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Influence of component proportion on heat transfer characteristics of ethane/propane mixture flow condensation in shell side of helically baffled shell-and-tube heat exchanger

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ABSTRACT

The component proportion of ethane/propane mixture varies during the condensation process in shell side of helically baffled shell-and-tube heat exchangers of nature gas liquefaction plants, which significantly influences the heat transfer characteristics. In the present study, the heat transfer coefficients of ethane/propane mixtures with ethane mass fraction of 8–50% (covering practical conditions) were tested, and were compared with those of pure propane (0% ethane mass fraction) to analyze the influence of component proportion. The research results indicate that, the maximum heat transfer coefficient of ethane/propane mixture occurs at vapor quality around 0.8; as the ethane mass fraction increases from 0% to 15%, the heat transfer coefficient decreases dramatically by a maximum of 66.3%; as the ethane mass fraction further increases from 15% to 50%, the heat transfer coefficient keeps almost constant, and the fluctuation is within −26.4% to 29.1%. A new heat transfer correlation has been developed, and its prediction deviations are within ± 25%.

1. Introduction

As helically baffled shell-and-tube heat exchangers (HBHXs) have better comprehensive performance, less fouling and less fluid-induced vibration than other baffled shell-and-tube heat exchangers [1–4], they are widely used in liquefied natural gas plants, especially as condensers in precooling cycles [5]. During the operation of HBHXs in the precooling cycle, the mixed hydrocarbon refrigerant flows and condenses in the shell side [6–9], and the cooling water flows in the tube side [10]. The heat transfer characteristics of mixed refrigerant in the shell side are very complicated because the component proportion varies with the condensation process and the composition of the source gas [6–9,11]. The variation of component proportion causes the changes of gliding temperature difference [12], flow pattern [13,14] and interfacial mass diffusion [15] in mixed refrigerants. In order to precisely predict the heat transfer performance of HBHX shell side, the influence of component proportion on flow condensation heat transfer characteristics of mixed hydrocarbon refrigerant in shell side of HBHX should be known. As ethane and propane are the main components of the mixed hydrocarbon refrigerant [6–9], ethane/propane mixtures are taken as the working fluids to investigate the influence of component proportion.

For the heat transfer characteristics in shell side of HBHXs, the existing researches covered the fluid convection [16–18], pure refrigerant condensation [19–22] and mixed refrigerant with fixed component proportion condensation [23,24]. The researches on the fluid convection show that the heat transfer coefficients of conduction oil [16,17] and water [18] in shell side of HBHXs were significantly influenced by the baffle construction, including the baffle overlap proportion, baffle shape and baffle helix angle. Those on the pure refrigerant condensation show that the heat transfer coefficient of steam in HBHX with dual thread baffles was 15.74% higher than that with single thread baffles [19–21], and the heat transfer coefficients of pure propane in HBHX cannot be well predicted by Nusselt correlation [22]. The researches on the mixed refrigerant with fixed component proportion condensation include the experimental investigation on the heat transfer characteristics of R407C [23] and hydrocarbon mixtures [24] as well as the development of heat transfer correlations. However, there is no report on the condensation of mixed refrigerant with variable components in shell side of HBHX.

For the influence of component proportion on flow condensation heat transfer characteristics of mixed refrigerant, the existing researches mainly focused on the flow in tube [11–15,25,26] and the flow across tube bundles without baffle [27]. The researches on the flow in tube include the experimental investigations on R32/R134a mixture

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Nomenclature

a, b	coefficient in Eq. (16)
A	effective heat transfer area, m^2
C_p	specific heat at constant pressure, J/kg K
d	diameter, m
g	gravitational acceleration, m/s^2
G	mass flux, $kg/m^2 s$
h	specific enthalpy, J/kg
i	latent heat of condensation, J/kg
L	effective tube length, m
m	mass flow rate, kg/s
n	thermocouple number
N	total number
P	pressure, MPa
q	heat flux, kW/m^2
Q	heat load, kW
R	function of n independent variables v_n
T	temperature, K
ΔT	temperature difference, K
v	independent variables
V	volume flow rate of water, m^3/s
x	vapor quality
Pr	Prandtl number
Re	Reynolds number
Le	Lewis number
Z	thermodynamic parameter
IF	composition influence factor

Greek symbols

α	heat transfer coefficient, $W/m^2 K$
β	helical baffle angle, °
λ	thermal conductivity, W/m K
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
Γ	film mass flow rate, kg/m s

Subscripts

cal	calculated value
cw	cooling water
exp	experimental value
f	liquid film
G	gas
i	inside surface
in	inlet
L	liquid
lat	latent
n	number
o	outside surface
out	outlet
pre	pre-condenser
r	refrigerant
sen	sensible
sat	saturated
t	tube
thermo	thermocouple
tw	tube wall

[12], R22/R42b mixture [13,14,25], CO2/DME mixture [15], ethane/propane mixture [26], etc. And these research results show that the heat transfer coefficient decreased as the less volatile component concentration increased from 0% to 30% [12–15,25]; the heat transfer coefficient of ethane/propane mixtures with different proportions were well predicted by Bell and Ghaly correlation [26]. The researches on the flow across tube bundles without baffle show that the mean heat transfer coefficient of R23/R134a mixture decreased as the R23 proportion increased from 0% to 11% [27]. However, there is no report about the influence of component proportion on flow condensation heat transfer characteristics in shell side of HBHX. The flow direction is inclined and varies at different locations in shell side of HBHX, which is completely different from the flow in tube or the flow across tube bundles without baffle. Thus the existing research results cannot be extended to the mixed refrigerants flow condensation in shell side of HBHX.

For the heat transfer correlations of mixed refrigerant flow condensation in shell side of shell-and-tube heat exchangers, the existing research on tube bundles [27,28] can reflect the influence of component proportion, and the existing research on HBHX [24] can reflect the influence of baffle effect. However, for the mixed refrigerants with different component proportions in shell side of HBHX, the flow condensation heat transfer characteristics are synthetically influenced by the helical baffle effect and the component proportion, which cannot be simultaneously reflected by the existing correlations for tube bundles [27,28] or the existing correlations for HBHX [24]. Therefore, a new correlation should be developed to reflect the influence of component proportion for mixed refrigerant flow condensation in HBHX shell side.

Though the flow condensation of pure propane and mixed hydrocarbon refrigerant with fixed component proportion in HBHX were investigated in [22,24], there is no research on the influence of component proportion for the flow condensation of mixed hydrocarbon in HBHX. The objective of this study is to obtain new experimental data of ethane/propane mixture flow condensation in shell side of HBHX and to propose a new correlation for predicting the heat transfer characteristics of mixed refrigerants flow condensation in shell side of HBHXs.

2. Design of experiments

2.1. Experimental conditions needed for analyzing the influence of component proportion

In order to quantitatively analyze the influence of component proportion on heat transfer characteristics of mixed hydrocarbon refrigerants in practical LNG HBHXs, ethane/propane mixtures (abbr. C2/C3) with five ethane mass fractions of 8%, 15% 31%, 38% and 50% were taken as the working fluid; the experimental conditions covered the heat flux of 3.0–6.0 kW/m^2, mass flux of 30–40 kg/m^2 s and vapor quality from 0.1 to superheated, as listed in Table 1. Moreover, the data of pure propane obtained by Yang et al. [22] are also included in

Table 1
Experimental conditions.

Working fluids	Mass flux, G (kg/m^2 s)	Heat flux, q (kW/m^2)	Vapor quality, x
Ethane/propane (C2/C3) (8 wt%/92 wt%)	30–40	3.0–6.0	0.1 to superheated
Ethane/propane (C2/C3) (15 wt%/85 wt%)			
Ethane/propane (C2/C3) (31 wt%/69 wt%)			
Ethane/propane (C2/C3) (38 wt%/62 wt%)			
Ethane/propane (C2/C3) (50 wt%/50 wt%)			
Propane (C3) [22]	30–50	3.0–7.0	