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ABSTRACT

In this study, boiling and condensation heat transfer characteristics of refrigerant R1234yf flowing inside a channel of plate heat exchanger were experimentally investigated. The test section consists of 8 plates where the refrigerant flow channel is formed by two plates grooved chevron pattern. Other plates are used to measure local temperature distribution and to form cooling /heating water channel. In this experiment three vertical flow channel exist in the test section and where the refrigerant flows in the middle channel (upward or downward directions) depending on evaporation or condensation process. In case of evaporation process the refrigerant flows upward in the middle channel and heat source water flows downward in the outer two channels. In condensation, refrigerant flows downward in the middle channel and the cooling water flows upwards in the two outer channels. In the test section, there are 160 measurement points in total with 4 sets of 8 symmetrical points in the horizontal direction and 5 symmetrical points in the vertical direction. In order to measure local heat transfer characteristics of the R1234yf, 20 thermocouples were set in the test section for measurement of wall temperature of the refrigerant and heat source water side. Local heat transfer coefficient was obtained under the experimental conditions of the mass flux of 10kg/$(m^2$s) and 50 kg/(m^2s). The local heat transfer coefficient is varied in horizontally and vertically. Local dryout in evaporation process was identified. The data of the R1234yf was also compared with the R32.

1. INTRODUCTION

In the technical field of refrigeration and air-conditioning, plate heat exchangers are getting attention due to their compactness and high thermal efficiency. Although these were mainly designed for liquid single-phase heat exchanger, its application was extended to two phase heat exchangers such as condensers and evaporators. Condensation and evaporation heat transfer coefficients in plate heat exchangers have been studied by many researchers. Most of the existing literatures, however, discussed mainly overall heat transfer characteristics (Longo et al., 2010, Yan et al., 1999). Local heat transfer behavior has not been clarified sufficiently. Because of the effects on global warming by the refrigerants used in the present heat pump/refrigeration systems, new synthetic refrigerants, hydrofluoroolefins (HFOs), which have low global warming potential (GWP) are recently getting attention as next generation refrigerants (Miyara et al., 2012, Zhang et al., 2017, Kariya et al., 2018). Longo et al. (2012, 2013, 2014, 2019) measured condensation and evaporation heat transfer of low GWP refrigerants, R1234yf, R1234ze(E), R1234ze(Z) and R1233ze(E) in a plate heat exchanger. Kwon et al. (2019) investigated condensation heat transfer and pressure drop of R1233zd(E) in a plate heat exchanger. When the plate heat exchangers are used as evaporator and/or condenser, maldistribution of refrigerant flow occurs in channels between the plates and headers to distribute it to the channels. This maldistribution deteriorates the heat exchanger performance. And local heat transfer coefficient may vary at flow direction and width direction in plate heat exchangers. It is important to investigate flow characteristics for understanding the heat transfer characteristic and for enhancing the heat transfer. Jin and Hrnjak (2017) observed flow characteristic during boiling heat transfer of R245fa in a plate heat exchanger. Lee et al. (2019) investigated two phase flow pattern of upward flow and pressure drop characteristics of R1234ze(E) in a plate hear exchanger under adiabatic conditions.

The data have been obtained from overall heat transfer performance and there is no sufficient discussion about local heat transfer characteristics. The local heat transfer coefficient varies not only flow direction but also width direction by gas-liquid distribution. In order to further understand the heat transfer characteristics, information about the local heat transfer is necessary. However, measurements of local wall temperatures and heat fluxes are difficult because of the complicated structure. In the present study, a specially designed test section has been constructed for the measurement of local heat transfer coefficient. Experiments on condensation and evaporation heat transfer of a low GWP refrigerant, R1234yf were carried out and local heat transfer characteristics were discussed.

2. EXPERIMENTAL SETUP AND THE DATA REDUCTION METHOD

2.1 Flow Loop of Refrigerant

Figure 1 shows experimental flow loop of refrigerant. It mainly consists of magnet pump, pre-heater, test section and cooler. After the refrigerant flows from magnet pump, mass flow rate is measured by coriolis flow meter. Then the refrigerant is heated by the pre-heater to set a designated enthalpy condition at the inlet of test section. After the refrigerant flows out through the test section, it is cooled by the cooler to keep a certain subcooling. And the subcooled liquid comes back to the magnet pump. Mixing chambers are installed at inlet of the pre-heater and inlet and outlet of the test section to obtain the bulk enthalpy from measured refrigerant pressure and temperature at the mixing chamber. The refrigerant is heated or cooled by water of which temperature is controlled by thermostatic bath. The flow rate of refrigerant is controlled by the flow control valve and the rotation speed of magnet pump.

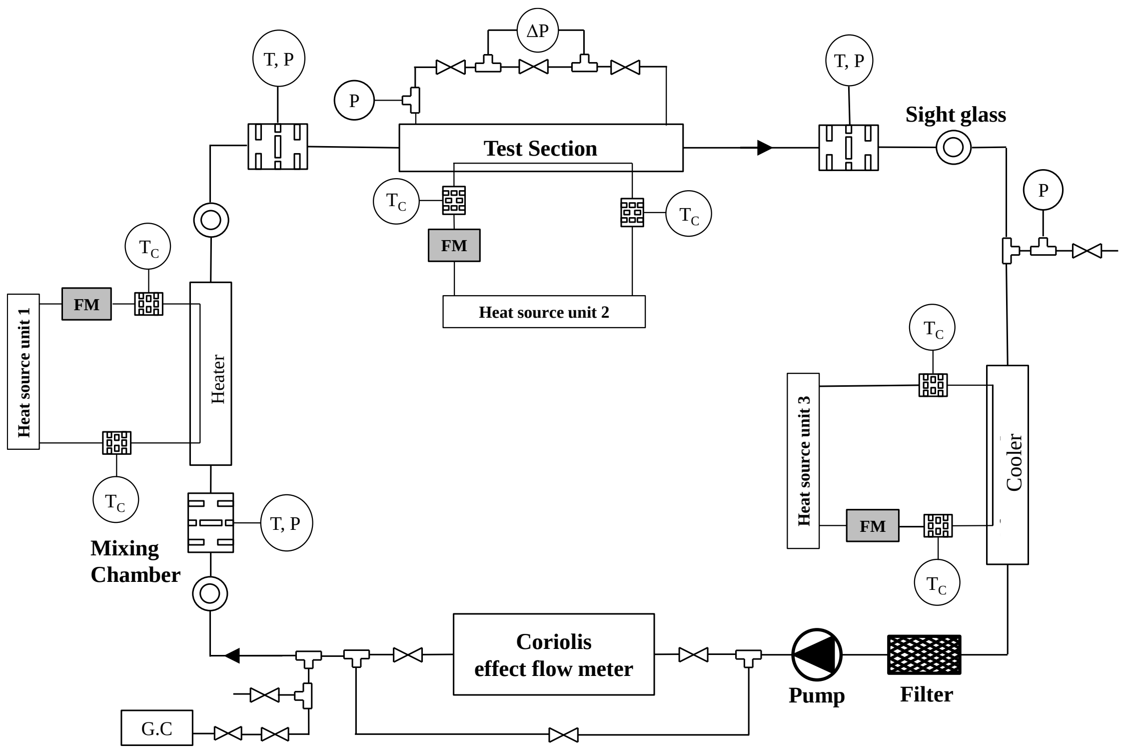


Figure 1: Schematic diagram of refrigerant flow loop

2.2 Test Section

For the measurement of local heat transfer characteristics of plate heat exchanger, a specially designed test section has been produced same as our previous study Kariya et al., 2018). Figure 2 shows the schematic of test section and the installed points of thermocouples with the photograph. Red and blue hatching region in right hand side of the figure indicate respectively refrigerant and cooling/heating water channels. Chevron shape grooved are dug over a stainless steel plate of which length, width and thickness are 186mm, 84mm and 5mm, respectively. The pitch and depth are 5.6mm and 1.5mm, respectively. A channel of the plate heat exchanger where the refrigerant flows is constructed by facing two grooved plats. Next of the grooved plates, flat plates are set to measure heat flux. Plates for the water channel are set outside of the flat plates. Whole of the test section is constructed with eight different kinds of plates which are brazed each other. The chevron directions of each plates which make a refrigerant flow channel are reversely assembled so that heat transfer enhance. The flat plates with 10mm in thickness have holes of 1.6mm in diameter on both sides where wire T-type thermocouples are installed and temperatures are measured. Positions of the temperature measurement are set at 4, 12, 20, 28, 36, 44, 52, 60 and 64 mm from end face of the cross section of the channel. Position of the inlet and outlet of refrigerant are 20 mm. Temperatures of local heat transfer surface at refrigerant and water sides are estimated from the measured temperature as explained later. The temperatures are also used to calculate the heat flux and heat transfer coefficient. The water channels consist of flat plates and the channel height is 5mm. Water flows into the channels from both sides of the test section, front and back. It should be noted, surface which have the inlet/outlet ports of refrigerant is called as inlet side and another side is call as opposite side. In addition, the center region is set for temperature measurement between the inlet and the opposite side as shown in the figure. The geometrical characteristics of the test section are listed in Table 1.

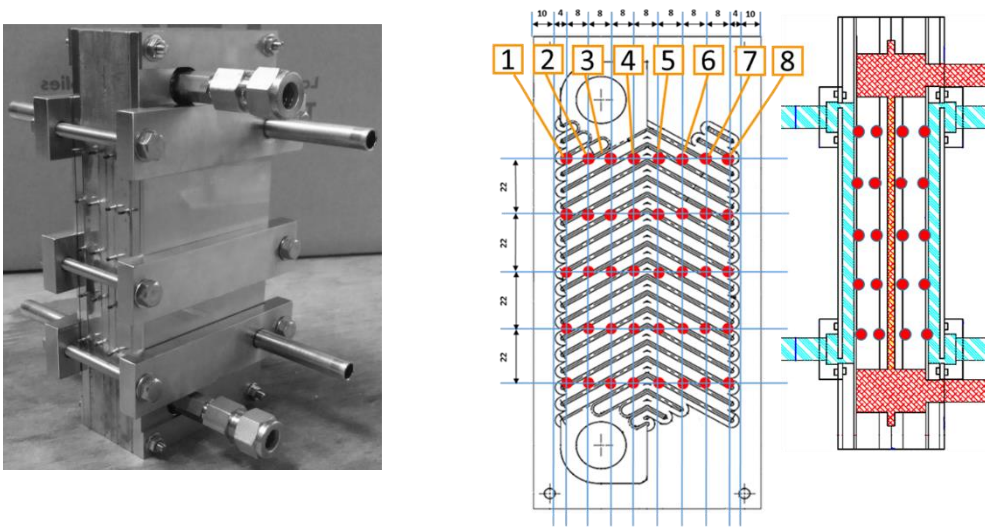


Figure 2: Photograph and Schematic of test section and place of temperature measurement

Table 1: Geometrical characteristics of the test section

Fluid flow plate length (mm)	117.5
Plate width (mm)	64
Area of the plate (m^2)	0.75
Corrugation type	Chevron
Angle of the corrugation (degree)	60
Corrugation pitch (mm)	5.6
Number of plates	8
Number of channels on refrigerant side	1
Number of channels on water side	2

2.3 Data Reduction Method

By assuming the steady sate one-dimensional heat conduction, the local heat flux q_x in test section is calculated from the temperatures measured at both sides of 10mm thick flat plates.

$$q_x = \frac{T_{w,ref} - T_{w,water}}{l} \lambda \tag{1}$$

plate. Wall surface temperature of refrigerant side is calculated with the following equation where the linear temperature distribution is assumed and the temperature is extrapolated to the representative of surface of refrigerant side. l_2 in the equation is the distance between the K-type thermocouple and the average surface of the refrigerant side.

$$T_{wall,x} = T_{w.ref} \pm \frac{q_x l_2}{\lambda} \tag{2}$$

The plus-minus sign means the plus for condensation experiment, and the minus for evaporation experiment.
The local heat transfer coefficient h_x is defined with the following equation.

$$h_x = \frac{q_x}{T_{wall,x} - T_{sat}} \tag{3}$$

Where, T_{sat} is the saturation temperature of refrigerant which is calculated from measured pressure. q_x and $T_{wall,x}$ are calculated with Eq.(1) and (2), respectively.
The local thermodynamic equivalent quality x in the plate channel is calculated by following equation.

$$x = \frac{i_x - i_l}{i_v - i_l} \tag{4}$$

Where i_x is the local specific enthalpy of the refrigerant, i_l and i_v are the specific enthalpy of saturated liquid. The local specific enthalpy can be calculated from the heat balance equation at the specific position, as explained in the following method.
First, specific enthalpy at inlet of pre-heater $i_{pre,in}$ is calculated by REFPROP version 10.0 (2019). And, the specific enthalpy at the test section inlet is calculated from the mass flow rate $\dot{m}$ and the heat transfer rate in the pre-heater Q_{pre}. Then specific enthalpy of inlet at test section i_{in} is calculated by follow equation.

$$i_{in} = i_{pre,in} + \frac{Q_{pre}}{\dot{m}} \tag{5}$$

Finally, the local specific enthalpy in the test section is calculated from mass flow rate $\dot{m}$ and the heat transfer rate from the inlet to a certain point which is obtained by integrating the heat flux, as expressed with the following equation.

$$i_x = i_{in} + \frac{1}{\dot{m}} \int_0^{A_x} q dA \tag{6}$$

3. RESULTS AND DISSCUSION

3.1 Experimental Condition

Table 2 indicates experimental conditions of the present study. Refrigerant is pure R1234yf. Flow direction of the refrigerant is the downward for condensation test and the upward for evaporation test. Saturated temperature are 30 °C and 13 °C for condensation and evaporation tests, respectively. Mass flux conditions are 10 and 20 kg/(m^2·s) in both experiments. In the case of mass flux 10 kg/(m^2·s) conditions for both condensation and evaporation experiment, temperature of cooling water (heat source at the test section) is controlled in order that the refrigerant flows into the test section as nearly saturated vapor (condensation) or liquid (evaporation) state and flows out as nearly saturated liquid (condensation) or vapor (evaporation). In the condition of mass flux 20 kg/(m^2·s), both condensation and evaporation experiment are carried out in two inlet conditions in order to measure large quality region. In the condensation and evaporation experiment, inlet conditions are nearly saturated vapor (condensation) or saturated liquid (condensation) and x = 0.5 (condensation and evaporation) with the same heat flux condition of mass flux 10 kg/(m^2·s).

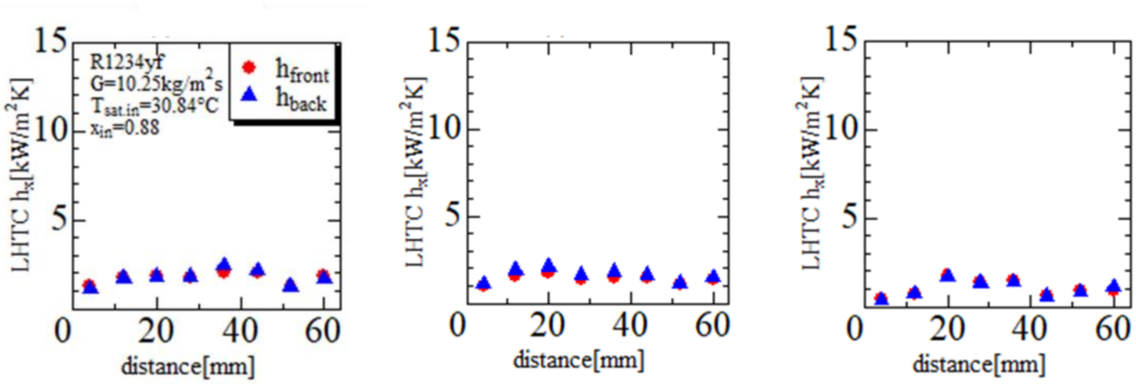
Table 2: Experimental conditions

	Refrigerant	Flow direction	T_{sat} [°C]	G [kg/(m²·s)]
Condensation	Pure R1234yf	Downward	30	10 and 50
Evaporation	Pure R1234yf	Upward	13	10 and 50

3.2 Results of Condensation

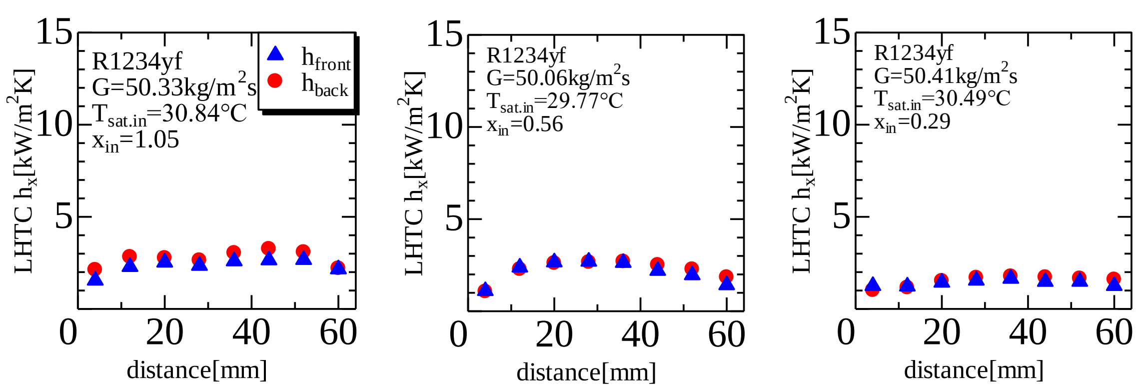
Figure 3 (a), (b) and (c) show condensation local heat transfer coefficient distribution of width direction of the channel at x = 0.63, 0.41 and 0.22 with mass flux G = 10 [kg/m²s], respectively. As shown in the figures, the position indicating maximum value of heat transfer coefficient is about 20 mm due to the inlet refrigerant effect and heat transfer coefficient represent the minimum value at the end face of the channel. The similar tendency is obtained in our previous study (Kawazoe et. al, 2015, Kariya et. al, 2016). From this result, it is inferred that maldistribution of condensate flow occurs in the channel of plate heat exchangers. It is also found that there are no remarkable difference of heat transfer coefficient between front and back side of the channel. Figure 4 (a), (b) and (c) show condensation local heat transfer coefficient distribution with G = 50 [kg/m²s], respectively. In this mass flux condition, experiments were conducted with three inlet quality condition in order to cover whole quality condition. Heat transfer coefficient characteristics is similar to the results of G = 10 kg/m²s (figure 3) and the value of heat transfer coefficients are slightly higher than that of G = 10 kg/m²s.

3.2 Results of Evaporation



(a) x = 0.63 (b) x = 0.41 (c) x = 0.22

Figure 3: Local condensation heat transfer coefficient (G = 10 kg/(m²·s))



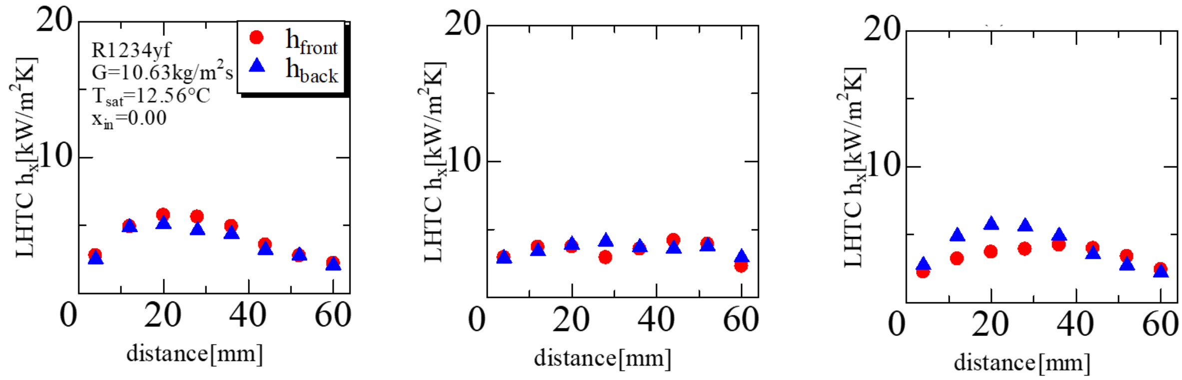
(a) x = 0.90 (b) x = 0.51 (c) x = 0.24

Figure 4: Local condensation heat transfer coefficient (G = 50 kg/(m²·s))

Figure 5 (a), (b) and (c) show evaporation local heat transfer coefficient distribution of width direction of the channel at x = 0.12, 0.37 and 0.74 with mass flux G = 10 [kg/m^{2}s], respectively. As shown in the figures, the position indicating maximum value of heat transfer coefficient is about 20 mm due to the inlet refrigerant effect and heat transfer coefficient represent the minimum value at the end face of the channel similar to the results of condensation experiment. The similar tendency is also obtained in our previous study (Kawazoe et. al, 2015, Kariya et. al, 2016). It is also found that there are no remarkable difference of heat transfer coefficient between front and back side of the channel. Figure 6 (a), (b) and (c) show condensation local heat transfer coefficient distribution with G = 50 [kg/m^{2}s], respectively. In this mass flux condition, experiments were conducted with two inlet quality condition in order to cover whole quality condition. Heat transfer coefficient characteristics is also similar to the results of G = 10 kg/m^{2}s (figure 5) and the value of heat transfer coefficients are slightly higher than that of G = 10 kg/m^{2}s.

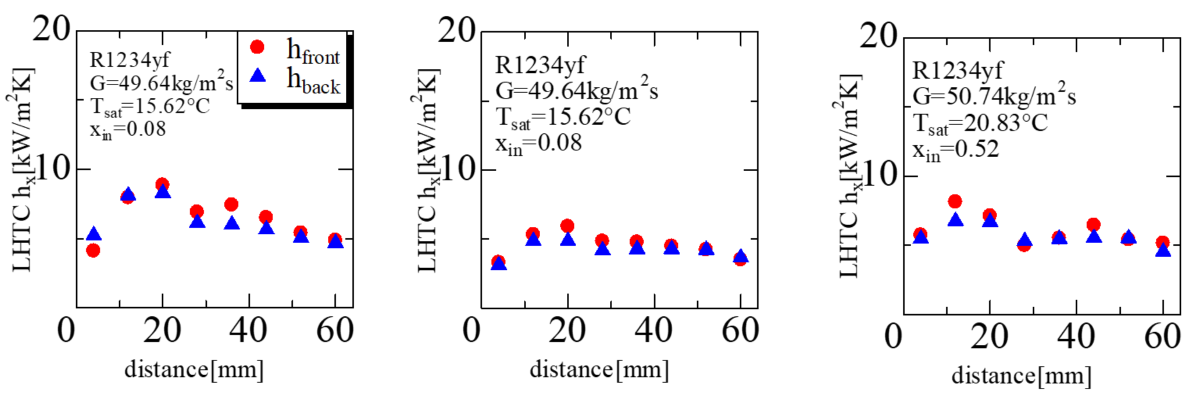
3.3 Comparison of another kind of refrigerant

Figure 7 (a) and (b) show comparison of cross-sectional average heat transfer coefficient of condensation and evaporation between R1234yf and R32 (Kariya et al, 2018), respectively. As shown in the figure (a), condensation heat transfer coefficient of R1234yf are about 50% lower than that of R32 in whole quality region. On the other hand, difference of evaporation heat transfer coefficient of R1234yf with G = 50 kg/(m^2·s) at high quality region decreases due to increasing HTC of R1234yf.



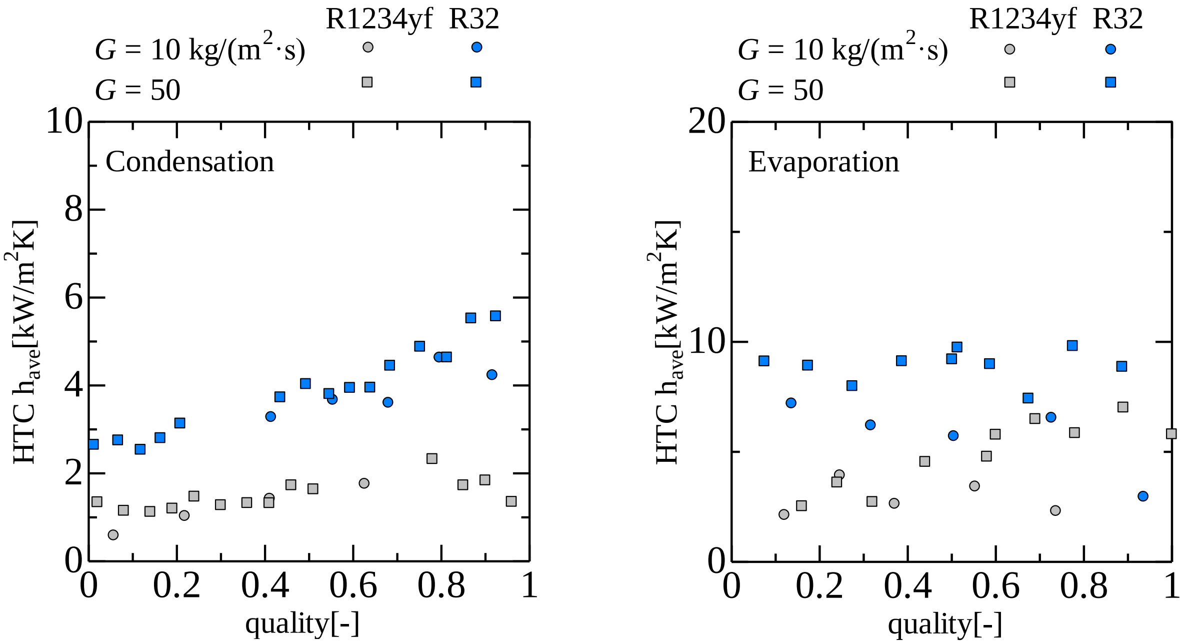
(a) x = 0.12 (b) x = 0.37 (c) x = 0.74

Figure 5: Local evaporation heat transfer coefficient (G = 10 kg/(m^2·s))



(a) x = 0.16 (b) x = 0.44 (c) x = 0.78

Figure 6: Local evaporation heat transfer coefficient (G = 50 kg/(m^2·s))



(a) Condensation (b) Evaporation

Figure 7: Comparison between R1234yf and R32 average heat transfer coefficient

4. CONCLUSION

In order to obtain local heat transfer coefficient during condensation and evaporation in plate heat exchanger, a special test section has been produced where the channel is formed with two stainless steel plate having chevron grooves. Experiments on condensation and evaporation of R1234yf have been carried out and the following results were obtained.

(1) From the measured wall temperatures at 160 points in the heat transfer wall, local heat transfer behaviour is considered for condensation and evaporation experiments.

(2) In condensation experiment, local heat transfer coefficient indicates maximum value near refrigerants inlet position and minimum value at end face position of cross section of the channel.

(3) Values of condensation heat transfer coefficient increase slightly with increasing mass flux.

(4) In evaporation experiment, local heat transfer coefficient indicates maximum value near refrigerants inlet position and minimum value at end face position of cross section of the channel.

(5) Values of evaporation heat transfer coefficient increase slightly with increasing mass flux.

(6) Values of condensation heat transfer coefficient of R1234yf are 50% lower than that of pure R32.

(7) Values of evaporation heat transfer coefficient of R1234yf are about 50% lower than that of pure R32 in the low quality region and approach to the R32 value with increasing quality.

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