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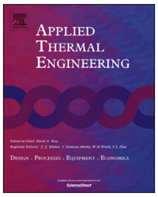

Research paper

Condensation of a hydrocarbon in the presence of a non-condensable gas: Heat and mass transfer

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HIGHLIGHTS

- Condensation of a hydrocarbon in the presence of non-condensable gases was studied.
- Mechanism of condensation heat and mass transfer was analyzed.
- Non-condensable gas decreases heat transfer due to mass transfer resistance increase.
- Vapor-shear enhances condensing by good mixing and thinning, ripping condensate film.
- Newly developed heat transfer correlations predict experimental data well.

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ABSTRACT

This paper presents experimental study for horizontal tubeside and shellside condensation of kerosene in the presence of a wide range of non-condensable gas. Using the heat and mass transfer analogy model, the heat and mass transfer mechanism of the condensate film and the vapor-gas phase has been analyzed. Convective condensation of hydrocarbon mixtures in the presence of non-condensable gases in shear-controlled flow is strongly dependent on the diffusion of the vapor molecules through the non-condensable gas onto the condensate film. The mass transfer resistance increases as the non-condensable gas concentration increases, and the interfacial temperature decreases as the less volatile components condense. Our experimental results demonstrate that the heat transfer performance is influenced by the non-condensable gas, vapor, condensate Reynolds numbers, Schmidt number and Jacob number. Comparisons of a newly developed heat transfer correlation based on the heat and mass transfer analogy with experimental data show a good agreement. The correlations can be applied to tubeside and shellside condensation of mixtures with non-condensable gases.

1. Introduction

Hydrocarbon condensation in the presence of non-condensable gases commonly occurs in petrochemical industry processes. The heat exchanger used for hydrogenation in refineries has a complicated heat transfer process and involves condensation of multi-component vapors mixed with non-condensable gases. The kerosene vapor condensation in the presence of air was studied for the objective of developing a practical heat transfer design method for predicting condensation heat and mass transfer of hydrocarbons in the presence of a non-condensable gas.

A large amount of investigation for condensation of vapor mixtures with and without non-condensable gases has been reported. Several typical condensation heat transfer models, such as stagnant film model, diffusion layer model, and heat and mass transfer analogy model, have been established. Othmer [1] conducted experiments and calculated the condensation heat transfer rate on a 1.22 m long copper tube of 76.2 mm diameter placed in a stagnant environment. An empirical correlation was derived relating the heat transfer coefficient to air/steam partial pressure ratio and temperature difference between the cooled surface and stagnant air/steam mixture. The author found that the heat transfer coefficient would decrease by 50% when a little amount of air (0.5%) was added to the steam chamber.

Uchida et al. [2] performed experiments for steam/gas condensation on the outer surface of a vertical tube under natural

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Nomenclature

C_p	specific heat, J/(kg K)
d	tube inner diameter, m
D	diffusion coefficient, cm^2/s
h	heat transfer coefficient, W/(m^2 K)
Ja	Jacobe number
k	thermal conductivity, W/(m K)
w	mass flow rate, kg/s
M	molecular weight, g/mol
Nu	Nusselt number
P	pressure, N/m^2
q	heat flux, W/m^2
Re	Reynolds number
Sc	Schmidt number
t, T	temperature, K
V	molecular volume, cm^3/mol
x	mass fraction

Greek symbols

Δq	i section heat flux, W/m^2
δ	tube wall thickness, m

Greek symbols

λ	latent heat of condensation, J/kg
μ	viscosity, N/(m^2 s)
ρ	density, kg/m^3

Subscripts

air	air
b	bulk flow
c	condensing
i	inner wall tube, i section
k	kerosene
l	condensate liquid
o	outer wall tube
r	reference point
sat	saturation
t	total
v	vapor
w	tube wall
x	position along the flow direction

convection condition. The air mass fraction ranged between 0.1 and 0.95. A correlation for the condensing heat transfer coefficient was developed including the effect of the air mass fraction in a mixture. The stagnant film model has been applied and developed by many researchers. Corradini [3], and Kim and Corrradini [4], studied the condensation of mixtures in nuclear reactors. Panchal and Bell [5] investigated the condensation thermal energy conservation used in open circulation ocean systems. To obtain the temperature at the vapor–liquid interface however, a numerical approach is required to solve several nonlinear equations coupled in the stagnant film model. Yao and Ghiaasiaan [6] and Yao et al. [7] proposed three important rules of the numerical solution, and established the theoretical approach for stagnant film model application. Since the changing physical properties in condensation, the effect of inertia, turbulence in the film, and superheated vapor are ignored in the stagnant film model, the calculated condensation heat transfer coefficient is lower than the experimental data.

In 1934, Colburn and Hougen [8] indicated that the condensation of a mixture depends upon the diffusion of vapor molecules through the gas mixture. The problem involving mass diffusion and heat transfer must be considered and solved simultaneously. They proposed a method for calculating the value of ($U\Delta t$) which involved equating, the heat transferred through the condensate, the tube wall, and the cooling-water film to the sum of the sensible heat transferred through the vapor-gas layer and the latent heat, which corresponds to the amount of vapor transferred by diffusion. This method requires the temperature at the vapor–liquid interface and the corresponding vapor pressure of the condensate. Over eight decades, the Colburn–Hougen method has been studied and simplified by many researchers and engineers for practical application in the industrial condenser design.

Peterson [9] presented a theoretical basis for the form of the Uchida's correlation [2]. The analysis presented in their paper shows that the correlation can generate substantial error in predictions of condensation rates when the bulk gas pressure departs significantly from 1 atm. Hasanein et al. [10] proposed a simple boundary layer model based on experimental results and the mass diffusion analysis. Herranz et al. [11] developed a model based on the diffusion layer theory and on the use of the heat and mass transfer analogy method. The condensate film resistance and the wave of vapor–liquid interface have been included in the authors' model.

Kuhn et al. [12] obtained a large amount of experimental data of local heat transfer for condensation in the presence of non-condensable gas inside a vertical tube. Authors presented three different correlations, implementing the degradation factor method, diffusion layer theory, and the mass transfer conductance model. Liao and Vierow [13] indicated that the original diffusion model is valid for gases having a molecular weight close to that of the vapor or low vapor mass transfer rates, but serious error may arise if a large gradient in the gas concentration exists across the diffusion layer. The authors presented a generalized model which included the effect of variable mixture molecular weights across the diffusion layer on mass diffusion and the effect of fog formation on the sensible heat.

Ren et al. [14] studied condensation of steam/air mixtures in a horizontal tube with a large range of the non-condensable gas mass flow velocities. A theoretical model was developed based on Liao's modified diffusion layer theory [13] including the roughness and the suction effect. The predicted values agreed well with their experimental and literature data. The average heat transfer coefficient decreased with increasing inlet non-condensable gas fraction, and decreasing inlet total mass flux.

Heat and mass transfer analogy models have a wide application for determining the condensation heat transfer coefficient for mixtures with and without non-condensable gases. Maheshwari et al. [15] developed a theoretical approach for studying the local heat transfer coefficient of condensing vapor in the presence of non-condensable gas. Two-phase heat transfer was analyzed using an annular flow pattern with a liquid film at the tube wall and a turbulent flow in the gas/vapor core. Their model incorporates the Nusselt equation with the McAdams modifier [16], and the Blangette model [17] for determining the film heat transfer coefficient, and Moody and Wallis' correlations [18,19] to account for film effect on the gas/vapor boundary layer.

Tandon et al. [20], and Doerr et al. [21] studied the condensation of refrigerant mixtures inside plain tubes. They found that the heat transfer was lower for refrigerant mixtures due to the