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Research Paper

Numerical investigation on flow condensation of zeotropic hydrocarbon mixtures in a helically coiled tube

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HIGHLIGHTS

- A numerical model was established to study the condensation heat transfer characteristics.
- Flow condensation heat transfer characteristics were analyzed.
- The effect of different component ratio on heat transfer characteristic was studied.
- A new flow pattern transitional line for annular/non-annular flows was proposed.
- An improved heat transfer correlation was proposed.

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ABSTRACT

A numerical investigation was carried out to study the condensation flow and heat transfer coefficient of methane/propane and ethane/propane mixtures in a helically coiled tube. Two-phase heat transfer simulations had been performed at saturation pressures of 0.3–3.7 MPa with mass flux of 200, 300, 400 kg/(m^2 s) and heat flux of 5 kW/m^2. The effects of mass flux, saturation pressure, vapor quality and component ratios on the heat transfer coefficient were examined. In addition, annular/non-annular flow patterns were obtained by numerical simulations and experiments, and a new flow pattern transitional line for annular/non-annular flows was proposed. Meanwhile, the results were compared with the existing condensation heat transfer correlations, and the improved heat transfer correlation was proposed and well coincided with the data with a mean absolute relative deviation (MARD) of 9.2%.

1. Introduction

Nowadays, natural gas has been widely used because of its characteristics of clean energy. Liquefied natural gas technology and equipment are gradually attracting interest, spiral wound heat exchanger (SWHE) is an important component of natural gas liquefaction, and natural gas is mainly composed of hydrocarbon mixed refrigerant composition, therefore, two-phase coefficients of heat transfer for natural gas liquefaction in a helical tube is a crucial parameter for the design of SWHE.

Natural gas is mainly composed of methane, ethane and propane, which are zeotropic mixtures. Many researchers have studied the characteristics of heat transfer for zeotropic mixtures. Smit et al. [1] investigated the heat transfer coefficients during the condensation of zeotropic refrigerant mixtures R-22/R-142b at different mass fractions in a smooth horizontal tube. It was found that the heat transfer coefficients decreased as the mass fraction of R-142b increased. Afroz et al. [2] investigated the heat transfer coefficients of DimethylEther and CO_2/DimethylEther. The results showed that the heat transfer coefficients decreased with the increase of mass fraction of CO_2 in the mixture, and the effect of mass transfer resistance on the heat transfer was lower at the high refrigerant mass flux. Jin et al. [3] presented a prediction model for the characteristics of condensation heat transfer for zeotropic refrigerant mixture R134a/R123 inside horizontal smooth tubes, and well validated by comparison with the experimental data. Wang et al. [4] investigated the characteristics of condensation heat transfer for zeotropic mixtures R1234yf/R32 (mass fractions:0.52/0.48, 0.77/0.23) inside a horizontal tube. Taking the mass transfers at both vapor side and liquid side into consideration, it was presented that the main mass transfer resistance was at the vapor side, while the mass transfer resistance at the liquid film had relatively less influence on the heat transfer coefficient, and a prediction model for evaluating the

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Nomenclature

Cp	specific heat at constant pressure, J/(kg K)
d	inside diameter of tube, m
D	the curvature diameter, m
Fr	Froude number, $Fr = G^2/(\rho_l^2 gd)$
G	mass velocity, kg/(m^2 s)
g	gravity acceleration, m/s^2
h	heat transfer coefficient, W/(m^2 K)
h_{film},h_g'	the liquid film, gas core heat transfer coefficient, respectively, W/(m^2 K)
i	specific sensible enthalpy, J/kg
i_{lg}	latent heat, J/kg
J_G	dimensionless gas velocity, $J_G = Gx/\sqrt{dg\rho_g(\rho_l-\rho_g)}$
J_G^T	transitional dimensionless gas velocity
$MARD$	mean absolute relative deviation
P	pressure, Pa
Pr	Prandtl number
q	heat flux, W/m^2
Re	Reynolds number, $Re = Gd/\mu$
Re_{lo}	liquid-only Reynolds number, $Re_{lo} = Gd/\mu_l$
r	positive numerical coefficient
S	mass source due to phase change, kg/(m^3 s)
Su_g	Suratman number, $Su_g = \rho_g\sigma d/\mu_g^2$
T	the temperature, °C
u	velocity, m/s
We	Weber number, $We = G^2d/(\rho_g\sigma)$
We^*	modified Weber number
X_{tt}	Lockhart-Martinelli parameter
x	vapor quality
Z	sensible heat ratio

Greek symbols

α	volume fraction
δ	the liquid film thickness, m
λ	thermal conductivity, W/(m K)
μ	molecular dynamic viscosity, Pa s
μ_t	turbulent viscosity, Pa s
ρ	density, kg/m^3
Φ	heat and mass transfer resistance in vapor core for mixtures, K/(m^2 W)
κ	interface curvature, m^{-1}
θ	percentage of points predicted within ±20% range
σ	surface tension, N/m

Subscripts

eff	effective
exp	experiment
g, l	vapor phase and liquid phase, respectively
lo	liquid only
pred	predicted
red	reduce
sim	simulation
sat	the saturation condition
so	Soliman (1982) modified Froude

characteristics of heat transfer was constructed. Ghim et al. [5] investigated condensation heat transfer for R245fa, n-pentane, and their mixture in a straight horizontal smooth tube, and the condensation heat transfer data of pure components R245fa and n-pentane were well predicted by Shah's correlation [6]. And a modified Shah's correlation with Bell & Ghaly correction well predicted the measured data within mean absolute error of 10.2%. Cavallini et al. [7] conducted an experiment investigation on condensation of zeotropic mixtures of R-125/R-236ea (mass fractions:0.3/0.7, 0.46/0.54, 0.64/0.36) in a tube-in-tube heat exchanger. They preferred a film method by Colburn and Drew to predict mass transfer thermal resistance rather than Silver [8] and Bell & Ghaly method [9], and predicted the data with the mean deviations less than 10%. Deng et al. [10] numerically studied the effects of heat and mass transfer resistances on the condensation process with equilibrium and non-equilibrium models. It was found that the non-equilibrium models gave better predictions than other equilibrium models, and the mass transfer resistance in the vapor phase had a significant influence on the condensation length.

For hydrocarbon mixture refrigerants. Thonon and bontemps [11] presented a study on the condensation heat transfer of pentane, butane, propane and mixtures (butane/propane) in a compact welded plate heat exchanger. They found that mass transfer had a significant effect on the heat transfer during condensation for the mixtures. In addition, a lower pressure could give higher heat transfer coefficient. Chang et al. [12] investigated the performance of a heat pump system with hydrocarbon refrigerants. It was found that the hydrocarbon refrigerant mixtures showed significant degradation in heat transfer coefficient. This depended on nonlinear physical properties and mass transfer resistance caused by composition variations near the vapor-liquid interface during the condensation process. Wen et al. [13] investigated the condensation heat transfer behavior of R-600, R-600/R-290 (50 wt.%/50 wt.%) and R-290 in the three-line serpentine small-diameter (2.46 mm) tube bank. They found that the heat transfer coefficients between R-600/R-290 and pure component were approximately the same, and Dobson and Chato's correlation [14] provided the best prediction for the average heat transfer coefficients with an average standard deviation of 12.8%. Maråk [15] investigated the characteristics of condensation heat transfer for methane and binary methane mixtures in small vertical channels with inner diameters of 0.25, 0.5 and 1 mm. For binary methane mixtures, the heat transfer coefficients were impaired as the drop in the interface temperature caused by the mass transfer effect. Furthermore, the heat transfer coefficient was dependent on the heat flux for binary fluid condensation.

A literature surveys show that few research efforts have been devoted to the heat transfer on hydrocarbon mixture refrigerant in a helical tube. Consequently, the purpose of the present work is to study the characteristics of condensation heat transfer for binary mixtures (ethane/propane, methane/propane), and a numerical model was established on condensation flow heat transfer for hydrocarbon mixture refrigerant in a helical tube and validated by the experiment data. Meanwhile, the characteristic of condensation heat transfer for different mixture compositions of zeotropic mixtures was investigated. In addition, the numerical results of heat transfer coefficient were also compared to the well-known correlations. Finally, a new correlation was proposed to calculate the heat transfer coefficient for different flow patterns on hydrocarbon mixture refrigerant in a helical tube.

2. Numerical simulation methods

2.1. Computational model

A CFD model was proposed in this paper to investigate the characteristics of condensation heat transfer in a helical tube. The model established in this paper was similar to that of Qiu et al. [16]. As shown in Fig. 1, the geometrical configuration of computational model was a coiled tube with 1.4 m long, a diameter of 10 mm, the coil diameter 2 m and helix angle 10°. And the whole test tube was divided into 3 sections, in which vapor quality development section (0.8 m) was used to