Experimental study of heat transfer and pressure drop characteristics of two-phase mixed hydrocarbon refrigerants flow boiling in shell side of spiral wound heat exchanger

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Abstract. The heat transfer and pressure drop characteristics of ethane/propane mixed hydrocarbon refrigerants flow boiling in shell side of spiral wound heat exchanger (SWHE) were investigated experimentally, and the ethane molar fractions of the mixed refrigerants cover 0%~60%. The results show that, as the vapor quality increases, the heat transfer coefficient (HTC) initially increases and then decreases sharply, representing a maximum value at vapor quality of 0.6~0.8; under mass flux of 40 kg m⁻²s⁻¹ and heat flux of 6 kW m⁻², as the ethane molar fraction increases from 0% to 60%, the HTC decreases maximally by 15% at vapor quality smaller than 0.7, while it increases maximally by 24% at vapor quality larger than 0.7. As the vapor quality is smaller than 0.4, the pressure drop of ethane and propane mixtures are lower maximally by 17% than that of pure propane; as the vapor quality is larger than 0.6, the pressure drop of ethane and propane mixtures are higher maximally by 41% than that of pure propane at the same working conditions.

1. Introduction

Spiral wound heat exchanger (SWHE) has been used as the main cryogenic heat exchanger in 90% of land-based liquefied natural gas (LNG) plants, due to the advantages of compact structure, large scale unit, good thermal compensation performance and multi-stream heat transfer capability [1]. The process of liquefying natural gas in SWHE is implemented through the heat transfer between the natural gas flowing upward at tube side and the two-phase hydrocarbon refrigerant flowing downward at shell side [2]. Comparing to tube side, the heat transfer and pressure drop characteristics of shell side influenced the performance of LNG SWHE more significantly [3].

During the operation process of SWHEs, the mixed hydrocarbon refrigerant in the shell side mainly consists of propane and ethane [4-5], and the refrigerant composition and the thermophysical properties constantly vary as the vapor quality increases, resulting in the complicated heat transfer characteristics in the shell side of SWHEs. Therefore, in order to design and optimize LNG SWHE, the heat transfer and pressure drop characteristics of two-phase hydrocarbon refrigerants flow boiling in the shell side of LNG SWHEs should be known.

In the present study, the flow patterns, the heat transfer coefficients and pressure drops of mixed refrigerants flow boiling in SWHE shell side will be experimentally investigated.
2. Experimental rig and conditions

The schematic diagram of the experimental rig is shown in Fig. 1. The experimental rig can be subdivided into three parts, including a main test circuit, a cooling circuit and a bypass flow path.

The main test circuit is highlighted by blue line. It is composed of a compressor, a plate heat exchanger, a regulating valve, an electric heater and a test section. The temperature of the working fluid coming out from the compressor is around 90–120°C. Then the working fluid is cooled by the front plate heat exchanger and the rear plate heat exchanger which will make the fluid reach a temperature range from -35 to -160°C. Then the subcooled working fluid goes through the regulating valve to reduce the pressure and temperature, and is heated by the front electric heater to get the experimental conditions of the vapor quality; then the working fluid enters into the test section, where the heat transfer coefficient and the frictional pressure drop will be tested. Then the working fluid will be heated to superheat state to go back to the compressor.

There are two cooling circuits which are highlighted by green line. One is chilled water circuit and the other is liquid nitrogen circuit. The chilled water circuit will cool down the working fluid to -35°C and the liquid nitrogen circuit will further cool down the working fluid to -160°C.

The thermophysical properties were obtained by NIST REFPROP program. The component proportion is adjusted by charging the required ethane mass into the experiment system, and it is measured by off-line method through a SHIMADZU GC-2010 gas chromatograph. The mixed refrigerant is sampled from two sampling ports. The component proportion is measured for three times, and the averaged value is taken as the experimental data.

The test section is shown in Fig. 2, and the structure parameters are same as the actual heat exchanger for LNG plants. For the test section, the outer diameter of the spiral tube is 12.0 mm, and the longitudinal tube pitch is 14.0 mm; the radial tube pitch is 16.0 mm, and the winding angle is 4°.

The experimental conditions include mass flux of 40–80 kg (m²∙s)^{-1}, vapor quality of 0.2–0.9 and heat flux of 6–10 kWm^{-2}.

![Test Rig Schematic Diagram](image)

Fig. 1 Schematic diagram of experimental rig
3. Data reduction and uncertainty

The local heat transfer coefficients are defined by the following equations:

\[ \alpha = \frac{q}{(T_w - T_f)} \]  
(1)

\[ T_f = \frac{T_{f,1} + T_{f,2}}{2} \]  
(2)

\[ q = \frac{Q}{4 \cdot (\pi \cdot R_{out} \cdot L)} \]  
(3)

where, \( \alpha \) is the local heat transfer coefficient, Wm\(^{-2}\)K\(^{-1}\); \( q \) is heat flux, kWm\(^{-2}\); \( T_w \) and \( T_f \) are the tube surface temperature and the average fluid temperature, respectively, K; \( T_{f,1} \) and \( T_{f,2} \) are the fluid temperatures at the inlet and outlet of the heat transfer test section respectively, K; \( Q \) is the electrical power of the test section, W; \( R_{out} \) is the radius of the heated tube, m; \( L \) is the length of heated tube, m.

To quantitatively analyze the influence of component proportion on the heat transfer characteristics, the molar fraction influence factor \( IF_{mix} \) is defined as the ratio of the heat transfer coefficient between the mixed refrigerant and the pure propane, as shown in Eq. (4).

\[ IF_{mix} = \frac{\alpha_{c2/c3}}{\alpha_{c2-0/c3}} \]  
(4)

The local shell side frictional pressure drop is calculated by Eq. (5).

\[ \Delta P_{fric} = \Delta P_{total} - \Delta P_{grav} - \Delta P_{acc} \]  
(5)

where, \( \Delta P_{fric} \) is the frictional pressure drop; \( \Delta P_{total} \) is the total pressure drop; \( \Delta P_{grav} \) is the gravity pressure drop; \( \Delta P_{acc} \) is the acceleration pressure drop [6].

The uncertainties of parameters are estimated based on the analysis of error propagation [7]. The maximum error of heat transfer coefficient and pressure drop are ±14.4% and ±4.0%, respectively.

4. Experiment results and discussion

4.1. Flow pattern observation

Figure 3 shows the flow patterns for the ethane and propane mixtures. Falling film flow and shear flow were observed for the mixed refrigerants with ethane molar fraction of 10% and 60%, respectively. The possible reason is that, as the ethane molar fraction increases, the gas density decreases, and the liquid is easily entrained by the gas, promoting flow pattern transition from falling film flow to shear flow for the refrigerant with larger ethane molar fraction.
4.2. Heat transfer characteristics

The experimental heat transfer coefficients at different ethane molar fractions under mass flux of 40 kg m$^{-2}$s$^{-1}$ and heat flux of 6 kW m$^{-2}$ are shown in Fig. 4. The influence of ethane molar fraction on the heat transfer coefficient depends on the value of vapor quality:

1) When the vapor quality is smaller than 0.7, the flow pattern is falling film and shear flow, and the liquid covers the tube wall; with the increasing ethane molar fraction, the diffusion resistance between the liquid and the vapor phases increases, resulting in the decrease of heat transfer coefficient by a maximum of 15%.

2) When the vapor quality is larger than 0.7, the increase of ethane molar fraction postpones the flow pattern transition from the shear flow to the mist flow, leading to the increase of heat transfer coefficient with the increasing ethane molar fraction.

![Fig. 4. Experimental heat transfer coefficients (G=40 kg m$^{-2}$s$^{-1}$)](image)

4.3. Pressure drop characteristics

The experimental pressure drops are shown in Fig. 5. The frictional pressure drop increases with increasing mass flux and vapor quality, and the slope of the frictional pressure drop gradient increases with increasing vapor quality. As the vapor quality is smaller than 0.4, the frictional pressure drop of ethane and propane mixtures are lower maximumly by 17% than that of pure propane at the same working conditions, and the frictional pressure drop decreases with increasing ethane molar fraction at the same working conditions; as the vapor quality is larger than 0.6, the frictional pressure drop of ethane and propane mixtures are higher maximumly by 41% than that of pure propane at the same working conditions.

![Fig. 5. Pressure drop characteristics](image)
conditions, and the frictional pressure drop increases with increasing ethane molar fraction at the same working conditions.

5. Conclusions

1) As the vapor quality increases, the heat transfer coefficient of the mixed refrigerants in the shell side of SWHE initially increases and then decreases sharply, representing a maximum value at vapor quality of 0.6-0.8.

2) As the ethane molar fraction increases, the heat transfer coefficient of the mixed refrigerants decreases at the vapor quality smaller than 0.7, but it increases at the vapor quality larger than 0.7.

3) As the vapor quality is smaller than 0.4, the frictional pressure drop decreases with increasing ethane molar ratio; when the vapor quality is larger than 0.6, the frictional pressure drop increases with increasing ethane molar ratio.

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