THE RESERCH OF TWO PHASE HEAT TRANSFER FOR R50, R170 AND R50/R170 BINARY MIXTURES

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ABSTRACT

A review on nucleate pool boiling, flow boiling and flow condensation heat transfer of R50, R170 and their binary mixtures in Technical Institute of Physics and Chemistry, Chinese Academy of Sciences (TIPC, CAS) is presented in this paper. First, the experimental results for pure R50 and R170 are discussed and analyzed. Then, their binary mixtures are investigated and compared with pure fluids. Research requirements for further two phase heat transfer studies are also proposed.

INTRODUCTION

As a clean energy source, natural gas is used prosperously and plays an important role in the economic and social development in recent decades. Attribute to the much larger density in liquid form, the liquefied natural gas (LNG) is important to the worldwide natural gas trade. Many fundamental parameters such as thermodynamic properties as well as the heat and mass transfer data are crucial in designing and manufacturing LNG facilities. The nucleate pool boiling, flow boiling and flow condensation heat transfer data for R50, R170 and their mixtures are particularly important, since LNG predominantly consists of them. In addition, R50 and R170 are also often-used components in mixture refrigerants for the low-temperature Joule-Thomson refrigerator. Therefore, it’s also important to study the heat transfer characteristics of R50, R170 and their mixtures for appropriate design and optimization of the low-temperature Joule-Thomson refrigerator.

NOMENCLATURE

D	[m]	Inner diameter
G	[kg m^{-2} s^{-1}]	Mass flux
h	[W m^{-2} K^{-1}]	Heat transfer coefficient
p	[MPa]	Saturation pressure
q	[kW m^{-2}]	Heat flux
ΔT	[K]	Fluid-to-wall temperature difference
ΔT_{bd}	[K]	Bubble and dew temperature difference
x	[-]	Vapor quality

Although the LNG industry has been developed for several decades, it is very difficult to find such measured nucleate pool boiling, flow boiling and flow condensation heat transfer data of R50, R170 and their mixtures in open published literatures. Nucleate pool boiling heat transfer curves for pure nitrogen, oxygen, argon, R50, and carbon tetrafluoride were measured on a horizontal, flat, circular, platinum plated disk for saturation pressures ranging from 0.1 MPa or less to the immediate vicinity of the critical pressure for each liquid by Kosky and Lyon [1]. It was found that boiling hysteresis of a type not previously reported was observed at intermediate and high saturation pressures on the surface for oxygen, argon, R50, and carbon tetrafluoride. von Hoffmann [2] measured the pool boiling heat transfer coefficients of nitrogen, R50, R170 and mixtures of nitrogen/R50 and R50/R170 at different pressures. He concluded that the Happel and Stephan correlation provided a good agreement with the results for the mixtures. Bier and Lambert [3] reported their measurement of the pool-boiling heat transfer for some low-boiling substances such as R50, R170, and argon, in which a horizontal copper cylinder with an outer diameter of 8 mm was used as the heat surface. Similarly, measurements of pool boiling heat transfer from single plain tubes with different degrees of surface roughness and different wall materials to R170, R290, propylene and hexane at saturation pressures of 0.03-3.9 MPa were reported by Gorenflo et al. [4]. It was shown that the effect of the heated wall on heat transfer coefficient was more complex than that considered by correlations. Chen and Shi [5,6] presented experimental studies on flow boiling heat transfer and pressure drop of LNG in vertical and horizontal smooth tubes with inner diameters of 8 and 14 mm at various inlet pressures from 0.3 to 0.7 MPa with mass flux of 16-200 kg m^{-2} s^{-1} and heat flux of 8-36 kW m^{-2}. The influences of vapor quality, inlet pressure, mass flux, heat flux and tube diameter on the heat transfer coefficient were examined and discussed. Maråk [7] investigated the condensation heat transfer and pressure drop of R50 and binary R50 mixtures in small vertical channels with inner diameters of 0.25, 0.5 and 1 mm. The experiments were conducted at the mass flux of 140-1370 kg m^{-2} s^{-1}, condensing pressure of 0.7-4.1 MPa, heat flux of 7.2-50 kW m^{-2} and vapor quality of 0.12-0.87. Compared with pure R50 condensation, the heat transfer coefficients were impaired as the drop in the interface temperature caused by the mass transfer effect for binary R50 mixtures. Macdonald and Garimella [8] showed the experimental data of flow condensation heat transfer coefficients of R170/R290 in a horizontal tube with inner diameter of 7.75 and 14.45 mm. The experiments were carried out at the reduced pressure varying from 0.46 to 0.87 and mass flux varying from 150 to 450 kg m^{-2} s^{-1}. The results pointed out that the degradation in heat transfer coefficient due to mixture effects was most significant at large temperature glides and in the larger tube diameter, and was least significant at higher mass fluxes. As can be seen above, only a few studies on nucleate pool boiling, flow boiling and flow condensation heat transfer are published.

This paper aims to present a comprehensive review of the experimental studies on nucleate pool boiling, flow boiling and flow condensation heat transfer of R50, R170 and their binary mixtures in TIPC. the related experimental conditions are summarized on **Table 1**.

Table 1 Experimental conditions of two phase heat transfer on R50, R170 and their mixtures in TIPC

Fluids	Component	p (MPa)	ΔT_{bd} (K)	q (kW m^{-2})	G (kg m^{-2} s^{-1})	x	D (mm)	References
Nucleate pool boiling heat transfer								
R50	——	0.1-0.4	——	0-400	——	——	——	[9-11]
R170	——	0.1-0.5	——	15-150	——	——	——	[12]
R50/R170	0.97/0.03, 0.93/0.07, 0.89/0.11, 0.85/0.15	0.1	26.1-42.2	25-250	——	——	——	[9]
Flow boiling heat transfer								
R50	——	0.3-0.6	——	5-62	110-350	0-0.25	6	[13]
R170	——	0.2-0.6	——	5-78	55-550	0-0.65	6	
R50/R170	0.76/0.24, 0.43/0.57, 0.31/0.69	0.3-0.7	39.67-55.3	5-62	150-250	0-0.2	6	
Flow condensation heat transfer								
R50	——	2-3.5	——	5.4-84.7	99-255	0-1	4	[14]
R170	——	1-2.5	——	21.3-104.2	99-257	0-1	4	[15]
R50/R170	0.27/0.73, 0.54/0.46, 0.7/0.3	1.5-2.5	47-51.3	15.2-42.3	99-255	0-1	4	

TWO PHASE HEAT TRANSFER DATA OF PURE R50 AND R170

Nucleate pool boiling

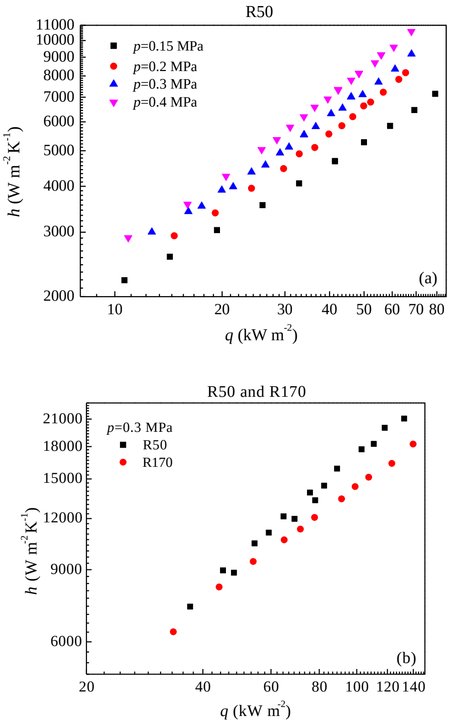


Figure 1 Nucleate pool boiling heat transfer data of R50 and R170

Figure 1 presents partial experimental data for nucleate pool boiling heat transfer on R50 and R170. For a given pressure, heat flux increases with the increasing surface superheat, and heat transfer coefficient increases nearly linearly as the heat flux increases in the double logarithmic coordinates. In addition, a higher saturation pressure results in a larger heat transfer coefficient for a given heat flux. It can be explained that higher pressure actives nucleation site density which improves the performance of nucleate pool boiling at a given surface superheat. Moreover, the heat transfer coefficients of R50 are larger than that of R170, and their difference increases with the increasing heat flux.

Flow boiling

Figure 2 illustrates partial experimental data for flow boiling heat transfer of R50 and R170. Similar as nucleate pool boiling, flow boiling heat transfer coefficient also increases with the increasing heat flux because of the nucleate boiling mechanism enhancing. The higher mass flux and vapor quality result in larger heat transfer coefficients. It can be explained that the forced convection boiling mechanism enhances with the increase of mass flux and vapor quality. The flow boiling heat transfer coefficient increases with the increasing saturation pressure in high heat flux, while the tendency is not obvious in low heat flux. As the saturation pressure increases, the nucleate boiling mechanism can be enhanced, and the forced convection boiling mechanism can be suppressed. A larger impact on nucleate boiling mechanism in higher heat flux leads to the flow boiling heat transfer coefficient increases with increasing saturation pressure. The flow boiling heat transfer coefficients of R50 are also larger than that of R170 similar to nucleate pool boiling. And the values of flow boiling heat transfer coefficients of R50 and R170 are higher than that of nucleate pool boiling on account of the effect of forced convection boiling mechanism.

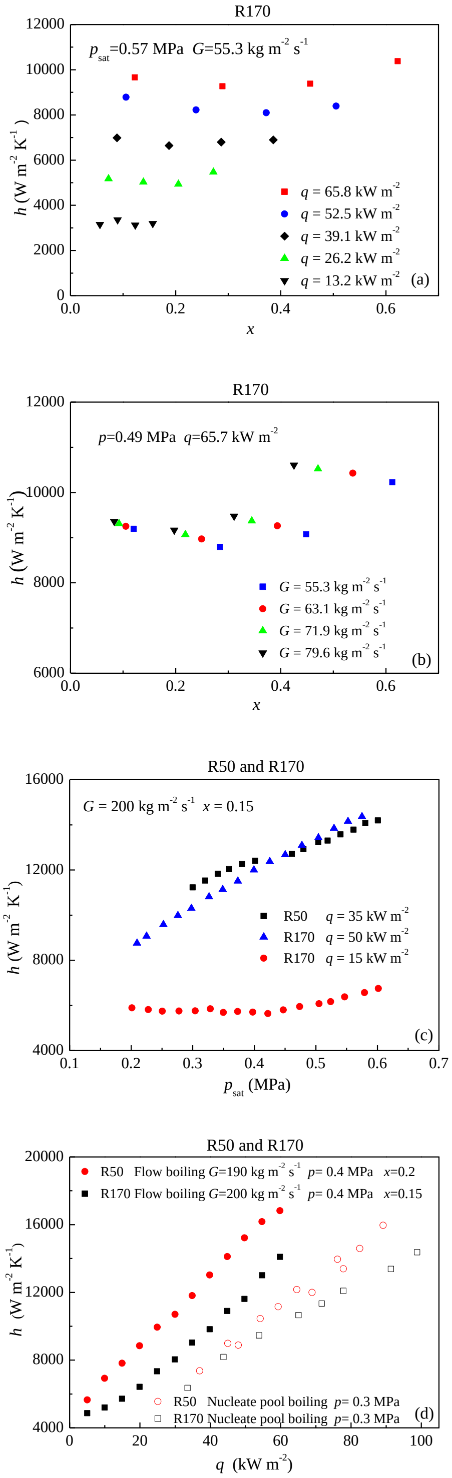


Figure 2 Flow boiling heat transfer data of R50 and R170

Flow condensation

Partial experimental data for flow condensation heat transfer of R50 are showed in **Figure 3**. Similar as flow boiling, the flow condensation heat transfer coefficient also increases with the increasing mass flux and vapor quality. Unlike flow boiling, the flow condensation heat transfer coefficient decreases with the increase of saturation pressure. The reason is that the flow condensation heat transfer coefficient has strong relation to the forced convection condensation mechanism which is suppressed by the increasing saturation pressure. In addition, the change of fluid-to-wall temperature difference affects little on the condensation heat transfer coefficients in a wide range of temperature difference under the experimental conditions. The reason is that the forced convection condensation mechanism which is independent of the temperature difference is the main heat transfer mechanism under the experimental conditions. The flow condensation heat transfer coefficients of R50 are also larger than that of R170 similar to nucleate pool boiling and flow boiling.

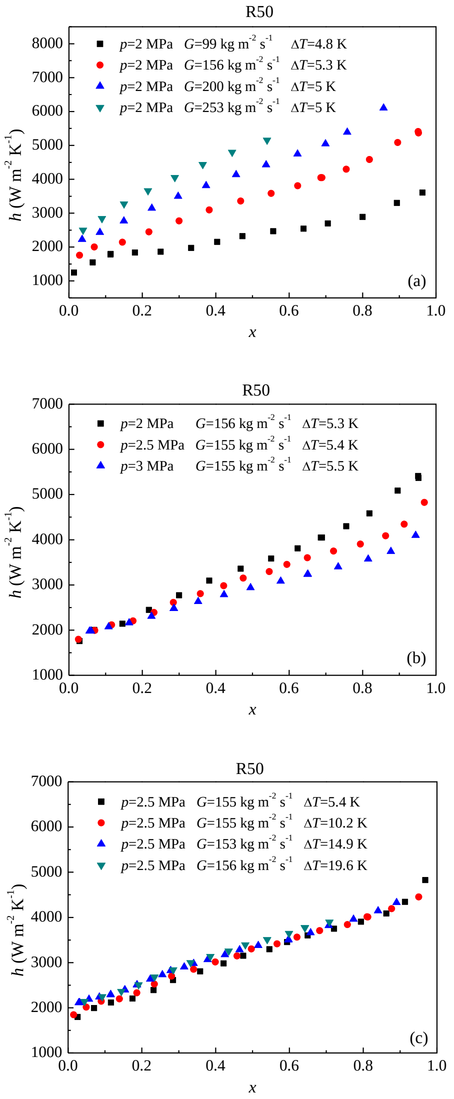


Figure 3 Flow condensation heat transfer data of R50

THE TWO PHASE HEAT TRANSFER DATA OF R50/R170 BINARY MIXTURE

Nucleate pool boiling

Figure 4 presents the nucleate pool boiling curves of R50/R170 at 0.13 MPa. It can be seen that the heat transfer performance of the mixtures are significantly degraded with the increasing molar concentration of R170 as the wall super heat increases. Since the mixtures of R50/R170 are zeotropic mixtures, there are large bubble and dew temperature differences (ΔT_{bd}) shown in **Table 1**. The decrease of heat transfer coefficient is due to the change of the mixture properties and the mass transfer resistance near the boiling surface. R50 which is the component with low-boiling temperature to R170 vaporizes first, and R170 almost remains liquid phase during the test. Thus, the concentration of R170 increases in the boiling boundary layer and contributes a lot to the mass transfer resistance. This deteriorates the boiling heat transfer. And the deterioration becomes obvious with the increasing concentration of R170.

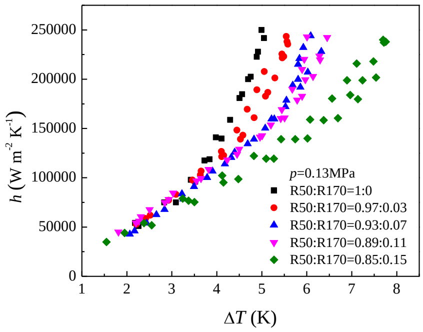


Figure 4 Nucleate pool boiling curves of R50/R170

Flow boiling

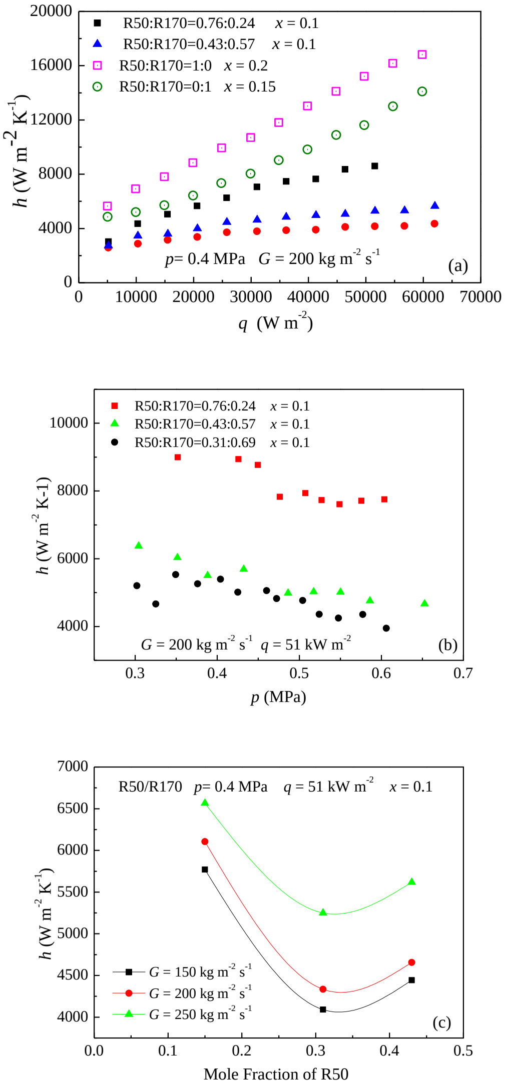
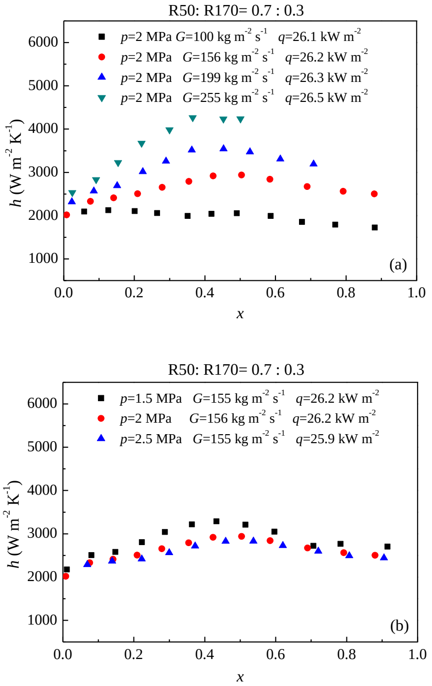


Figure 5 Flow boiling heat transfer data of R50/R170

Figure 5 illustrates partial experimental data for flow boiling heat transfer on R50/R170. Similar as pure R50 and R170, the higher heat flux and mass flux result in larger heat transfer coefficients. However, the influence extent of heat flux on mixtures is suppressed compared to pure fluids especially for the R50 molar concentration of 0.31. The reason is that the nucleate boiling mechanism is suppressed by the mass transfer resistance. Unlike pure fluids, the flow boiling heat transfer coefficient decreases with the increasing saturation pressure for the mixtures. As the saturation pressure increases, the nucleate boiling mechanism can be enhanced, while the forced convection boiling mechanism can be suppressed. A larger impact on forced convection boiling mechanism for the mixtures of R50/R170 leads to the flow boiling heat transfer coefficient decreased with the increase of saturation pressure. For mixtures, the flow boiling heat transfer coefficients are also obvious lower than the pure fluids, in particular with a higher heat flux and a lower mass flux. The mass transfer resistance reduces as the heat flux decreases and mass flux increases.

Flow condensation

Partial experimental data for flow condensation heat transfer of R50/R170 are showed in **Figure 6**. Similar as pure R50 and R170, the heat transfer coefficient increases with the increasing mass flux and decreases with the increase of saturation pressure. However, the influence extent of saturation pressure on mixtures is suppressed especially for higher R50 molar concentration and in high vapor quality. The mass transfer resistance enlarges as the R50 molar concentration increases in high vapor quality. In addition, the flow condensation heat transfer coefficient increases with the increasing heat flux for the mixtures like the flow boiling in low vapor quality when the flow pattern is non-annular flow. And the impact enhances as the R50 molar concentration increases and vapor quality decreases. The heat transfer coefficients for mixtures are higher than pure R170 while lower than pure R50 in low vapor quality. And in high vapor quality, the heat transfer coefficients for mixtures are lower than both pure R50 and R170. It can be explain that the effect of mass transfer resistance is more obvious in high vapor quality than in low vapor quality.



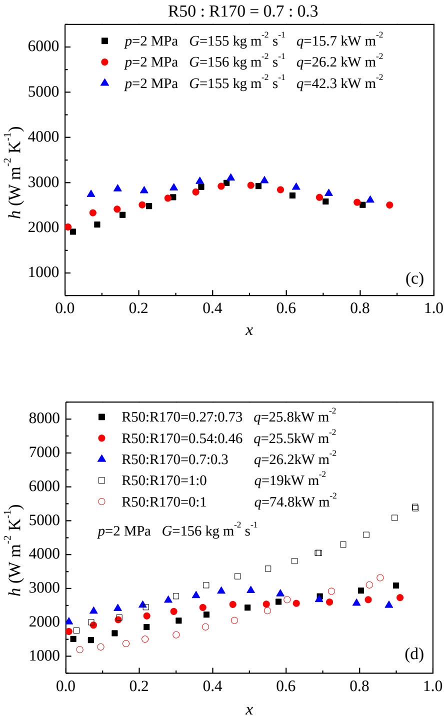


Figure 6 Flow condensation heat transfer data of R50/R170

CONCLUSIONS

A comprehensive review of the studies on nucleate pool boiling, flow boiling and flow condensation heat transfer of R50, R170 and their binary mixtures in TIPC is presented in this paper. The related heat transfer data cover a wide range of experimental conditions. Those heat transfer data has been used in designing and manufacturing LNG facilities such as a portable small liquefier for natural gas or coal-bed methane liquefaction which has many advantages over a traditional fixed LNG plant for scattered gas resources [16]. In the future, authors of present work intends to continue this study to a wider condition range on nucleate pool boiling, flow boiling and flow condensation heat transfer, and would carry out other studies on other cryogenic refrigerants and the multicomponent mixtures which used in composing mixture refrigerants for the low-temperature Joule-Thomson refrigerator.

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