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Numerical study on condensation heat transfer and pressure drop characteristics of ethane/propane mixture upward flow in a spiral pipe

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ABSTRACT

Spiral wound heat exchangers (SWHE) has been the most widely used in large-scale liquid natural gas (LNG) plants. However, few studies have been focused on the condensation heat transfer and pressure drop for hydrocarbon mixture refrigerant in SWHE tube side. In this paper, the condensation heat transfer and pressure drop characteristics for ethane/propane mixture upward flow in a spiral pipe were numerically investigated. The numerical model was established and verified based on the existing experimental results and new flow pattern observation experiments. It discussed the variation trends of void fraction, frictional pressure drop, heat transfer coefficient and heat and mass transfer resistance with various parameters, such as, vapor quality, mass flux, heat flux, saturation pressure and inclination angle. Comparing with the existing correlations, the results showed that Steiner's correlation, modified Fuchs's correlation, Boyko's correlation could better predict the void fraction, frictional pressure drop, film heat transfer coefficient with mean absolute deviation of 6.08%, 10.67% and 13.06%, respectively. Meanwhile, modified Silver approach was used to modify the mixed effects of ethane/propane mixture on heat transfer. The study provides some constructive instructions to understand the condensation of zeotropic mixtures in the spiral pipe, and is helpful in designing more effective SWHE.

1. Introduction

Spiral wound heat exchanger (SWHE) (as shown in Fig. 1) is probable the most comment type of main cryogenic exchanger in large-scale liquid natural gas (LNG) plants since its multi-stream capability, high compactness, efficient heat transfer, sufficient flexibility and better robustness [1–4]. Meanwhile, hydrocarbon mixtures are usually used as working medium in LNG field. Therefore, the condensation flow and heat transfer for hydrocarbon mixtures is the main phenomenon in SWHE tube side. However, due to its complex, such as the mixed effect of zeotropic mixtures, it is still insufficient to understand this phenomenon in a spiral tube. A better understanding of this phenomenon can be contributed to the design and optimization of SWHE. The geometric parameters of common LNG SWHE are shown in Table 1.

Until now, there are many studies on condensation of zeotropic mixtures in tubes. Fronk and Garimella [7] reviewed experimental and analytical results corresponding on the coupled heat and mass transfer phenomena during condensation of different zeotropic fluid mixtures in tubes. In this paper, it showed that for zeotropic mixtures, the heat and mass transfer resistances in vapor and liquid phases increased the overall heat transfer resistance beyond what would be expected from a weighted average of corresponding resistances for pure components. From an experimental viewpoint, Berrada et al. [8] measured condensation heat transfer coefficients for R23/R134a refrigerant mixtures at three different component ratios in a horizontal tube to appreciate the glide effect on heat transfer. The results showed that no glide effect on heat transfer coefficients was observed. However, Shao et al. [9] found that a greater temperature glide would lead a greater degradation of heat transfer coefficients for R32/R134a mixtures, especially at low mass flux. Shao et al. [10,11] also experimentally investigated the condensation flow and heat transfer of pure, azeotropic and zeotropic refrigerants in a horizontal tube. The results indicated that for pure, azeotropic and zeotropic refrigerants with a small temperature glide, heat transfer coefficients were independent on mass flux in wavy flow regions, and increased with the increasing mass flux in annular flow regions; but for other zeotropic refrigerants, it always increased with the increase of mass flux within tested ranges. Eckels et al. [12] compared the average condensation heat transfer coefficients of R32/R134a mixtures with those of R22 in a

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Nomenclature

A_{lv}	interfacial area density between liquid phase and vapor phase, m^{-1}
ARD	average deviation, Eq. (50)
Bo	Boiling number, $Bo=q/(m\gamma_{lv})$
C_D	drag coefficient, $C_D = 0.44$
C_μ, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$	constant with the values of 0.09, 1.44 and 1.92, respectively
C_f	Correction factor of the two-phase enhancement at the interface on vapor core heat transfer
Cp	specific heat at constant pressure, J/(kg K)
d	hydraulic diameter, m
d_{lv}	mean interfacial length scale between the liquid phase and vapor phase, m
D	curvature diameter, m
f	friction factor
$\dot{f}_{\sigma,lv}$	surface force acting on vapor phase due to the presence of the liquid phase per unit area, N/m^2
$\vec{F}_{lv}$	interfacial forces acting on liquid phase due to the presence of the vapor phase, N/m^3
$\vec{F}_{D,lv}$	drag force acting on vapor phase due to the presence of the liquid phase per unit volume, N/m^3
$\vec{F}_{\sigma,lv}$	surface force acting on vapor phase due to the presence of the liquid phase per unit volume, N/m^3
Fr_{l0}	full-liquid Froude number, $Fr_{l0} = m^2/(\rho_l^2 gd)$
Fr_{tp}	mixture Froude number, $Fr_{tp} = m^2/(gd\rho_{tp}^2)$
g	gravity acceleration, m/s^2
h	heat transfer coefficient, $W/(m^2\,K)$
h_{film}, h_{core}, h_{mix}	the liquid film, vapor core and mixed heat transfer coefficient, respectively, $W/(m^2{\cdot}K)$
h'_v	the smooth gas superficial single-phase heat transfer coefficient
h_v, h_l	heat transfer coefficient of liquid phase and vapor phase on one side of the phase interface, respectively, $W/(m^2\,K)$
h_{lv}	heat transfer coefficient between vapor phase side and liquid phase side, $W/(m^2\,K)$
k	turbulent kinetic energy, m^2/s^2
L	length of test section, m
m	mass flux, $kg/(m^2\,s)$
$\dot{m}_{lv}$	mass flow rate in per unit interfacial area from vapor phase to liquid phase, $kg/(m^2\,s)$
MARD	mean absolute deviation, Eq. (51)
$\vec{n}_{lv}$	interface normal vector pointing from liquid phase to the vapor phase
Nu_{lv}	Nusselt number between vapor phase side and liquid phase side, $Nu_{lv} = h_{lv}d_{lv}/\lambda_{lv}$
p	pressure, Pa
P	saturation pressure, Pa
P_{cr}	critical pressure, Pa
P_k	turbulence production, Pa/s
P_{kbi}	buoyancy turbulence production, Pa/s
Pr	Prandtl number, $Pr = \mu Cp/\lambda$
q	heat flux, W/m^2
q_{tot}, q_{core}	the total, vapor core heat flux, respectively, W/m^2
q_v, q_l	sensible interphase heat transfer to the vapor phase across the interface with the liquid phase and to the liquid phase across the interface with the vapor phase per unit volume, respectively, W/m^3
Q_v, Q_l	total interphase heat transfer to the vapor phase across the interface with the liquid phase and to the liquid phase across the interface with the vapor phase per unit volume, respectively, W/m^3
Re_{eq}	equivalent Reynolds number, $Re_{eq} = m[1 - x + x(\rho_l/\rho_v)^{0.5}]d/\mu_l$
Re_l	liquid Reynolds number, $Re_l = m(1 - x)d/\mu_l$
Re_{l0}	full-liquid Reynolds number, $Re_{l0} = md/\mu_l$
Re_v	vapor Reynolds number, $Re_v=mdx/\mu v$
T	temperature, K
T_c	vapor core temperature, K
u	velocity, m/s
We_{tp}	mixture Weber number, $We_{tp} = m^2d/(\sigma\rho_{tp}^2)$
x	vapor quality
X_{tt}	Lockhart-Martinelli parameter, $X_{tt} = [(1 - x)/x]^{0.9}(\rho_v/\rho_l)^{0.5}(\mu_l/\mu_v)^{0.1}$
Z	the ratio between sensible to total heat flux

Greek symbols

α	volume fraction or void fraction
β	inclination angle
ρ	density, kg/m^3
μ	dynamic viscosity, Pa s
μ_t	turbulent viscosity, Pa s
λ	thermal conductivity, W/(m K)
γ	enthalpy, J/kg
γ_{lv}	latent heat of phase change, J/kg
γ_{vS}, γ_{lS}	interfacial values of enthalpy carried into vapor phase and liquid phase due to phase change, respectively, J/kg
σ	surface tension coefficient, N/m
σ_k, σ_ε	constant with the values of 1.3 and 1.0, respectively
δ	the liquid film thickness, m
δ_{lv}	interface delta function, m^{-1}
ΔP_f	Frictional pressure drop, Pa/m
κ_{lv}	surface curvature, m^{-1}
θ	Correction factor of mass transfer on vapor core heat transfer
ε	turbulent dissipation rate, m^2/s^3
ξ	condensation heat ratio
φ_{1v}	two-phase enhancement factor, $\varphi_{1v} = \left[\left(\frac{dp}{dl}\right)_{tp} - \left(\frac{dp}{dl}\right)_{l0}\right] \Big/ \left[\left(\frac{dp}{dl}\right)_{v0} - \left(\frac{dp}{dl}\right)_{l0}\right]$
ϕ_{l0}^2	full-liquid frictional pressure drop multiplier, $\phi_{l0}^2 = \left(\frac{dp}{dl}\right)_{tp} \Big/ \left(\frac{dp}{dl}\right)_{l0}$
ϕ_v^2	vapor frictional pressure drop multiplier
Φ	heat and mass transfer resistance in vapor core for mixtures, $K\,m^2\,W^{-1}$, $\Phi = Z/h_{core}$
ψ_{l0}	ratio of the two-phase and full-liquid single phase heat transfer coefficient, $\psi_{l0} = h_{film,s}/h_{l0}$
Γ_{lv}	mass flow rate in per unit volume from vapor phase to liquid phase, $kg/(m^3\,s)$
Γ_{lv}^+	positive mass flow rate in per unit volume from vapor phase, $kg/(m^3\,s)$

Subscripts

c, *s*	coiled or straight pipe
cr	critical
exp	experimental value
i	any
l	liquid phase
l0	all the mass flux is taken as liquid
pre	predicted value
ref	reference
sat	saturation
sim	simulated value
S	interfacial
t	turbulent
tp	two phase
v	vapor phase
v0	all the mass flux is taken as vapor