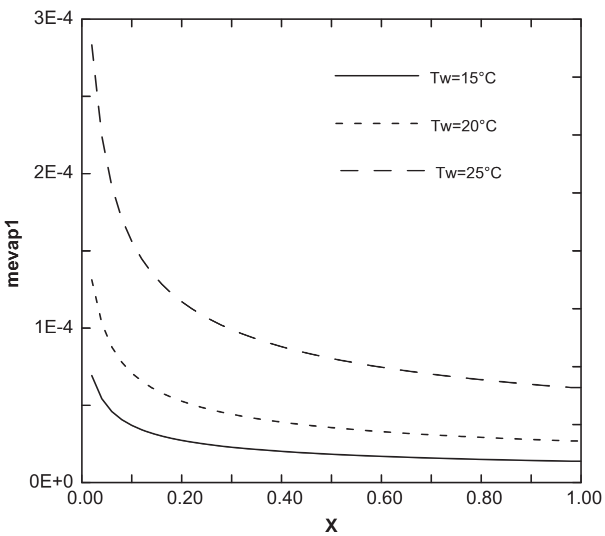

Fig. 5. Effect of the humid plate temperature on the local evaporation rate of water.

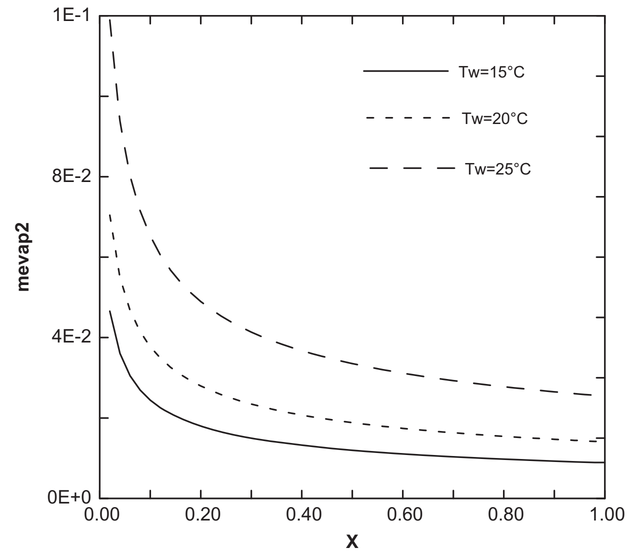

Fig. 6. Effect of T_w on the local evaporation rate of ammonia.

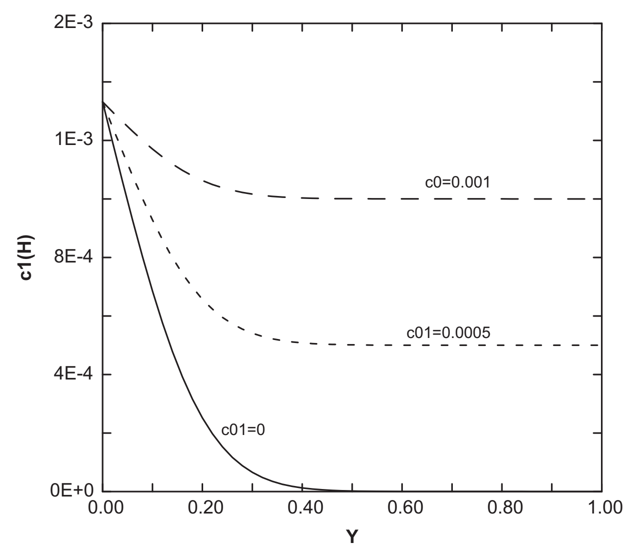

Fig. 7. Effect of the inlet water vapour concentration on its outlet concentration profile.

Fig. 3(b) shows that the saturation pressure values for ammonia are larger than those of water. On the other hand, the specific energy needed for the evaporation of ammonia is lower than that of water.

Fig. 4 shows the effect of the humid plate temperature, T_w, on the transversal variation of the gas temperature at the channel exit ($x = H$). One can see that this effect is limited to the boundary layer which becomes thinner when increasing T_w, while the major part of the fluid has a uniform temperature equal to the inlet temperature $T_0 = 30^\circ C$.

Figs. 5 and 6 show the axial distribution of the local evaporating rates of water and ammonia for three values of T_w. For all the curves, the evaporation rates decrease when the gas mixture flows downstream until reaching a plateau near the developed region. Besides, the evaporation process is enhanced significantly when T_w becomes equal to $25^\circ C$. However, and although similar patterns are observed for the cases of water and ammonia, the evaporating rates for water are much lower than those of ammonia.

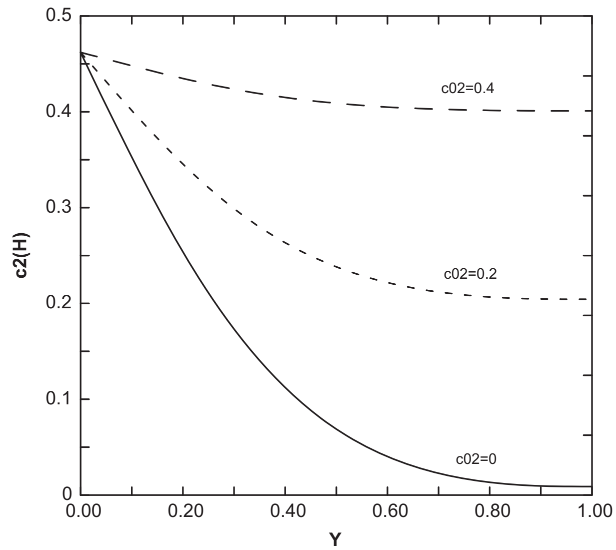

Fig. 8. Effect of the inlet ammonia vapour concentration on its outlet concentration profile.

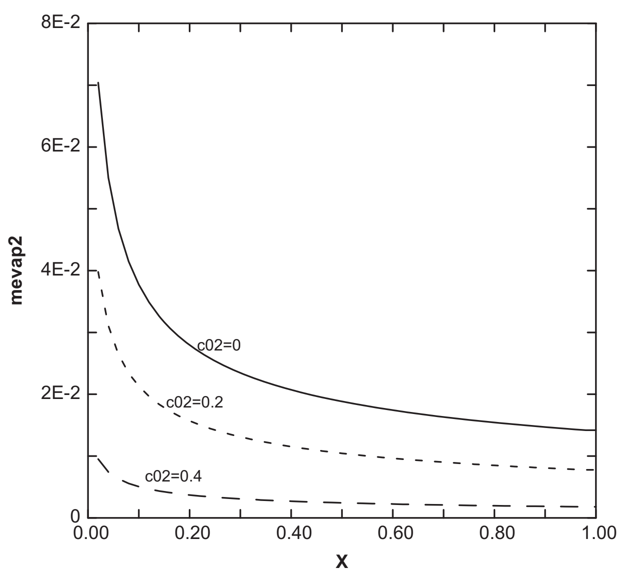

Fig. 9. Effect of the inlet ammonia vapour concentration on its local evaporation rate.

Fig. 7 gives the effect of the inlet water vapour concentration on the temperature profile of the water vapour concentration c_1. The figure shows a significant decrease of c_1 in the boundary layer region in particular when the initial concentration is zero.

Regarding the ammonia concentration transversal profile at the channel exit shown in Fig. 8, the boundary layer is larger than in the case of water vapour (Fig. 7). It is obvious that an augmentation of the ammonia vapour concentration at the channel entry increases its values at its exit. The decrease of the evaporation rates observed in Fig. 9 when increasing the initial ammonia vapour concentration is attributed to the decrease of the concentration c_2 gradients.

5. Conclusion

The evaporation of a binary liquid mixture composed of ammonia and water is studied numerically in this paper. The results focused on the effect of the inlet amount of water vapour and that of ammonia vapour on the evaporating rates of these two components as well as on the distribution of the concentration profiles.

The evaporation rates for the ammonia are found to be higher than those of water.

Other results will be added soon on the effect of the other controlling parameters on the phase change process.

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Nomenclature

H	channel length, m
c_i	mass fraction vapour for species i
c_{Li}	mass fraction liquid for species i
c_p	specific heat at constant pressure, kJ/kg/K
D_i	mass diffusivity of species i vapour in the gas mixture, m^2/s
G	gravitational acceleration, m/s^2
L	channel width, m
L_{vi}	latent heat of species i, kj/kg
m_{evapi}	local evaporation rate for species i, kg/ms
M_i	molar mass of species i
p	pressure, Pa
T	temperature, K
u	axial velocity, m/s
v	transversal velocity, m/s
w_i	molar liquid fraction of the species i
x	axial coordinate direction, m
y	transversal coordinate, m
N_x	number of nodes along the x direction
N_y	number of nodes along the y direction
z	liquid mass fraction of ammonia

Subscripts

a	Air
v	Vapour

i species
sat saturation
0 inlet condition
1 water
2 Ammonia

Greek symbols

μ dynamic viscosity, kg/ms
ρ density, kg/m^3
λ thermal conductivity, W/mK

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