

Investigation of Condensation Heat Transfer Characteristics for R1234ze(E), R32, R410A and Zeotropic Mixture of R1234ze(E) and R32 inside Smooth Tube

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Abstract

This research work presents experimental results of two-phase flow condensation heat transfer characteristics of the refrigerants R1234ze(E), R32, R410A and zeotropic mixtures of R1234ze(E)/R32 (55/45 and 70/30 mass%) inside smooth horizontal tube. The test section is a horizontally installed smooth tube with effective length of 3.6 m and inner tube inner diameter of 4.35 mm. The experiment has been carried out under the conditions of mass flux varying from 150 to 445 kg m⁻² s⁻¹, at condensation saturation temperatures 35, 40 and 45°C over the vapor quality range of 0.0 to 1.0. The effect of vapor quality, mass flux and saturation temperature on HTC have been conducted and analyzed. The experimental results show that the heat transfer coefficient decreases as the condensation progresses for both pure and mixture refrigerants. The refrigerants exhibit high heat transfer coefficient at the high mass flux. There is not so significant effect of saturation temperature on the heat transfer coefficient. The mixtures show lower heat transfer coefficient than pure. Among the mixtures, 70% R1234ze(E) shows lower heat transfer coefficient than 55% R1234ze(E) mixture. It is seen from the results that the heat transfer coefficient of R1234ze(E)/R32 (55/45 mass %) is almost similar to R410A. So, Zeotropic mixture of R1234ze(E)/R32 (55/45 mass %) could be a good alternate of R410A.

Keywords: Zeotropic mixture, Refrigerant, Heat transfer coefficient.

1. Introduction

Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) have been phased out under the Montreal and Kyoto protocol, respectively. HFOs (hydrofluoroolefins) such as R1234yf and R1234ze(E) have much more awareness in recent era because of their low global warming potential (GWP). Pure R1234ze(E) is inferior in the fields of room and packaged air conditioning and heat pump systems because of low operating pressure. HFC refrigerant, especially R32 (difluoromethane) is a high pressure and superior as a refrigerant. R32 has also relatively lower GWP among HFCs. So, mixture of R1234ze (E) and R32 can be effectively used in the field of air conditioning due to their mild impact on environment. Two special attributes of zeotropic mixture are identified as temperature glide and composition shift during phase change can possibly be utilized to improve the energy efficiency or the coefficient of performance of a system for cooling/heating application. Some property measurement works had done such as Akasaka, Brown et al., Grebenkov et al., Higashi, Miyara et al., Motta et al., Srinivasan et al., Tanaka et al., Yamaya et al. [1-9] are listed in the reference. Hossain et al. [10] experimentally studied on condensation heat transfer and pressure drop in horizontal smooth tube for R1234ze (E), R32 and found that for mass flux of around 300 kg m⁻² s⁻¹, HTC of R1234ze(E) is about 30% lower than R32 and about 28% higher than R410A. Koyama et al. [11] recommended that pure R1234ze (E) is not suitable for an alternative of R410A, but mixtures of R1234ze(E) and R32 are promising candidates for replacing R410A in domestic heat pump systems. The present work deals with the comparative study of heat transfer coefficient of R1234ze(E), R32, R410A and zeotropic mixtures R1234ze(E)/R32 (55/45, 70/30 mass%) during horizontal in-tube condensation.

2. Experimental Method

Fig. 1 shows the schematic diagram of the experimental apparatus which is a vapor compression heat pump cycle comprising a inverter controlled compressor, an oil separator, a condenser, a subcooler, an expansion valve and a test condenser. Cold water kept at a constant temperature is supplied to the test condenser from the source unit. The refrigerant flow rate is regulated by varying the rotating speed of the compressor and opening the expansion valve and is measured by a coriolis type mass flow meter. Fig. 2 shows the test section. The test section is a horizontally installed double tube heat exchanger. The total length of the test section is 6.59 m where the effective heat transfer length is 3.6 m which is split into two parts for space accommodation and connected the two parts by a U-bend. Refrigerant flows inside an inner tube and cooling water flows through the annular space in a counter current. In order to measure quasi-local heat transfer, the annular channel is divided into 12 subsections with each 2 subsection length 300 mm. The inner tube is the smooth test tube made of copper and of

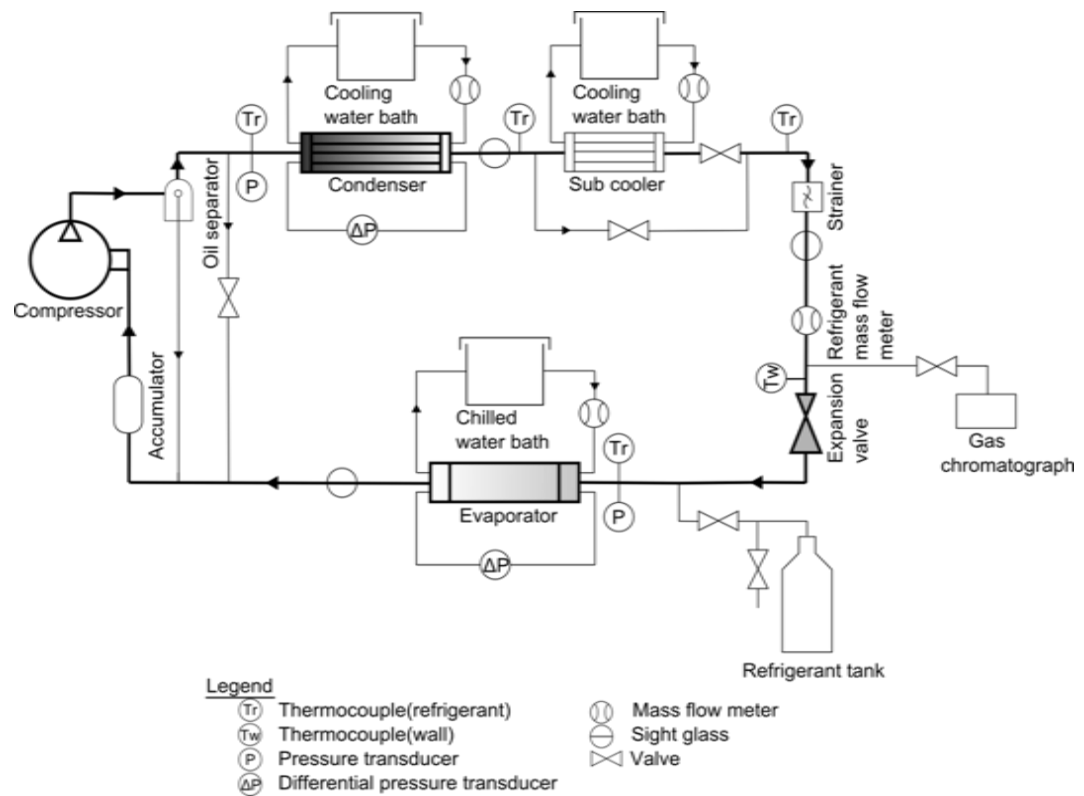


Fig. 1. Schematic diagram of experimental apparatus

4.35 mm inner diameter and 6.35 mm outer diameter. The outer tube is made of poly-carbonated resin and of 9 mm inner diameter and 13 mm outer diameter. Details of the experimental measurement and uncertainties has discussed in Hossain et al. (2012) [16].

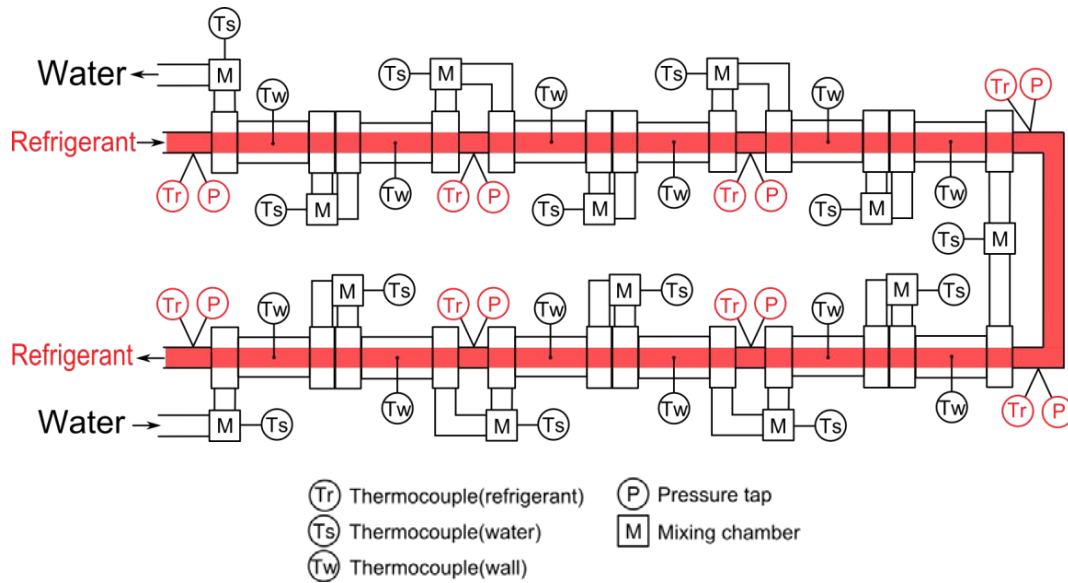


Fig. 2. Test section

The quasi-local condensation heat transfer coefficient of each subsection is defined as follows-

$$\alpha_{\text{exp}} = \frac{q_R''}{T_s - T_{wi}} \quad (1)$$

where, α_{exp} is local heat transfer coefficient, T_s is the saturation temperature of the refrigerant, q_R'' is refrigerant heat flux and T_{wi} is the inner tube wall temperature. The representative inner wall temperature at middle length of each subsection of the test tube is obtained by

$$T_{wi} = T_{wo} - \frac{q_s \eta_{HB} \ln(d_o / d_i)}{2\pi\lambda_c \Delta z} \quad (2)$$

Here, T_{wo} is average outer wall temperature calculated from measurement point of Top, right, bottom and left, q_s is heat transfer rate for the subsection, η_{HB} is heat balance factor, d_o, d_i are outer and inner diameter of the tube, λ_c is coolant thermal conductivity, and Δz is the pressure drop length. Table 1 shows the experimental conditions.

Table 1 Test range for the condensation experiment

Refrigerant	R1234ze (E)	R32	R410A	R1234ze(E)/R32
G ($\text{kg m}^{-2} \text{s}^{-1}$)	147-403	220-400	215-400	169-395
T_{sat} ($^{\circ}\text{C}$)	35, 40, 45	40	40	35, 40, 45
x (-)	0.02-0.99	0.007-0.99	0.007-0.99	0.01-0.98
P (kPa)	650-900	2505-2641	2339-2440	1462-1987

3. Results and Discussion

Fig.3 shows the flow pattern map plotted by using El Hajal et al equations. Fig. 3(a) is for pure refrigerants and Fig. 3(b) is for R1234ze(E)/R32(55/45 mass%) zeotropic mixture at the saturation temperatures of 35, 40 and 45°C for condensation inside a horizontal smooth tube. It is seen from the figures that most of the data points are in the intermittent and annular flow and a very few are in the stratified wavy flow regime.

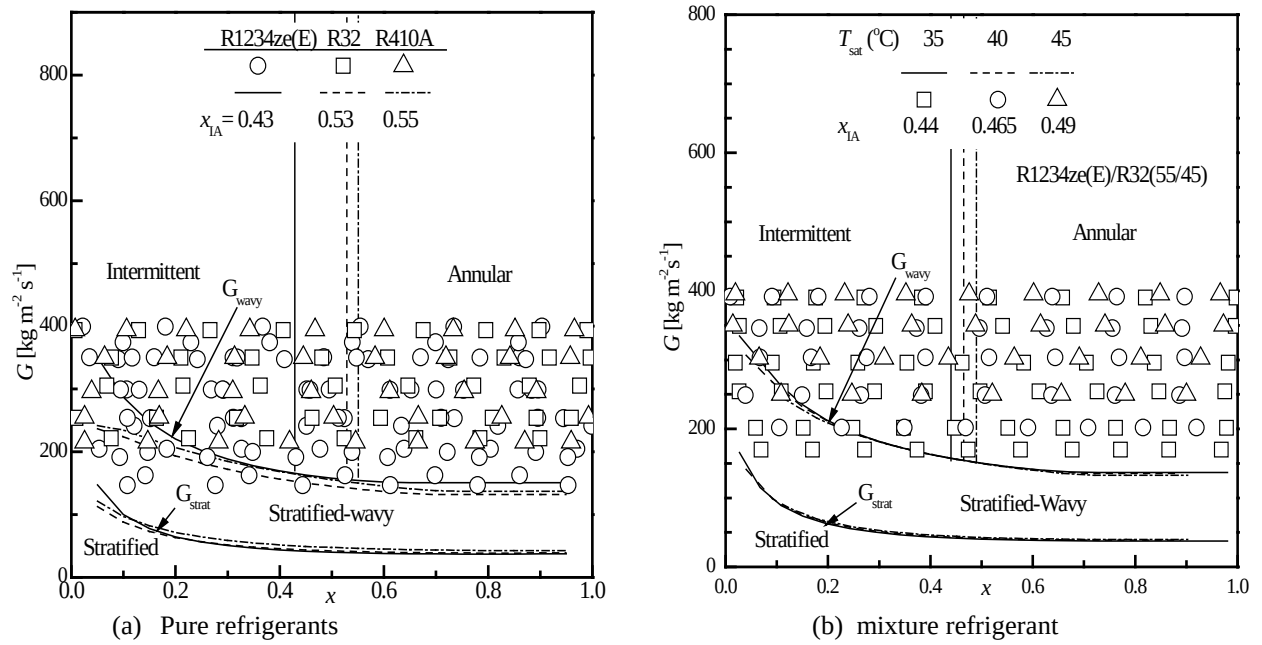


Fig. 3. Flow pattern map plotted by using El Hajal et al. (2003)

It is seen from the flow pattern map that there is noticeable variation among the transitional vapor quality (x_{IA}) between intermittent flow and annular flow among the pure refrigerants R1234ze(E), R32, R410A and mixture refrigerant at saturation temperatures of 35, 40 and 45°C because (x_{IA}) is a function of density and viscosity ratio. As the ratio of density and viscosity is high the value of (x_{IA}) will be low Hajal et al (2003). For pure refrigerants, x_{IA} is higher for R410A and R32 from R1234ze(E) because of density ratio. For mixture, x_{IA} increased with increasing saturation temperature due to the increased of density and viscosity ratio. Fig.4 shows the effect of saturation temperature on experimental heat transfer coefficient for R1234ze(E)/R32 (55/45 mass%). It is seen from this figure that there is not so significant effect of saturation temperature on the heat transfer coefficient because with saturation temperature change the system pressure also change as well as the thermal and transport properties of the refrigerants.

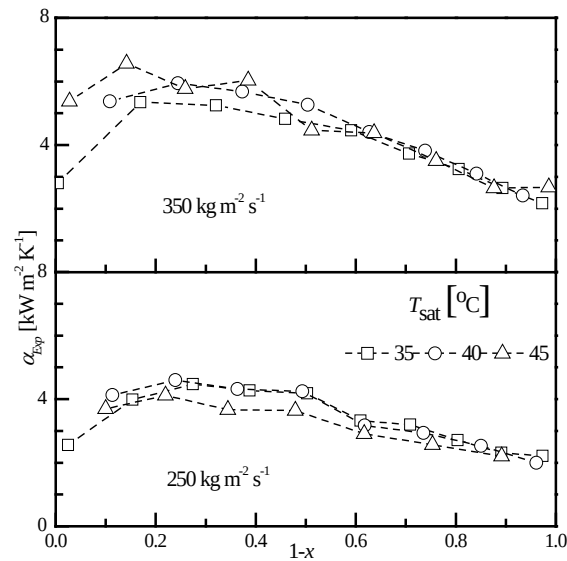


Fig. 4. Effect of saturation temperatures on experimental heat transfer coefficient for R1234ze (E)/R32 (55/45 mass %).

Fig.5 shows the local heat transfer coefficient variation along the tube with respect to $(1-x)$ at 40 °C saturation temperature and at 300 and 400 kg m⁻² s⁻¹ mass flux of refrigerants R1234ze (E), R32, R410A and mixtures of R1234ze (E) and R32. Experimental results show that the heat transfer coefficient decreases as the condensation progresses for both pure and mixture refrigerants. The mixtures show lower heat transfer coefficient than the pure R1234ze (E) and R32 and among the mixtures, 70% R1234ze (E) shows lower heat transfer coefficient than 55% R1234ze (E) mixture.

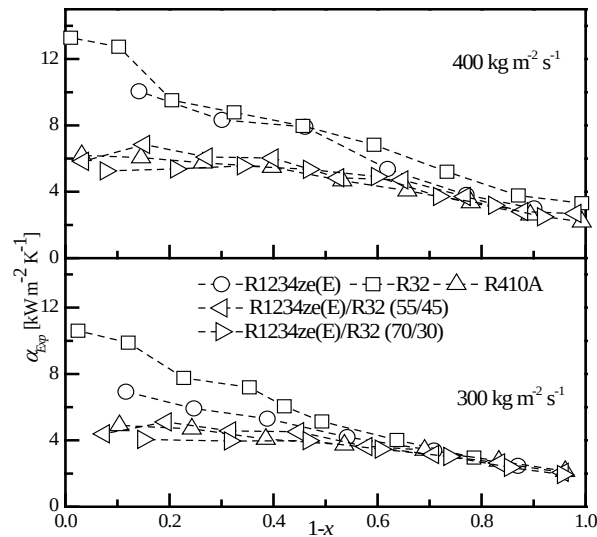


Fig. 5. Comparison of experimental local heat transfer coefficient.

The variation of temperatures of the refrigerants and tube wall are shown in Fig.6 and the variation of the heat flux is shown in Fig.7. When condensation occurs at the vapor-liquid interface of the mixture the temperature at the interface is always less than the temperature of the axial vapor flow, so that the mass fraction of more volatile component (R32) at the interfacial vapor is always greater than the mass fraction of the bulk axial vapor flow.

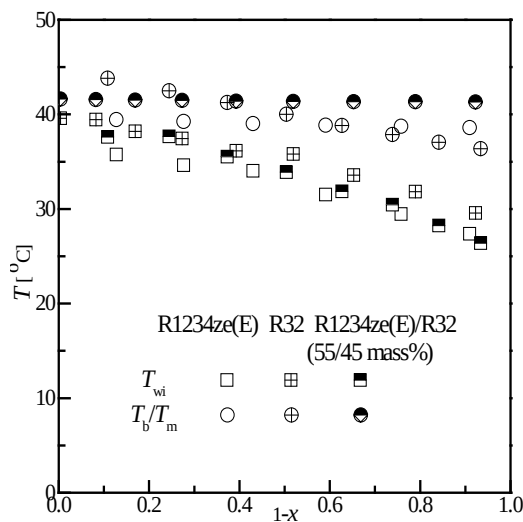


Fig.6. Temperature variation with vapor quality at mass flux 350 kg m⁻² s⁻¹ and $T_{sat}=40$ °C.

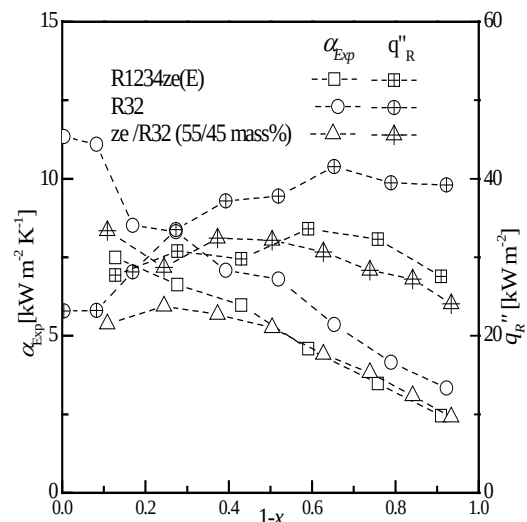


Fig.7. Effect of vapor quality on heat flux and heat transfer coefficient at mass flux 350 kg m⁻² s⁻¹ and $T_{sat}=40$ °C.

A counter diffusion of more volatile component (R32) from the interface to the bulk vapor flows occurs, which retards the mass diffusion from the vapor core to the interface and results in a reduction of the condensation and thus the heat transfer rate. This mass transfer resistance also causes decrease of vapor-liquid interface temperature and heat transfer is degraded. Moreover, the higher liquid thermal conductivity of pure R32 is

responsible for its higher heat transfer coefficient than the mixture. Among the mixtures, 45% R32 mixture has higher liquid thermal conductivity than the 30% R32 mixture at same saturation temperature [5] so the later shows higher HTC than the former. In comparison with R410A, 45% R32 mixture shows higher heat transfer coefficients than that of the R410A while for 30% R32 mixture it is closer to the R410A. Fig.5 also shows that the refrigerants R1234ze(E), R32, R410A and the mixtures exhibit high heat transfer coefficient at the high mass flux. This is due to the thin liquid film on the tube surface at high mass flux. For the mixture, the effect of the mass transfer resistance due to the composition and temperature shift of the vapor phase decreases as the vapor velocity increases. R1234ze(E) is more dominant by mass flux because the force convection is more effective for R1234ze(E).

4. Conclusion

The condensation heat transfer coefficient of R1234ze (E), R32, R410A and zeotropic mixture R1234ze (E)/R32 has been measured experimentally. The local heat transfer coefficient of pure R1234ze (E), R32 and R410A is higher than the mixtures and as the mass fraction of R32 increases in the mixture the heat transfer coefficient increases. The effect of saturation temperature on heat transfer coefficient is not so significant during condensation of R1234ze (E)/R32 mixture inside smooth tube. It can be concluded that pure R1234ze (E) is not suitable for an alternative of R410A, but mixtures of R1234ze(E) and R32(55/45 mass %) are promising candidates for replacing R410A in domestic heat pump systems.

5. References

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