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Research Paper

The influence of structural parameters on heat transfer and pressure drop for hydrocarbon mixture refrigerant during condensation in enhanced spiral pipes

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HIGHLIGHTS

- The condensation flow in three enhanced spiral pipes was numerically investigated.
- Different pipe types and structural parameters were studied on flow and heat transfer.
- The comprehensive heat transfer enhancement was more evident at low vapor qualities.
- Spiral grooved pipes showed best overall heat transfer performance among others.
- The optimal enhanced spiral pipe was elected with the average *CHF* of 1.413.

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ABSTRACT

In this paper, the condensation heat transfer and pressure drop characteristics for hydrocarbon mixture upward flow in smooth and enhanced spiral pipes were numerically investigated. The numerical model was established and verified by experimental results in literatures. It discussed the influence of geometrical parameters on condensation heat transfer and pressure drop in three kinds of enhanced spiral pipes, which contained square corrugated pipe, sinusoidal corrugated pipe and spiral grooved pipe. The results indicate that in enhanced spiral pipes, both frictional pressure drop and heat transfer coefficient increase with the rise in corrugation (groove) height and the decrease of corrugation (groove) pitch. Meanwhile, compared to the smooth pipe, the augmentation on heat transfer for square corrugated, sinusoidal corrugated and spiral grooved pipes are 0.934–2.052, 1.103–2.216 and 1.206–1.804 times, respectively, while the increase of frictional pressure drop are 1.805–10.930, 1.272–7.176 and 0.851–3.587 times, respectively. Besides, the comprehensive heat transfer enhancement factor (*CHF*) was introduced to evaluate the overall heat transfer performance of enhanced pipes. It is found that as the corrugation (groove) height increases, the *CHF* increases in square and sinusoidal corrugated pipes but decreases in spiral grooved pipe; at the meantime, with the increase of corrugation (groove) pitch, the *CHF* first decreases and then increases in square and sinusoidal corrugated pipes while first increases and then decreases in spiral grooved pipe. The average *CHF*s for all square corrugated pipes, sinusoidal corrugated pipes and spiral grooved pipes are 0.872, 1.083 and 1.275, respectively. Moreover, the spiral grooved pipe with the relative groove height and pitch of 0.03535 and 5.0 shows the best overall heat transfer performance among others, whose average *CHF* can reach to 1.413. These results provide some instructions for the application of enhanced spiral tube in the design of spiral wound heat exchange (SWHE).

1. Introduction

With the gradual consumption of energy, the energy conservation becomes more and more important. Spiral pipes, as one of high efficiency passive heat transfer enhancement techniques, have been widely used in many industrial fields, such as chemical, refrigeration, liquefied natural gas (LNG) and so on. However, for the spiral wound heat exchange (SWHE, as shown in Fig. 1), the enhancement of heat transfer is often accompanied by an increase in flow resistance. Thus, in order to obtain higher heat transfer efficiency, it is necessary to study the

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Nomenclature

A_{lv}	interfacial area density between liquid phase and vapor phase, m^{-1}
C_D	drag coefficient, $C_D = 0.44$
C_μ, $C_{\varepsilon1}$, $C_{\varepsilon2}$, $C_{\mu,RNG}$, $C_{\varepsilon2,RNG}$, $C_{\varepsilon1,RNG}$	constant with the values of 0.09, 1.44, 1.92, 0.085, 1.42 and 1.68, respectively
C_f	correction factor of the two-phase enhancement at the interface on vapor core heat transfer
CHF	comprehensive heat transfer enhancement factor
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
e	molar Helmholtz free energy, J/mol
$\bar{e}$, $\bar{e}^0$ and $\bar{e}^r$	total, ideal and residual reduced molar Helmholtz free energy, respectively, $\bar{e} = e/(RT)$
$\overrightarrow{F_{lv}}$	interfacial forces acting on liquid phase due to the presence of the vapor phase, N/m^3
$\overrightarrow{F_{D,lv}}$	drag force acting on vapor phase due to the presence of the liquid phase per unit volume, N/m^3
$\overrightarrow{F_{\sigma,lv}}$	surface force acting on vapor phase due to the presence of the liquid phase per unit volume, N/m^3
g	gravity acceleration, m/s^2
h	heat transfer coefficient, $W/(m^2{\cdot}K)$
h_{film}	the liquid film heat transfer coefficient, $W/(m^2{\cdot}K)$
h'_v	the smooth gas superficial single-phase heat transfer coefficient, $W/(m^2{\cdot}K)$
h_v, h_l	heat transfer coefficient of liquid phase and vapor phase on one side of the phase interface, respectively, $W/(m^2{\cdot}K)$
h_{lv}	heat transfer coefficient between vapor phase side and liquid phase side, $W/(m^2{\cdot}K)$
H	corrugation (groove) height, m
HF	heat transfer enhancement factor
k	turbulent kinetic energy, m^2/s^2
L	length of test section, m
m	mass flux, $kg/(m^2{\cdot}s)$
$\overrightarrow{n_{lv}}$	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_k	turbulence production, Pa /s
P_{kbi}	buoyancy turbulence production, Pa /s
Pr	Prandtl number, $\mathrm{Pr} = \mu Cp/\lambda$
PF	frictional pressure drop enhancement factor
q	heat flux, 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
R	molar gas constant, $R = 8.314472$ J/(mol·K)
Re_l	vapor Reynolds number, $\mathrm{Re}_l = md(1-x)/\mu_l$
Re_v	vapor Reynolds number, $\mathrm{Re}_v = mdx/\mu_v$
s	corrugation (groove) pitch, m
T	temperature, K
u	velocity, m/s
x	vapor quality
y	mole fraction

Greek symbols

α	volume fraction or void fraction
β	inclination angle
θ	wall contact 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, $\sigma_{k,RNG}$, $\sigma_{\varepsilon,RNG}$	constant with the values of 1.3, 1.0, 0.7179 and 0.7179, respectively
ΔP_f	frictional pressure drop, Pa/m
ϑ	correction factor of mass transfer on vapor core heat transfer
ε	turbulent dissipation rate, m^2/s^3
ξ	condensation heat ratio
δ	reduced density, $\delta = \rho/\rho_{cr}$
τ	inverse reduced temperature, $\tau = T_{cr}/T$
Φ	heat and mass transfer resistance in vapor core for mixtures, $K{\cdot}m^2{\cdot}W^{-1}$
Γ_{lv}	mass flow rate in per unit volume from vapor phase to liquid phase, $kg/(m^3{\cdot}s)$

Subscripts

cr	critical
$enhanced$	enhanced tube
exp	experimental value
i	any
l	liquid phase
o	property of the pure substance
ref	reference
sat	saturation
sim	simulated value
$smooth$	smooth tube
S	interfacial
t	turbulent
tp	two phase
v	vapor phase

condensation flow and heat transfer for hydrocarbon mixture in spiral pipes with enhanced surface, which is helpful to design more compact, low-cost, high efficiency SWHE using in LNG field.

Nowadays, many researches have been carried out on condensation flow and heat transfer in smooth spiral pipes. Wongwises and Polsongkram [2] compared the condensation heat transfer coefficient and pressure drop of R134a in a helically tube with those in a straight tube and found that they both increased, which was also found in condensation experiment by Mozafari et al. [3]. Gupta et al. [4] evaluated the thermodynamic advantage of R134a condensation flow in a helical tube by using an enhancement parameter, which was defined as the ratio between the relative heat transfer and pressure drop of the helical coil against straight tube. The result indicated that the enhancement parameter increased as the vapor quality and mass flux decreased while the saturation temperature had little effect on it. Salimpour et al. [5] experimentally investigated condensation heat transfer of R404A in helically tubes with different structural parameters. It was found that the condensation heat transfer coefficient increased with the decrease of curvature radii and coil pitch. An experimental study was conducted by Neeraas [6] on condensation heat