



Approximate equations for film condensation in the presence of non-condensable gases



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ABSTRACT

Non-condensable gases greatly influence vapor condensation, resulting in a substantial reduction in the condensation heat transfer coefficient. Although extensive analytical and numerical investigations of condensation heat transfer in the presence of non-condensable gases have been done, most of the solutions are quite complicated. Based on a thermodynamics analysis, when the vapor is not close to its critical state and the mass fraction of the non-condensable gas in the main stream is less than 0.1, an equation which relates the vapor/gas-liquid interface parameters and the main stream parameters was developed in the present work. For forced convection film condensation heat transfer on the outside surface of a horizontal tube, the present equation combining with an existing analytical solution as well as a heat transfer correlation given by previous investigators, gives the heat flux and the interfacial parameters of the water vapor-air mixture. The results show that the predicted heat flux is in good agreement with experimental data available in the literature and that even a small amount of air substantially reduces the heat flux. An algebraic equation set is given to calculate free convection film condensation on a vertical flat surface, which associates the interfacial and main stream parameters, an integral solution and an analytical solution given by previous investigators. The calculated results are in good agreement with experimental data in the literature.

1. Introduction

Dropwise condensation and film condensation are the two main forms of condensation. Generally, the heat transfer coefficient for dropwise condensation is higher than that of film condensation while film condensation is more stable and common in practice. Thus, this study focuses on film condensation. Non-condensable gases in the vapor flow will substantially reduce the condensation heat transfer since the vapor mass transfer to the surface will be weakened due to the non-condensable gas which gathers at the vapor-liquid interface and forms a gas boundary layer. Studies have shown that when water vapor contains 0.5% mass fraction of air, the condensation heat transfer efficiency is reduced by 50% or more [1]; therefore, much attention has been focused on the influence of non-condensable gases on the vapor condensation heat transfer characteristics.

There have been extensive theoretical and numerical studies of condensation heat transfer. In 1916, Nusselt [2] studied the condensation of pure vapor and developed an analytical heat transfer solution for laminar film condensation of pure vapor based on the assumption that the main thermal resistance to the condensation was from the vapor

side. Colburn and Drew [3] qualitatively analyzed the gas boundary layer to study vapor condensation heat transfer in the presence of non-condensable gases. Sparrow et al. [4,5] gave a set of equations for the gas boundary layer for vapor condensation for free convection along a vertical plate and forced convection on a horizontal plate in the presence of non-condensable gases, including the continuity equation, momentum equation and mass transfer equation. Then, these equations were solved numerically with the results showing that the impact of non-condensable gases on the free convection condensation was much larger than that on forced convection condensation. Based on the equations for the gas boundary layer, Rose [6] used assumed boundary layer velocity and non-condensable gas concentration distributions in the integral method to calculate the free convection condensation heat transfer of vapor-gas mixtures along a vertical plate. Their approximate integral solution for the thermal resistance showed good agreement with the numerical solution of Sparrow et al. [4]. Rose [7] also used a similarity solution to obtain the approximate equations for vapor-gas mixtures for forced convection condensation on a flat plate surface and on the outside surface of a horizontal tube, but the solution was somewhat complicated. Dehbi et al. [8] proposed a self-contained

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Nomenclature

d	tube diameter, m
D	diffusivity, m^2/s
g	gravity, m/s^2
k	thermal conductivity, $W/(m\ K)$
L	vertical plate length, m
m	vapor mass flux at the condensing surface, $kg/(m^2\ s)$
M	molecular weight
Nu	Nusselt number
P	pressure, Pa
q	heat flux, W/m^2
r	latent heat, J/kg
Re	Reynolds number
Sc	Schmidt number
T	temperature, K
u	velocity component in the x-direction, m/s
U	free-stream velocity, m/s
v	velocity component in the y-direction, m/s
W	mass fraction of the non-condensable gas

x	distance measured along the surface, m
y	distance measured normal to the x-direction, m

Greek symbols

β	$(m/\rho U_{main})Re^{1/2}$
δ	boundary layer thickness, m
μ	dynamic viscosity, $kg/(m\ s)$
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3

Subscripts

c	condensate
g	non-condensable gas
main	main stream
sat	saturation
v	vapor
w	wall
0	two-phase interface

model to predict the condensation heat transfer inside a vertical condenser tube with non-condensable gases. Li and Peng [9] developed a mathematical model of local heat transfer coefficient to study laminar film condensation in the presence of non-condensable gases over a horizontal tube. Liao et al. [10] theoretically analyzed mixed natural and forced convection of steam–gas along a vertical surface and proposed a criterion for steam–gas mixtures for engineering calculations to predict the transition from natural convection to mixed convection. Denny and South [11] analytically investigated laminar film condensation of vapor–gas mixtures at the forward stagnation point of a horizontal cylinder. Park et al. [12] experimentally investigated film condensation with and without a non-condensable gas on a vertical wall. Then, Park et al. [13] proposed a correlation of vapor-side heat transfer coefficients for condensation of a steam–air mixture on a vertical surface. Ge et al. [14] experimentally investigated the steam condensation with CO_2 on a horizontal tube with the results showing that the heat transfer coefficient decreases by nearly 99% when the CO_2 mass fraction reaches 89.7%. El Hammami et al. [15] numerically simulated water vapor condensation inside a vertical tube with a high concentration of air with the predicted Nusselt number and local condensation heat transfer coefficient in good agreement with the results of Dharma Rao et al. [16]. Chen and Lin [17] numerically analyzed forced convection condensation heat transfer of water vapor–gas mixtures on the outer surface of a horizontal tube using the finite volume method to solve the boundary layer equations with the results in good agreement with the numerical solutions of Yang [18]. The results also showed that the local Nusselt number and the film thickness decreased as the wall temperature increased. Shang and Zhong [19] numerically investigated laminar free film condensation of water vapor in the presence of air, and confirmed that the presence of the non-condensable gas is a decisive factor in decreasing the heat and mass transfer of the film condensation. Merouani et al. [20] numerically investigated the forced convection condensation of vapor in the presence of non-condensable gases between two coaxial vertical cylinders and concluded that the total heat flux at the inner wall increased with increasing molar mass of the non-condensable gas and the inlet vapor concentration. The forced convection condensation of water vapor on the inner wall of a 1 mm horizontal tube with and without non-condensable gases was investigated numerically by Yin et al. [21]. They found that the mass transfer rate decreased sharply along the vapor–liquid interface due to the non-condensable gas and analyzed the influence of the gas thermal conductivity on the heat transfer coefficient. Yin et al. [22] gave a three dimensional simulation

of laminar film condensation heat transfer of water vapor and oxygen in six horizontal minichannels with different cross sectional shapes using the volume of fluid method. The results showed a substantial reduction of the heat transfer coefficient by the oxygen for inlet volume fractions up to 3%. Recently, Huang et al. [23] reviewed the studies of vapor condensation heat transfer in the presence of non-condensable gases.

In summary, extensive analytical and numerical investigations of vapor condensation heat transfer in the presence of non-condensable gases have been performed. Approximate solutions were obtained for free convection film condensation along a vertical surface and for forced convection along a vertical surface and on the outer surface of a horizontal tube in the presence of non-condensable gases when the molecular weight of the non-condensable gas was greater than that of the vapor. However, the solutions are quite complicated. This study develops a theory that simplifies the solutions of vapor condensation heat transfer in the presence of non-condensable gases.

2. Thermodynamic analysis

During condensation, when the pressure of the gas mixture in the mainstream is much less than its critical pressure, the vapor and the non-condensable gas can be modeled as an ideal gas mixture. Furthermore, at the vapor and liquid interface, the vapor is saturated; thus, the interfacial mass fraction of the non-condensable gas can be expressed by Dalton's law and the ideal gas equation of state as [7,24]:

$$W_0 = \frac{P_{main} - P_{sat}(T_0)}{P_{main} - (1 - M_v/M_g)P_{sat}(T_0)} \quad (1)$$

When the mass fraction of the non-condensable gas in the main stream vapor is less than 0.1, the difference between the main stream pressure and the saturated pressure of the vapor based on the main stream temperature is very small; therefore:

$$P_{main} - P_{sat}(T_{main}) \ll P_{main} \quad (2)$$

Using Eq. (2), P_{main} can be replaced by $P_{sat}(T_{main})$ and Eq. (1) can be written as:

$$\frac{1}{W_0} = \frac{P_{main}M_v/M_g}{P_{sat}(T_{main}) - P_{sat}(T_0)} + 1 - \frac{M_v}{M_g} \quad (3)$$

According to the Clapeyron equation:

$$\frac{dP}{dT} = \frac{r}{T\Delta v} \quad (4)$$

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