International Journal of Heat and Mass Transfer 124 (2018) 646–654

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Forced convective condensation flow and heat transfer characteristics of hydrocarbon mixtures refrigerant in helically coiled tubes

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ARTICLE INFO

Article history:
Received 22 December 2017
Received in revised form 23 February 2018
Accepted 27 March 2018

Keywords:
Condensation
Hydrocarbon refrigerant
Heat transfer
Helical tube
Numerical simulation

ABSTRACT

Helical tube has been widely used in liquefied natural gas (LNG) liquefying applications. However, studies on the heat transfer performance of hydrocarbon mixture refrigerant in a helical tube have rarely been conducted. In this paper, condensation heat transfer characteristics of hydrocarbon mixture refrigerant in a helical tube were investigated numerically. The tests were conducted at saturation pressure of 2–4 MPa, mass flux of 100–400 kg/(m^2·s) and vapor quality 0–1. The numerical model was well verified by experimental data. And the effects of different structural parameters (tube diameter, helix angle and curvature diameter) and operating parameters (mass flux, heat flux and saturation pressure) on the heat transfer of hydrocarbons refrigeration were considered. The results showed that the tube diameter and mass flux had significant effect on condensation heat transfer coefficient. Meanwhile, stratified flow, half-annular flow and annular flow were observed during the condensation of methane/propane mixtures refrigerant by simulations, and a new flow pattern transition line for hydrocarbon refrigerants condensation process was proposed. Finally, the simulation results were compared with several well-known condensation heat transfer correlations. The research results will provide some constructive instructions for more effective design of LNG heat exchanger.

1. Introduction

Due to the large heat transfer efficiency and advantages of compact structure, helical tube has been widely used in liquefied natural gas (LNG) liquefying applications, and LNG predominantly consists of hydrocarbons refrigeration. Meanwhile, the two-phase condensation phenomenon in a helical tube is more complex than that in a straight tube. Therefore, to study the influences of different structural parameters and operating parameters on the heat transfer of hydrocarbons refrigeration is essential for the design of heat exchanger.

There are a few researchers on two-phase flow condensation heat transfer characteristics of refrigerant flow in tube. Mozafari et al. [1] investigated the condensation characteristics of R-600a inside a helical tube-in-tube heat exchanger. The results showed that the heat transfer coefficient increased with the increase of mass flux and average vapor quality for every inclination angle. Hajeri et al. [2] studied the effect of coolant temperature on the condensation of R-134a in annular helical tubes. They found that the local heat transfer coefficient on the refrigerant side decreased as the mass flux of refrigerant or the Reynolds number of coolant water flow increased. Macdonald and Garimella [3] investigated the condensation heat transfer of propane inside horizontal tubes. They found that the heat transfer coefficient increased with mass flux and quality, while it decreased with saturation temperature. For the effect of saturated temperature on condensation heat transfer characteristics of R-134a, some researchers [4–6] found that the heat transfer coefficient decreased with the increase of saturated temperature. Mosaad et al. [7] investigated the condensation heat transfer characteristics of R-134a in a coiled double tube. The results illustrated that the overall heat transfer coefficients increased with the increase of mass flux, while decreased with the increase of condensation temperature difference. Maråk [8] presented a study on condensation heat transfer of methane and binary methane mixtures in small vertical channels with inner diameters of 0.25, 0.5 and 1 mm. For flows with pure fluids, the heat transfer coefficient increased with the increasing mass flux and larger vapor fraction, and it generally decreased with the increase of pressure. And the effect of heat flux had a little effect on the heat transfer coefficient. For binary methane mixtures, and the heat transfer coefficient was dependent on the heat flux. In addition, geometric parameters variables have a certain effect on the heat transfer in helical tube. Salimpour et al. [9] discussed

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.03.097
0017-9310/

Nomenclature

d	inside diameter of tube, m
D	the curvature diameter, m
G	mass velocity, kg/(m^2·s)
g	gravity acceleration, m/s^2
h	heat transfer coefficient, W/(m^2·K)
i	specific sensible enthalpy, J/kg
i_{lg}	latent heat, J/kg
$MARD$	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

Greek symbols

α	volume fraction
λ	thermal conductivity, W/(m·K)
μ	molecular dynamic viscosity, Pa·s
μ_t	turbulent viscosity, Pa·s
ρ	density, kg/m^3
κ	interface curvature, m^{-1}
η	percentage of points predicted within ±20% range
β	helix angle, °
σ	surface tension, N/m

Subscripts

cal	calculated
eff	effective
exp	experiment
g, l	vapor phase and liquid phase, respectively
lo	liquid only
pred	predicted
sim	simulation
sat	the saturation condition

the effect of structural parameters on condensation heat transfer of R404A in helically coiled tubes, and they found that heat transfer coefficients increased with the decreasing coil diameter, while they decreased with the increase of coil pitch at low vapor qualities. Akhavan-Behabadi et al. [10] found the heat transfer rate of a nanofluid would be increased by reducing the coil-to-tube diameter ratio or increasing the coil pitch to tube–diameter ratio inside vertical helically coiled tubes. Salem et al. [11] experimentally investigated the effect of coil curvature on the convective heat transfer characteristics in horizontal shell and coil heat exchangers. They found that the overall heat transfer coefficients increased with the increase of coil curvature ratio. Jamshidi et al. [12] found a larger coil diameter, coil pitch and mass flow rate in shell and tube could enhance the heat transfer rate in shell and helical tube heat exchangers. Naphon and Suwagrai [13] concluded that the centrifugal force had a significant effect on the enhance of heat transfer in a horizontal spiral tube.

The experimental measurement points are limited compared with the numerical method, and numerical simulations could give additional details on the flow and heat transfer. Different numerical methods can be used for the study of the condensation process. Qiu et al. [14] used the VOF scheme to study flow condensation of propane in an upright spiral tube. They found that the effect of the entrainment of liquid droplet on the heat transfer coefficients were remarkable. Ferng et al. [15] investigated the effects of Dean number (De) and pitch size on the heat transfer characteristics in a helically coil-tube heat exchanger by the computational fluid dynamics (CFD) method. They found that Nusselt number increased as the pitch size increases. Mirgolbabaei et al. [16] studied the forced convection heat transfer characteristic in vertical helically coiled tubes. They found that the heat transfer coefficient decreased with the increase of coil pitch in medium range and the tube diameter for the same dimensionless coil pitch, while it increased with the increase of the pitch. Li et al. [17–23] numerically and experimentally investigated the condensation heat transfer characteristics of R410A inside horizontal round and flattened tubes. Liquid-vapor interfaces and local heat transfer coefficients were also presented to give a better understanding of the condensation process inside these tubes. And a new frictional pressure drop correlation for horizontal micro-fin tubes was developed.

According to the literature review, few work has been conducted to study the effect of different structural parameters on heat transfer rate for hydrocarbon mixtures refrigerant in a helical tube. In this paper, a numerical simulation considering hydrocarbon mixtures refrigerant methane/propane condensation in helically coiled tubes was presented. The effect of mass flux, heat flux, saturation pressure, tube diameter, helix angle and curvature diameter on heat transfer rate in a helical tube were studied. Meanwhile, a new flow regime transition line between annular and non-annular flow was obtained according to the flow pattern obtained by simulations. Finally, the simulation results were compared with the correlation calculations on heat transfer coefficient from literatures.

2. Numerical simulation methods

2.1. Governing equations

ANSYS Fluent is used to perform the numerical simulations. The Volume of Fluid (VOF) method is used to track the vapor–liquid interface. The mathematical models include continuity, momentum, energy equations.

The continuity equations are solved as:

$$\frac{\partial}{\partial t}(\alpha_l) + \nabla \cdot (\vec{u}\alpha_l) = \frac{S}{\rho_l} \tag{1}$$

$$\frac{\partial}{\partial t}(\alpha_g) + \nabla \cdot (\vec{u}\alpha_g) = \frac{S}{\rho_g} \tag{2}$$

where S is the mass source term; α is the volume fraction.

The unsteady Navier-Stokes equations are used for momentum in the cells where only one of the phases in the two phases exists, and the force due to the surface tension F can be taken into account as:

$$\frac{\partial}{\partial t}(\rho\vec{u}) + \nabla\cdot(\rho\vec{u}\vec{u}) = -\nabla p + \nabla\cdot[(\mu+\mu_t)(\nabla\vec{u}+\nabla\vec{u}^T)] + \rho\vec{g} + \vec{F} \tag{3}$$

The vapor–liquid interface is treated as a transition region of finite thickness, and the surface normal is computed as the gradi-