Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

R245fa Evaporation Heat Transfer and Pressure Drop in a Brazed Plate Heat Exchanger for Organic Rankine Cycle (ORC)

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Key words: Heat transfer; Brazed plate heat exchanger; Heat transfer coefficient; Pressure drop; ORC

ABSTRACT

Evaporator which is of great importance in Organic Rankine cycle (ORC) receives less attention compared with the ORC system itself. An evaporator selected correctly not only can improve the thermal efficiency, but also can save refrigerant. It is crucial to determine the heat transfer features of refrigerant in an evaporator. In paper presents an experimental study on the heat transfer and pressure drop of R245fa in a brazed plate heat exchanger (BPHE) for organic Rankine cycle (ORC) was carried out. The effects in terms of heat flux, refrigerant mass flux, saturation temperature, and superheat degree at the outlet of the BPHE were investigated. Experiments were conducted for refrigerant mass flux ranging from 120 to 210 kg/h at saturation temperatures ranging from 78℃to 92 ℃. The heat flux was varied between 20 kw m^{-2} and 29kw m^{-2}. The current study indicated that the heat transfer coefficients show great sensitivity to heat flux and refrigerant mass flux. However, the corresponding pressure drop increased with increasing the mass flux and heat flux.

1. INTRODUCTION

Traditional plate heat exchangers (PHE) have been wildly used in processing, heat and power, air-conditioning and refrigeration, heat recovery, and other manufacturing industries for many years (Wang,2007). Compared with other heat exchangers, traditional PHE have some obvious advantages such as flexible thermal sizing, easy cleaning for sustaining extreme hygienic conditions, close approach temperature, and enhanced heat transfer performance. In the interest of energy conservation and space saving, PHE are being used in organic Rankine cycle (ORC) system. As refrigerants used in ORC are corrosive and high-pressure substance, traditional PHE are not proper. So another kind of PHE, the brazed plate heat exchanger (BPHE) in which stainless steel plates are vacuum brazed together using copper as the brazing material are employed.

In the open literature, it is possible to find some investigations on refrigerant vaporization inside PHE or BPHE. But the refrigerants used are mainly low-temperature and high-pressure refrigerant, such as R-134a, R-410A and ammonia. Besides, most experiments are conducted at air-conditioning condition. There are rather limited data available on evaporation features of refrigerants which are high-temperature and low-pressure in BPHE for ORC. In the following the relevant literature on the present work are briefly reviewed.

Yan and Lin (1999) experimentally investigated evaporation heat transfer and pressure drop of refrigerant R-134a inside BPHE in terms of mean vapor quality, mass flux, heat flux and saturation pressure. They showed that both the evaporation heat transfer coefficient and pressure drop increase with the vapor quality. In addition, empirical correlations for the evaporation heat transfer coefficient and pressure drop were proposed. With the same experimental facility used by Yan and Lin (1999), Hsieh and Lin (2003) extended their work by doing research on characteristics of heat transfer and pressure drop for R-410A flowing in a BPHE. From the measured data, raising the imposed heat flux is found to significantly improve the heat transfer coefficient for the entire range of the mean vapor quality, while the pressure drop is insensitive to the imposed heat flux and refrigerant pressure. Lee et al. (2013) reported experimental data on flow boiling heat transfer of R-134A in PHE at low mass flux condition in terms of vapor quality, heat flux, evaporation pressure, and mass flux. It indicated that heat transfer was mainly dominated by nucleate boiling heat transfer and the mass flux had a mild effect on the boiling heat transfer at a low fluid mass flux. Han et al. (2003) presented experimental data on evaporative heat transfer and pressure drop measured during R-410A and R-22 vaporization inside a BPHE, respectively. Attention was payed on the effect of mass flux, saturation temperature, vapor quality, heat flux and plate geometry (inclination angle of the corrugation). Furthermore, empirical correlations for the heat transfer and pressure drop were proposed. Djordjevic and Kabelac (2008) studied heat transfer coefficients of R-134a and ammonia in a PHE, respectively. They stated that the parallel flow case had a better heat transfer performance than the counterflow case, and the low chevron angle corrugations could improve the evaporation heat transfer. Longo et al. (2007a,2007b,2007c) reported experimental data on vaporization heat transfer coefficients and pressure data on R-134a, R-410A, and R-236fa inside a BPHE, respectively. Data related to heat flux, refrigerant mass flux, saturation temperature, outlet conditions and fluid properties were obtained. Taboas et al. (2010) experimentally analyzed the flow boiling heat transfer and pressure drop of ammonia/water mixture in a PHE and found that for the selected operating conditions the boiling heat transfer coefficient was highly dependent on the mass flux, while the pressure drop increased with increasing mass flux and quality. Khan et al.(2012a) and Khan et al.(2012b) investigated heat transfer and pressure drop characteristics of ammonia in 60° and 30° chevron PHE, respectively. They reported that the heat transfer coefficient increased with an increase in saturation temperature, mass flux and the exit vapor quality, while the friction factor decreased with an increase in exit vapor quality and equivalent Reynolds number. They also proposed correlations for two phase Nusselt number and friction factor.

Many studies have been conducted for refrigerants vaporization heat transfer characteristics in PHE or BPHE with air-conditioning conditions. However, experiments on refrigerants evaporation in BPHE with ORC conditions are relatively scarce.

The objective of the work presented here is to contribute to the development of BPHE as evaporator in ORC system. For the purpose an apparatus was set up to measure the heat transfer coefficients and pressure drop during R-245fa vaporization in a BPHE. The effects of refrigerant mass flux, heat flux, saturation temperature, and superheat degree at the outlet are investigated.

2. EXPERIMENTAL APPARATUS AND PROCEDURES

2.1 Apparatus

The experimental apparatus, as shown in Fig.1, consists of three main loops such as a refrigerant loop and two water loops (one for the evaporator heating and the other for the condenser cooling). Besides, a data acquisition system is also included to obtain different test conditions.

The refrigerant loop contains a refrigerant pump (the diaphragm pump), a mass flow meter, an evaporator (the brazed plate heat exchanger (BPHE)), a turbine, a condenser and a receiver. The refrigerant pump with changeable stroke piston is driven by a motor which is controlled by a variable-frequency drive. The liquid flow rate of R245fa is varied by a changeable stroke piston, and it also can be further adjusted by a variable-frequency drive through changing the current frequency. The R245fa flow rate is measured by a mass flow meter with an accuracy of ±0.2 percent. In the evaporator, energy balance is used to calculate the heat transferred from the hot water to the refrigerant. The R245fa vapor can go through the turbine or a valve, both of which can reduce the vapor pressure. Meanwhile, a condenser is used to condense the R245fa vapor from the turbine by a cold water loop. After condensing, the liquid refrigerant flows back to the receiver. The pressure of the refrigerant loop can be controlled by varying the flow rate and temperature of the cold water in the condenser, and it also can be changed by adjusting the opening size of the valve in the loop.

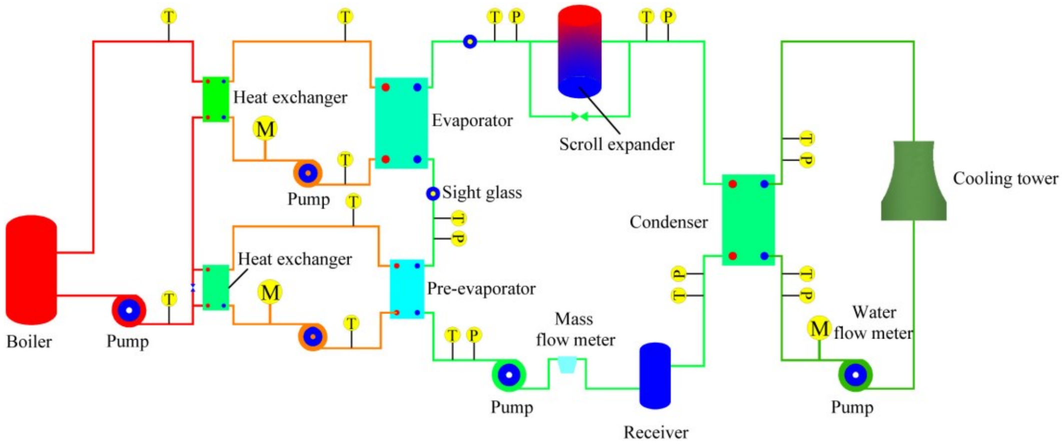

Fig.1 Schematic diagram of experimental system

The BPHE studied in this paper, as schematically shown in Fig.2, consists of 6 plates. The plate surfaces are stamped to become grooved with corrugation type of herringbone. Each plate is 2.22mm thick and the pitch between the plates is 3.2mm. More detailed geometrical characteristics of the BPHE tested are shown in Fig.2 and Table 1.

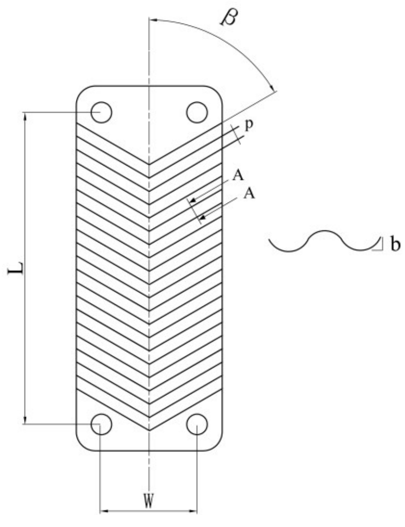

Fig.2 Schematic diagram of the plate

Table 1 Geometrical characteristics of the evaporator

Plate length, L (mm)	158
Plate width, W (mm)	76
Nominal area of the plate, A (㎡)	0.012
Corrugation type	Herringbone
Angle of the corrugation, β(degrees)	60
Corrugation amplitude, b (mm)	1.5
Corrugation pitch, p (mm)	2.22
Number of plates	28
Channels on refrigerant side	14
Channels on water side	13

The water loop in the experimental system for evaporator heating contains a water thermostat with a 18kW heater and a 500w pump which is used to drive the hot water to the plate heat exchanger with a specified water flow rate. The water flow rate is measured by a turbine flow meter with an accuracy of ±0.5 percent.

Another water loop designed for condensing the R245fa vapor contains a cooling tower with a cooling capacity of 20kW. A 500w pump is used to drive the cooling water to the condenser. The water flow rate is also measured by a turbine flow meter with an accuracy of ±0.5 percent.

The data acquisition system includes a recorder and a 24V power supply. The 24V power supply is used to drive the water flow meter and differential pressure transducer to output an electric current 4-20mA. The recorder is a 80 channel YOKOGAWA GP20 recorder which is used to record the temperature and voltage data, and it also can be used to analyze the data collected.

2.2. Procedures

The experiment is conducted in terms of the heat flux exchanged between hot water and R245fa, the mass flux of the R245fa, the temperature of the hot water inlet and the saturation vapour pressure of R245fa. Before each test, the evaporator and the condenser are fed with water at a constant temperature, respectively. Then, the temperature and flow rate of the hot water for the evaporator are adjusted to keep the saturation vapour pressure at a desired value, and the heat flux also can be calculated from the hot water. Finally, the refrigerant flow rate in the evaporator can be controlled by adjusting the volumetric pump. Once the temperature, pressure and flow rate steady state conditions are achieved at the evaporator inlet and outlet both on refrigerant and water sides, all the readings are recorded for a set time, and the average value during this time is calculated for each parameter recorded.

3. DATA REDUCTION

3.1 Heat transfer

The procedures to calculate the overall heat transfer coefficient in the evaporator are described in the following. Firstly, the total heat transfer rate between the counter flows in the brazed plate heat exchanger (BPHE) is calculated from the hot water side,

$$Q_{e,w} = W_{e,w} c_p (T_{e,w,i} - T_{e,w,o}) \tag{1}$$

Then, the vapor quality at the evaporator inlet is evaluated from the refrigerant state at the pre-evaporator through energy balance. The heat transfer rate is calculated from the water side,

$$Q_{p,w} = W_{p,w} c_p (T_{p,w,i} - T_{p,w,o}) \tag{2}$$

The heat transfer to the refrigerant in the pre-evaporator contains two parts, one part is used to heat the refrigerant to the saturation temperature (sensible heat transfer), and the other part is used on the evaporation process (latent heat transfer). Thus

$$Q_{p,w} = Q_{p,r} \tag{3}$$

where,

$$Q_{p,r} = W_r (h_{p,r,o} - h_{p,r,i}) \tag{4}$$

The overall heat transfer coefficient U for the evaporation of R-245fa in the BPHE can be expressed as

$$U = \frac{Q_{e,w}}{A \cdot LMTD} \quad (5)$$

Where A is the heat transfer area accounting for the actual corrugated surface of the plates. The log mean temperature difference (LMTD) is determined by the inlet and outlet temperatures of two counterflow channels of the BPHE

$$LMTD = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1 / \Delta T_2)} \quad (6)$$

where

$$\Delta T_1 = T_{e,w,i} - T_{e,wf,o} \quad (7)$$

$$\Delta T_2 = T_{e,w,o} - T_{e,wf,i} \quad (8)$$

In equations (10) and (11), $T_{e,wf,o}$ and $T_{e,wf,i}$ are the saturation temperatures of R-245fa corresponding respectively to the inlet and outlet pressures for the refrigerant in the BPHE.

Finally, the average heat transfer coefficient on the refrigerant side of the evaporator is derived from the equation assuming no fouling resistances:

$$\frac{1}{h_{wf}} = \frac{1}{U} - \frac{1}{h_w} - \frac{\delta_p}{\lambda_p} \quad (9)$$

where h_w is deduced from the empirical correlation for the single phase water to water heat transfer in the BPHE.

3.2 Pressure drop

The calculation of the frictional pressure drop Δp_f associated with the R-245fa evaporation in the BPHE is carried out on the condition that the evaporation process is looked as a homogeneous model. It is computed by subtracting the acceleration pressure drop Δp_a , the gravity pressure drop Δp_g and the manifolds and ports pressure drops Δp_{mp} from the total pressure drop measured $\Delta p_{\exp}$

$$\Delta p_f = \Delta p_{\exp} - \Delta p_a - \Delta p_g - \Delta p_{mp} \quad (13)$$

The acceleration and gravity pressure drops are derived from the equations

$$\Delta p_a = G^2 (v_g - v_l) \Delta x \quad (14)$$

$$\Delta p_g = g \rho_m L \quad (15)$$

where v_l and v_g are the specific volume of liquid and vapor phase, respectively, Δx is the vapor quality change between the inlet and outlet and the average density of the two-phase between inlet and outlet is given as

$$\rho_m = \left[x_m / \rho_g + (1 - x_m) / \rho_l \right]^{-1} \quad (16)$$

The pressure drops in the inlet and outlet manifolds and ports is empirically suggested by Shah and Focke, as follows

$$\Delta p_{mf} = 1.5 G^2 / 2 \rho_m \quad (17)$$

All the thermodynamic properties of the refrigerant R-245fa in this paper are evaluated by REFPROP 9.0.

4. RESULTS AND DISCUSSION

A series of vaporization tests are conducted at four different saturation temperatures (78,85,90 and 92℃) with different evaporator outlet conditions (different degrees of superheat), whereas the degree of supercoiling of refrigerant at the inlet ranges between 1 and 3 degree. Table 2 gives the operating conditions in the evaporator under test: refrigerant saturation temperature T_{sat} and pressure

p_{sat}, inlet and outlet refrigerant conditions $T_{in,supc}$ and $T_{out,suph}$, mass flux of refrigerant G, and heat flux q. All the conditions shown in Table 3 are typical for the evaporator in ORC system.

Table 2 Operating conditions during experimental tests

T_{sat} （℃）	p_{sat} （ bar）	$T_{in,supc}$ （℃）	$T_{out,suph}$ （℃）	G (kg/h)	q(kW/m^2)
78-92	6.04-10.34	1-3	0-18	144.58-205.86	20.62-28.62

4.1 Heat transfer

The variations of evaporation heat transfer coefficient in the BPHE with different mass fluxes, heat fluxes, and superheat degrees are shown in Figures.3-5 for different saturation temperatures. Fig.3 presents the relationship between the heat transfer coefficient and the mass flux. During the experiment the mass flux ranges from 144.6 to 205.9 kg/h. The heat transfer coefficients show great sensitivity to heat flux with different saturation temperatures. Heat transfer coefficient decreases quickly with the increase of the refrigerant mass flux. With saturation temperature 78℃, the heat transfer coefficient at mass flux around 145 kg/h is two times of the heat transfer coefficient at mass flux around 175 kg/h. Fig.4 gives the effect of heat flux on the heat transfer coefficient with different saturation temperature. The same relationship between heat transfer coefficient and heat flux is found compared with mass flux. In Fig.5 the variations of heat transfer coefficient with the superheat degree are shown. The marked decrease of the heat transfer coefficient with mass flux and heat flux is due to the increase of temperature different between the refrigerant and the hot water. Fig.3-5 also indicate that saturation temperature has a positive effect on the heat transfer coefficient. Therefor, properly increasing the saturation temperature can enhance the heat transfer.

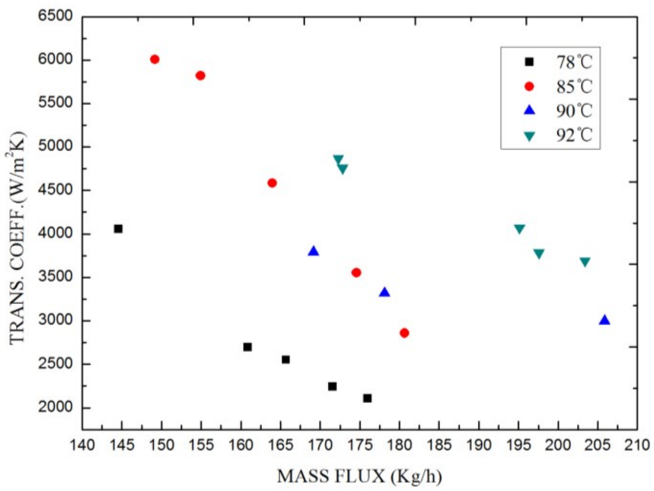

Fig.3. Variations of evaporation heat transfer coefficient with refrigerant mass flux

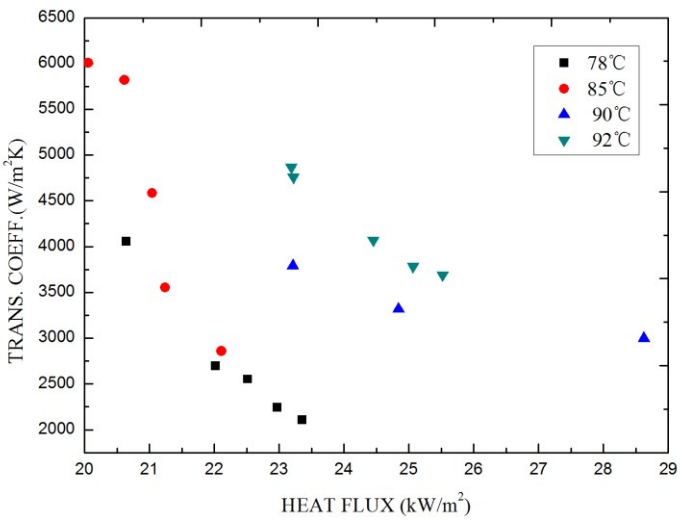

Fig.4. Variations of evaporation heat transfer coefficient with heat flux

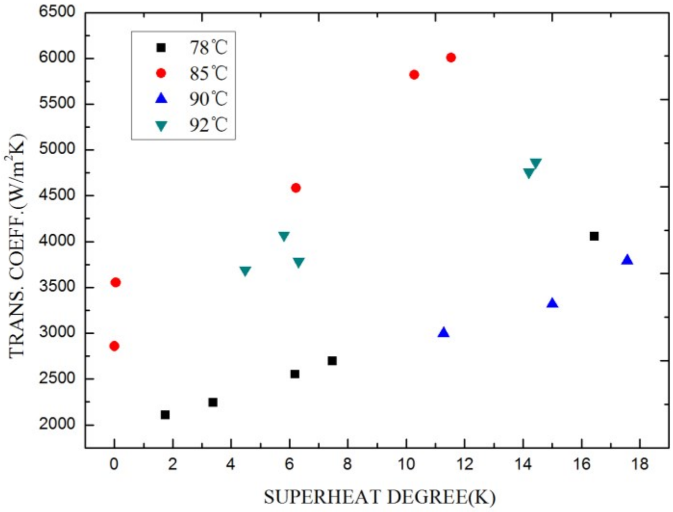

Fig.5. Variations of evaporation heat transfer coefficient with superheat degree

4.2 Pressure drop

Figs.6-8 present the variations of the pressure drop with the mass flux, heat flux, and superheat degree. Different with the evaporation heat transfer coefficient, the pressure drop shows positive relation with the mass flux and heat flux, and negative relation with the superheat degree. It is noted that the higher mass flux results in a higher pressure drop for different saturation temperature, as shown in Fig.6. Moreover, at a higher mass flux, the effects are stronger. Figs.6-7 also indicate that the pressure drop in the evaporator is reduced with an increase in the system pressure (that is for a higher saturation temperature) with the reason that at a higher system pressure, the specific volume of the vapor and the viscosity of the liquid R-245fa are lower. The pressure drop decreases with the increase of the superheat degree for a small portion of the liquid R245-fa, as shown in Fig.8.

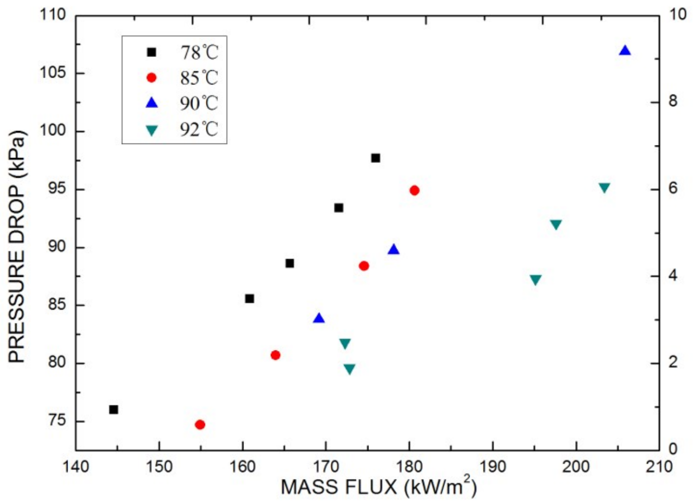

Fig.6. Variations of pressure drop in evaporator with refrigerant mass flux

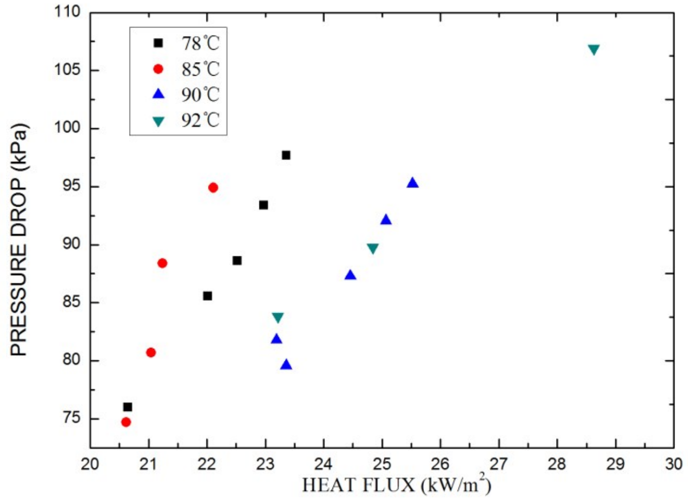

Fig.7. Variations of pressure in evaporator drop with heat flux

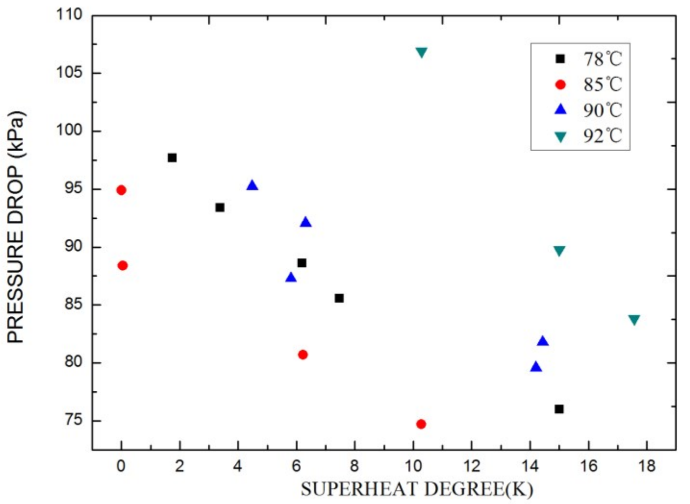

Fig.8.Variations of pressure drop in evaporator with superheat degree

5. CONCLUSION

An experimental investigation has been conducted in the present study to measure the heat transfer coefficient and pressure drop of R-245fa during the evaporation in a brazed plate heat exchanger (BPHE) in terms of the refrigerant mass flux, heat flux and the the superheat degree at the outlet of the BPHE evaporator. The results show that the heat transfer coefficient decreases with the increase of mass flux and heat flux, whereas, the pressure drop shows a opposite trend. It was also noted that the heat transfer coefficient has a sharp decline with small increase in mass flux at the beginning. Besides, the saturation temperature had a positive effect on the heat transfer coefficient. Finally, it was noted that at a higher saturation temperature, the heat transfer coefficient was higher, and the pressure drop was lower.

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Nomenclature

A	heat transfer area of the plate, m^2	Greek symbols	
b	height of the corrugation, m	β	Inclination angle of the corrugation
Bo	boiling number	Δ	difference
c_p	specific heat capacity, J/kg ℃	λ	thermal conductivity, w/m K
d_h	hydraulic diameter, m	ρ	Density, kg/m^3
G	mass flux, kg/m^2 s	subscripts	
h	heat transfer coefficient, w/m^2 ℃	a	momentum
i	specific enthalpy, J/kg	mp	manifold and port
i_{fg}	enthalpy of vaporization, J/kg	f	frictional
L	channel length, m	g	gravity
LMTD	log mean temperature difference, ℃	i,o	inlet and outlet
m	mass flow rate, kg/s	l	liquid phase
n_{ch}	number of channels	lat	Latent heat
p	pressure, Pa	sens	sensible heat
P	pitch, m	e	evaporator
Pr	Prandtl number	p	pre-evaporator
Q	heat flux, W/m^2	r	refrigerant
Re	Reynolds number	w	water
s	plate wall thickness, m	wall	Wall/fluid near the wall
T	temperature, K	sat	saturation
U	overall heat transfer coefficient, W/m^2 K		
W	mass flow rate, kg/s		
X	vapour quality		