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Experimental and theoretical investigation on condensation inside a horizontal tube with noncondensable gas

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A B S T R A C T

An experimental and theoretical investigation on condensation from steam/air mixture was carried out in a horizontal tube with a large range of noncondensable gas fractions and inlet gas Reynolds number. A theoretical model is developed based on Liao's modified diffusion layer theory including the roughness and suction effect. The model predictions were compared with experiment and literature data. The effect of noncondensable gas on overall heat transfer performance was studied. Moreover, the local parameters such as temperatures, gas concentrations and heat transfer coefficients were analyzed along the tube. The predicted values agree well with the experiment and literature data, showing the validation of theoretical model. The average heat transfer coefficient decreases with the increase of inlet noncondensable gas fraction and the decrease of inlet mass flux. The heat transfer rate increases with the increase of inlet pressure, while the heat transfer coefficient shows an opposite trend. The variation tendency of bulk temperature is consistent with that of bulk noncondensable gas fraction. For stratified flow, the heat transfer coefficients at the top part are higher than that at the bottom. But the difference is gradually closing especially at higher inlet noncondensable gas fractions due to the different distributions of thermal resistances. The heat flux decreases along the tube especially near the outlet. Meanwhile, increasing the inlet mass flux could significantly enhance the heat flux.

1. Introduction

Horizontal condensation heat exchanger is one of the widely used heat exchangers in many industrial processes because of its high removal capability, such as nuclear industry, seawater desalination industry, air conditioning and refrigeration industry and chemical process industry. The typical construction is the fixed tubesheet, shell-and-tube heat exchanger, with refrigerant condensing on the outside of the tubes, and water flowing inside the tubes [1]. However, on some specific occasions, only in-tube condensation can be used due to different reasons. For example, during the production of pure terephthalic acid (PTA), a series of horizontal condensers is used to condense mixed vapor evaporated from oxidation reactor. Titanium tubes are used for in-tube condensation due to the strong corrosivity of acetic acid in mixed vapor. Moreover, high fractional air involved in mixed vapor serves as a noncondensable (NC) gas. The mass fraction of noncondensable gas in these condensers can reach up to 40%, which makes designing this type of condensers difficult.

It is well known that the presence of small amount of noncondensable gas significantly reduces the performance of condensation. As steam condenses on the liquid surface, the noncondensable gas accumulates at the liquid–gas interface and forms a gas layer which adds mass transfer resistance. Since Othemer [2] initially found out this phenomenon, many other researchers have investigated this problem by experimental and theoretical approaches. For natural convection condition, Uchida et al. [3] performed experiments on steam/gas condensation on the outside wall of vertical tube. Al-Diwany and Rose [4] experimentally measured heat transfer rate for film condensation on a vertical surface in the presence of several noncondensable gases. Dehbi [5] conducted his experiments over a vertical and internally cooled copper cylinder enclosed in a large pressure vessel. Liu et al. [6] measured condensation heat transfer coefficients on a vertically mounted smooth tube to evaluate the heat removal capacity of a passive cooling unit. For forced convection condition, most of the experiments were carried out in a vertical tube. Vierow [7] measured local condensation heat transfer coefficient along a vertical tube and correlated his results in terms of a degradation factor. Siddique et al. [8] obtained a correlation in which condensation Nusselt number was correlated with mixture Reynolds number, Jakob

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Nomenclature

b_h	heat transfer blowing parameter
d	tube diameter, m
D_{ab}	diffusion constant, m^2/s
f	friction factor
G	mass flux, kg/(m^2 s)
Ga	Galileo number
h	heat transfer coefficient, W/(m^2 K)
h_{fg}	enthalpy of vaporization, J/kg
j_g^*	dimensionless gas velocity
k	thermal conductivity, W/(m K)
k_c	condensation thermal conductivity, W/(m K)
m_c''	condensation mass flux, kg/(m^2 s)
$\dot{m}_s$	mass flow rate, kg/s
M_s	steam molecular weight
M_g	air molecular weight
Nu	Nusselt number
Pr	Prandtl number
p_t	total pressure, Pa
Q	heat transfer rate, W
q	heat flux, W/m^2
R	gas law constant = 8.31451
R_w	heat transfer resistance, (m^2 K)/W
Re	Nusselt number
Sc	Schmidt number
Sh	Sherwood number
St	Stanton number
T	temperature, K
U	overall heat transfer coefficient, W/(m^2 K)
u	velocity, m/s
x	vapor quality
x_g	noncondensable gas mole fraction
$\bar{x}_g$	log mean mole fraction
X_{tt}	Martinelli parameter

Greek symbols

β	ratio of gravitational force to viscous force
μ	dynamic viscosity, Pa s
ω	noncondensable gas mass fraction
ρ	density, kg/m^3
ε	liquid film thickness

Subscripts

b	bulk
c	in-tube condensation
cd	gas region condensation
co	coolant
f	film
i	interface; inner
in	inlet
l	liquid
m	gas mixture
o	outer
s	convection
v	vapor
w	wall

Abbreviations

an	annular
exp.	experimental
NC	noncondensable gas
sat	saturation
strat	stratified

number and noncondensable gas mass fraction. Kuhn [9] developed the degradation factor considering the interfacial shear thinning effect and waviness effects. Lee and Kim [10] performed experiments in a vertical tube with small inner diameter to study the effect of interfacial shear. Instead of using the jacket cooling method, Oh and Revankar [11] conducted steam/air condensation experiments with secondary pool boiling. Recently, Ma et al. [12] experimentally studied the heat transfer characteristics of dropwise condensation on a vertical superhydrophobic plate for a variety of noncondensable gas concentration.

The theoretical analysis of heat and mass transfer during condensation in presence of noncondensable gas has involved either boundary layer method or heat and mass analogy method. The boundary layer method is a technique solving the governing equations for both the gas-mixture and liquid film regions. Sparrow and Lin [13] firstly analyzed the film condensation on an isothermal vertical plate for a stagnant vapor–gas mixture. From then on, researchers have investigated this phenomenon by using boundary layer method for both free and forced convection condensation [14–18]. However, due to the significantly long computational time, boundary layer method is commonly applied in steady-state and two-dimensional cases.

The heat and mass analogy model follows the general methodology of Colburn and Hougen [19]. The principle of this method is the balance between the heat transferred from vapor–gas mixture and the heat transferred through the condensate film. Since Colburn and Hougen, there have been many researchers on the heat and mass transfer analogy method, including Corradini [20], Wang and Tu [21], No and Park [22], Maheshwari et al. [23] and Chantana and Kumar [24]. Recently, Ambrosini et al. [25] focused on some of the different forms of the analogy between heat and mass transfer and quantified the related differences in the application to real experimental data. de la Rosa et al. [26] proposed an alternative formulation for the suction factor under turbulent condensation showing more appropriate than Bird's original formulation. Nevertheless, this iterative solution method requires convergence of two unknown variables, the interface temperature and gas mole fraction, resulting in the intractability to use. Peterson et al. [27] developed a diffusion layer model where the mass transfer coefficient was converted into condensation thermal conductivity by using Clausius–Clapeyron equation. Then the temperature difference between mixture bulk and interface became the only driving force for both heat and mass transfer. As a more efficient iterative solution method, diffusion layer model was adopted by Hasanein et al. [28], Herranz et al. [29] and Liao and Vierow [30].

Nevertheless, due to the condensate stratification and multidimensional nature, the mechanism of condensation in the presence of noncondensable gas in horizontal tubes have not yet well understood compared with the extensively investigations on condensation for the vertical orientation. From the aspect of experiments, Wu and Vierow [31] studied the heat transfer and fluid flow phenomena in a horizontal condenser tube, together with the heat transfer reduction effect of the noncondensable gas. They found that the condensation heat transfer coefficients on the tube top were much greater than the values at the bottom and the noncondensable gas significantly reduced the heat transfer rate. Caruso et al. [32] conducted an experiment where steam–air mixtures condensate inside near horizontal tubes with air-cooled externally. The influence of the air mass fraction, the inlet flow rate and the tube diameter had been analyzed. Meanwhile, very few researchers have developed models for predicting the heat transfer performance of condensation in horizontal tubes in presence of noncondensable