

Numerical Modeling of Non-Condensable Gases Type during Condensation of Steam-Water Mixture

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Abstract: *The purpose of this study is to analyse the combined heat and mass transfer of the type of non-condensable gas in a steam-gas mixture (steam vapor-Argon, steam vapor-Air and steam vapor-Neon) during condensation along a vertical pipe with a constant wall temperature. Both liquid and gas mixtures are approached by two coupled laminar boundary layer. An implicit finite difference method is employed to solve the coupled governing equations for liquid film and gas flow together with the interfacial matching conditions. The systems of equations obtained by using an implicit finite difference method are solved by TDMA method. The numerical results obtained in this study show that, the heat and mass transfer is influenced by increasing of molar mass of non-condensable gases.*

Keywords: *condensation, non-condensable gas, two-phase flow, heat and mass transfer, molar mass*

1. Introduction

The study of gases-mixture condensation in vertical pipe have traditionally found many industrial applications, including in the process industry, the air conditioning, the nuclear power generation industry and refrigeration industry and for condensation of mixed vapors for distillation of hydrocarbons. Numerous studies have been made on modeling heat and mass transfer in condensing two-phase flows in the presence of non-condensable in order to provide predictions that could improve the design of equipment in those application areas. Condensation process of water vapor from the vapor-gas mixtures with non-condensable gas is more complex than that of pure vapor and is an important phenomenon in passive containment cooling systems; because of its build up at the liquid-mixture interface. Siddiqui et al. [1] performed a theoretical study of the condensation by forced convection of a mixture steam-gas in a vertical tube, considering different gases (air, hydrogen, helium). They showed that the presence of air, hydrogen or helium, respectively, leads to condensation rate increasingly higher. An experimental investigation of the condensation of steam and mixtures of non-condensable gas inside a vertical tube immersed in a water reservoir was introduced by Oh et al. [2] in order to analyze the influence of the pressure of the vapor on the condensing. The results show that heat transfer coefficient and density of the heat flow to the wall decreases with increase of mass fraction of the air. Also, heat flow transferred to the wall decreases when pressure of vapor phase increases, while the density of heat flow to the wall increases with the pressure. El Hammami et al. [3] modeled film condensation from a steam-air mixture with small concentrations of vapor (i.e., high air mass fraction) in a vertical tube. They showed that the condensation of small concentration of vapors is improved at lower wall temperature and the gas content causes a resistance to heat and mass transfer. Merouani et al. [4] presented a numerical modeling of the convective condensation of a mixture of steam in the presence of a gas non condensable (Argon, Air, Helium, hydrogen) between two vertical coaxial cylinders. They result, that heavier mixture (vapor-argon) has a low mass fraction of steam in the outlet, and therefore, the thickness of the liquid film, the rate of condensation and the mass flow of liquid are higher for this mixture. Recently Hassaninejadfarahani et al. [5] developed a numerical analysis for laminar film condensation from high air mass fraction steam-air mixtures in vertical tube with constant wall

temperature. They used a finite volume method to the transformed parabolic governing equations in a set of non-linear algebraic equations. Their results included radial-direction profiles of axial velocity, temperature, air mass fraction, as well as axial variation of film thickness, Nusselt number, interface and bulk temperatures, interface and bulk air mass fraction, and proportion of latent heat transfer. The objective of the present work is designed to study the effects of non condensable gas type in laminar film condensation from steam-gas mixture along a vertical pipe.

2. Physical Model

The physical model studied, with the boundary conditions, is shown at the figure 1

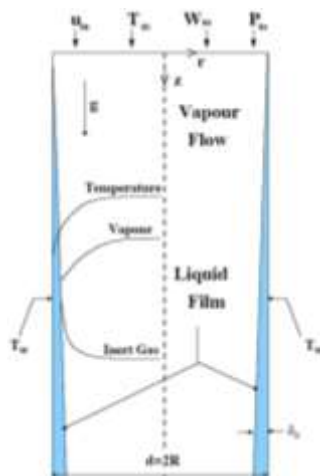


Fig.1: Physical Model

2.1. Liquid Film Equations

The steady laminar momentum and heat transfer in the liquid film can be described in the cylindrical coordinates by the following equations:

– Momentum:
$$\frac{1}{r} \frac{\partial}{\partial r} (r u_l \frac{\partial u_l}{\partial r}) + \rho_l g = 0 \quad (1)$$

– Energy:
$$\frac{\partial}{\partial z} (\rho_l C_{pl} u_l T_l) = \frac{1}{r} \frac{\partial}{\partial r} (r \lambda_l \frac{\partial T_l}{\partial r}) \quad (2)$$

2.2. Gas Flow Equations

The two-dimensional boundary layer flow in the gas side is governed by the following conservation equations:

– Continuity:
$$\frac{\partial}{\partial z} (r \rho_g u_g) + \frac{\partial}{\partial r} (r \rho_g v_g) = 0 \quad (3)$$

– Momentum:
$$\frac{\partial}{\partial z} (\rho_g u_g^2) + \frac{1}{r} \frac{\partial}{\partial r} (\rho_g r v_g u_g) = -\frac{dP_d}{dz} + \frac{1}{r} \frac{\partial}{\partial r} (r u_g \frac{\partial u_g}{\partial r}) + (\rho_g - \rho_{in}) g \quad (4)$$

– Energy:
$$\frac{\partial}{\partial z} (\rho_g C_{pg} u_g T_g) + \frac{1}{r} \frac{\partial}{\partial r} (\rho_g C_{pg} r v_g T_g) = \frac{\partial}{\partial r} (r \lambda_g \frac{\partial T_g}{\partial r}) \quad (5)$$

– Diffusion:
$$\frac{\partial}{\partial z} (\rho_g u_g W) + \frac{1}{r} \frac{\partial}{\partial r} (\rho_g r v_g W) = \frac{1}{r} \frac{\partial}{\partial r} (r \rho_g D \frac{\partial W}{\partial r}) \quad (6)$$

2.3. Boundary And Interfacial Conditions

The boundary conditions for this matching type problem are:

$$z = 0 : \quad u_g = u_{in} \quad T_g = T_{in} \quad W = W_{in} \quad P = P_{in} \quad (7)$$

$$r = R : \quad u_l = v_l = 0 \quad T_l = T_w \quad (8)$$

$$r = 0 : \quad \frac{\partial u_g}{\partial r} = 0 \quad \frac{\partial T_g}{\partial r} = 0 \quad \frac{\partial W}{\partial r} = 0 \quad v_g = 0 \quad (9)$$

The solution from the liquid side and gas side satisfy the following interfacial matching conditions ($r = R - \delta_z$):

- Continuities of velocity and temperature.

$$u_l(z) = u_{g,I} = u_{l,I} \quad T_l(z) = T_{g,I} = T_{l,I} \quad (10)$$

- Continuity of shear stress.

$$\tau_l = \left(\mu \frac{\partial u}{\partial r}\right)_{l,I} = \left(\mu \frac{\partial u}{\partial r}\right)_{g,I} \quad (11)$$

- Heat balance at the interface implying

The total convective heat flux from the film interface to the gas stream can be expressed as follows:

$$Q_l = -\lambda_l \frac{\partial T_l}{\partial r} = -\lambda_m \frac{\partial T_m}{\partial r} + \dot{m}_l h_{fg} = Q_{sen,I} + Q_{Lat,I} \quad (12)$$

At every axial location, the overall mass balance in the gas flow should be satisfied:

$$\frac{\dot{m}_{in}}{2\pi} = \int_0^{R-\delta_z} r \rho_m u_m dr + \int_{R-\delta_z}^R r \rho_l u_l dr \quad (13)$$

3. Numerical Method

In view of the impossibility of obtaining an analytic solution for the non-linear coupling differential equations, the conjugated problem defined by the parabolic systems, equation (1) – (6) with the appropriate boundary conditions are solved by a finite difference numerical scheme. The axial convection terms are approximated by the backward difference and the transversal convection and diffusion terms are approximated by the central difference. Each system of the finite-difference equations forms a tridiagonal matrix equation, which can be solved by the TDMA Method. In the centerline ($r = 0$) of the tube, the diffusional terms are singular. A correct representation can be found from an application of L'Hospital's rule. In this study, the cylindrical coordinate r are transformed into η coordinate system, such that the centre line is at $\eta = 2$ the liquid-mixture interface is at $\eta = 1$, and the wall is at $\eta = 0$. The equations that relate the η coordinate system to the r coordinate system are:

$$\begin{cases} \eta = 2 - \frac{r}{R - \delta_z} & \text{for } 0 \leq r \leq R - \delta_z \\ \eta = \frac{R - r}{\delta_z} & \text{for } R - \delta_z \leq r \leq R \end{cases} \quad (14)$$

Please acknowledge collaborators or anyone who has helped with the paper at the end of the text.

4. Results and Discussion

A study was performed to examine the effect of non-condensable gases (Argon, Air and Neon) during condensation of water vapor inside a vertical tube with length $L=2\text{m}$, diameter $d=2\text{cm}$. The results were obtained for the following operating requirements: inlet vapor mass fraction ($W_{in}=0.8$ and $W_{in}=0.9$), temperature difference between inlet vapor gas mixture and wall $\Delta T=20^\circ\text{C}$, inlet Reynolds number $Re_{in}=2000$ and inlet pressure $P_{in}=1\text{atm}$. The gas-steam mixture is saturated (relative humidity $H_r=100\%$).

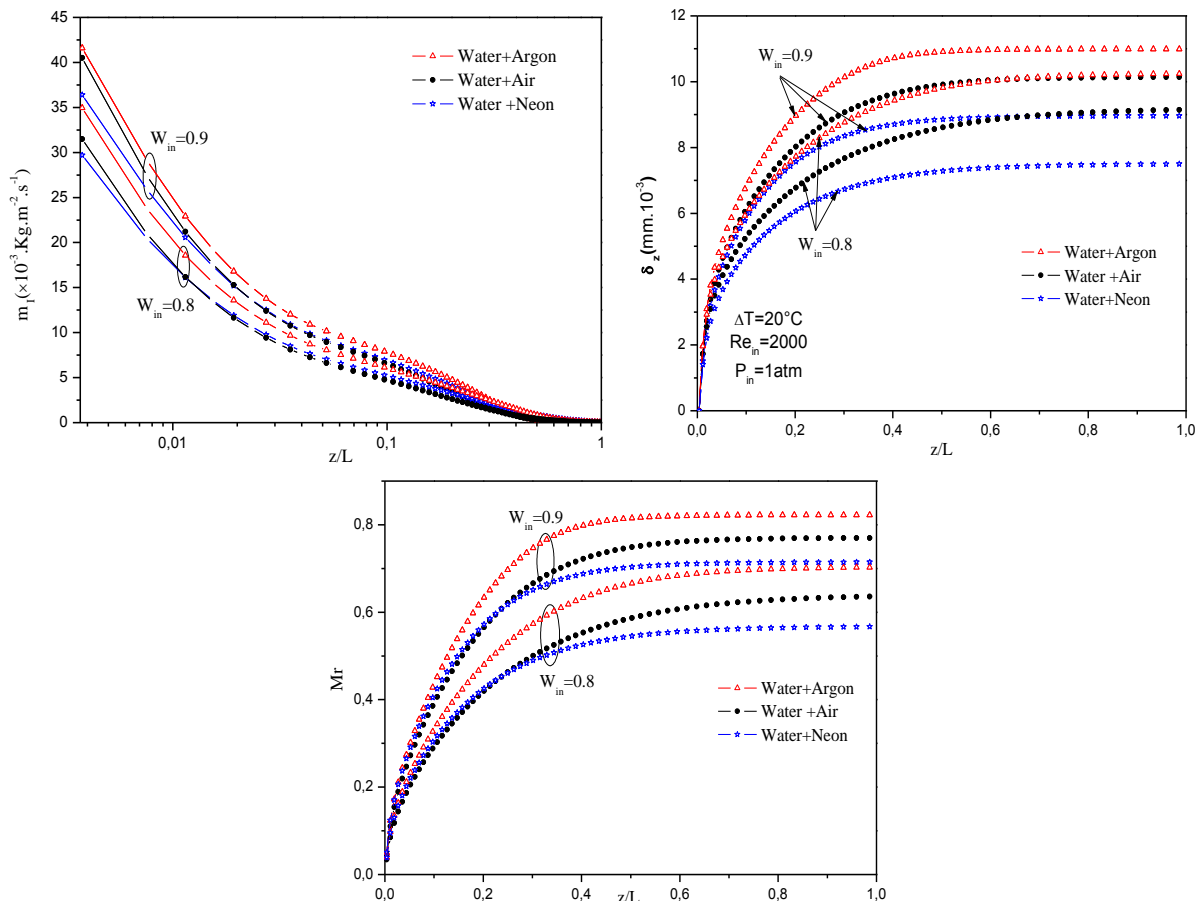


Fig.2: Axial variation of interfacial mass condensation rate (a) liquid film thickness (b) and accumulated condensate rate (c) along the tube for different non-condensable gases.

Fig 2 shows the effect of the concentration and type of gas during steam condensation along a vertical pipe. The variation of interfacial mass condensation rate, liquid film thickness and the accumulated condensate rate along the tube for the different non-condensable gases are shown respectively in figures 2(a), 2(b) and 2(c).

The condensed mass flow decreases very rapidly to 0 for all steam-gas mixtures which means the end of condensation. It should be noted that the condensed mass flow rate and the thickness of the liquid film of the mixture steam-Argon which the heavier (higher molecular weight) is the highest to those of other gas mixtures, which means that the increase the mass density and the decrease of the gas mixture diffusion coefficient causes an increase in Schmidt number which characterizes the flow of the gaseous mixture.

To analyze the mass transfer to the same effects, figure 2 (c) shows the condensed rate Mr . This increase of waning of the fraction of non-condensable gas, i.e. by increasing the fraction of the water vapour. This explains why water vapour condenses better by reducing the amount of non-condensable gas, this finding is illustrated for Argon vapour mixture that has a number of Schmidt higher compared to mixtures of steam-Air and Steam-Neon.

To analyze the heat and mass transfer between the two liquid-vapour phases, figure 3 (a) and (b) represent respectively the temperature variation of the wall and the interface for the different gas mixture. We note that for P_{in} , W_{in} and ΔT are constant, the wall and the interface temperature in the steam mixture Argon are significantly

higher and those of the steam mixture of Neon are lower compared the other mixtures. This is explained by the increase of the molecular weight of the gas, which leads to an increase of the density of the gas mixture and consequently an increase of the saturation pressure and the saturation temperature of the mixture which promotes condensation. This can be also explained by the fact that the conductivity of the Argon gas is lower compared with Air it is even lower compared to the conductivity of the gas of the Neon. Note that the temperature of the wall and of the interface drops sharply along the tube and tends asymptotically towards the wall temperature, this decrease results from the energy expended for the condensation. This indicates that the energy needed to sustain condensation must be from the internal energy of the liquid film.

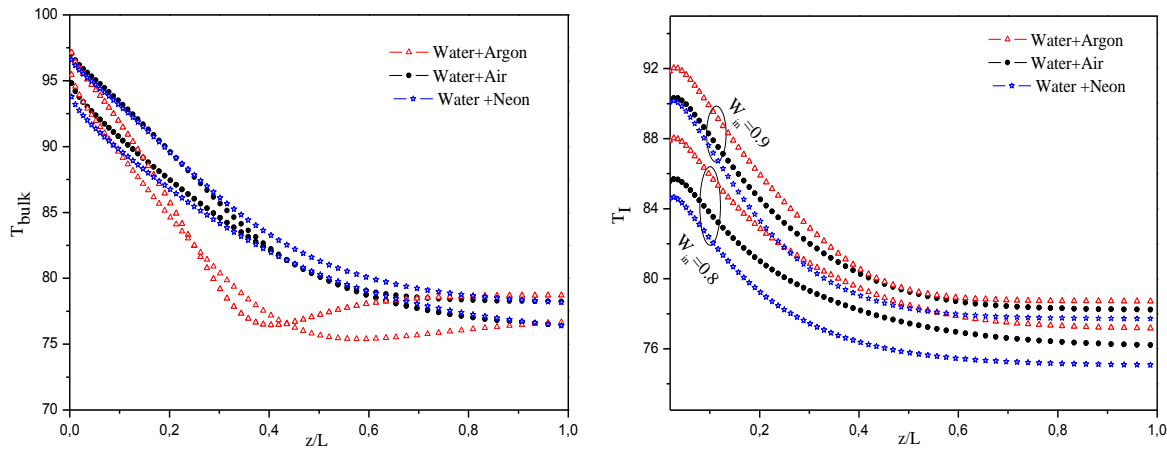


Fig.3: Axial Variation of (A) Bulk Temperature And (B) Interface Temperature Along the Tube For Different Non-Condensable Gases.

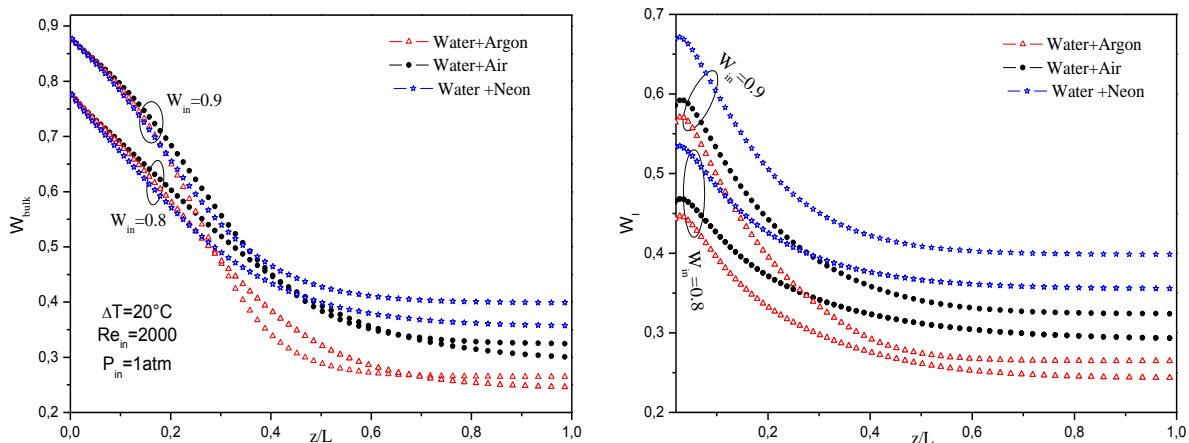


Fig.4: Axial variation of (a) bulk vapor mass fraction and (b) interface vapor mass fraction along the tube for different non-condensable gases.

The influence of the type of non-condensable gas on the bulk mass fraction and interface vapor mass fraction along the tube is illustrated in figures 4 (a) and (b). The mass fraction of vapor interface decreases along the tube for all the non-condensable gases and varies in the same way that the interface temperature figure 3 (b). This variation is due to the thermodynamic equilibrium at the interface between the two liquid-gas phases. Note that the steam-Neon mixture having a lower density gas mixture, the bulk mass fractions and the interface mass fractions are highest, this is due to the increase in pressure and saturation temperature.

Distribution of dimensionless vapor mass fraction for different sections of the tube is shown in figure 5(a). The water vapor mass fraction increases from the interface toward the centre of the tube and also decreases from the inlet of tube where it becomes almost constant. Increasing the molar mass of the gas causes a decrease in the final saturation concentration, where the Argon-steam mixture being the lowest, this is confirmed

by fig 4. Figure 5(b) shows the variation of dimensionless velocity of steam for different section of the tube. Moving away from the tube inlet and with increasing of z^* , it is found that the mixture velocity decreases from the symmetry axis of the tube to approach a value of the liquid phase at the liquid-vapor interface.

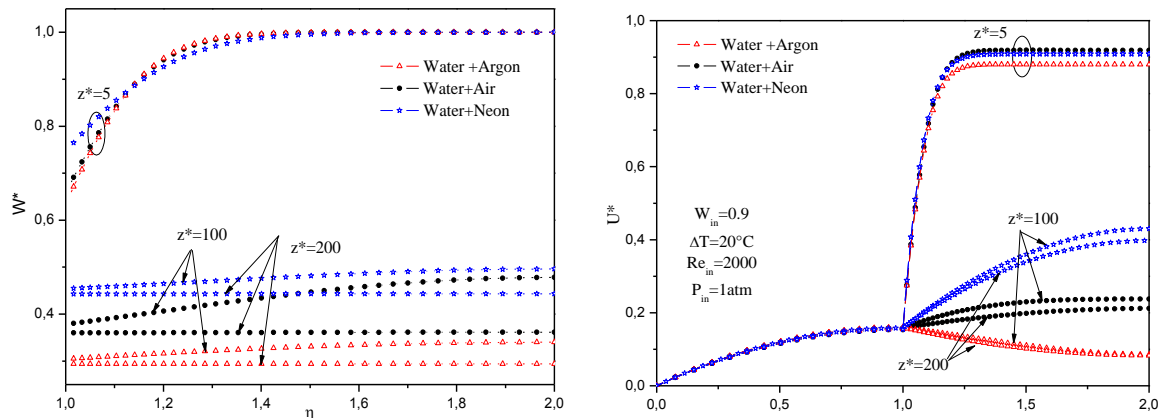


Fig.5: Dimensionless Vapor Mass Fraction Profiles (A) and Dimensionless Axial Velocity (B)

In the liquid phase, the velocity profiles continue to decrease until the tube wall, and they become almost independent of z^* where they are confounded for the three non-condensable gas. This trend is due to the transfer of mass of mixture to the liquid, which implies that the mixture loses mass which is gained by the liquid film. A boundary layer is seen from the mixing zone to the liquid-vapor interface, the thickness of this boundary layer increases with increasing z^* . We also observe that the steam velocity in the presence of non-condensable gas Argon is lower compared to the other gas mixtures; this is confirmed by fig 4(a).

5. Conclusion

A numerical simulation was presented for laminar film condensation of vapor-gas mixtures in the presence of non-condensable gases (Argon, Air and Neon) in axisymmetric downward flow in a vertical tube, based on the complete two phase parabolic governing equations. The main conclusions from the study are summarised below. Results were obtained for steam-air mixtures by specifying the following values at the inlet to the tube: Reynolds number, pressure inlet, temperature difference, and relative humidity. The non-condensable gas type plays an important role on the intensity of heat and mass transfer which occur between the two phases. Thereby an increase of the molar mass of gas leads to an increase of the mixture density, its saturation temperature, wall temperature and a decrease of the saturated vapor concentration. Therefore, the heaviest mixture (steam-Argon) presents the lowest vapor mass fraction in tube exit.

6. References

- [1] M.Siddique, M.W. Golay, M.S. Kazimi. Theoretical modelling of forced-convection condensation of steam in a vertical tube in the presence of a noncondensable gas, *Nuclear Technology*, 106, 202-215, 1994.
- [2] S. Oh, S.T. Revankar, Effect of noncondensable gas in a vertical tube condenser, *Nuclear Engineering and Design*, 235, No 16, 1699-1712, 2005.
<https://doi.org/10.1016/j.nucengdes.2005.01.010>
- [3] Y. El Hammami, M. Feddaoui, T. Mediouni, & A. Mir Numerical study of condensing a small concentration of vapour inside a vertical tube *Heat and Mass Transfer*, 48: 1675-1685, 2012.
<https://doi.org/10.1007/s00231-012-1011-0>
- [4] L.Merouani, B.Zeghamati, Belhamri A. september, Numerical modelling of convective vapour condensation with non-condensable gases between two coaxial vertical cylinders. *The canadian journal of chemical engineering*, Vol 91, pp.1597-1607, 2013.
<https://doi.org/10.1002/cjce.21747>
- [5] F. Hassaninejadfarahani, M.K. Guyot, S.J. Ormiston Numerical analysis of mixed convection laminar film condensation from high air mass fraction steam-air mixtures in vertical tubes. *International Journal of Heat and Mass Transfer*, 78 170-180, 2014.
<https://doi.org/10.1016/j.ijheatmasstransfer.2014.06.047>