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## Condensation heat transfer and pressure drop characteristics of R-513A as an alternative refrigerant of R-134a

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### Abstract

Two phase condensation heat transfer and pressured drop characteristics of R-513A in a 9.52 mm O.D. horizontal microfin copper tube are investigated experimentally. Test facility has a straight test section with a length of 2.0 m and is cooled by cold water circulated in a surrounding annular space. The water-side annular space heat transfer coefficients are measured using the Wilson plot method. Average heat transfer coefficients and pressure drop data are reported at the condensation temperature of 35°C in range of 100–440 kg/m<sup>2</sup>s mass flux. The test data of R-513A are compared with those of R-134a, R-1234yf and R-1234ze(E).

*Keywords:* Microfin tube; low-GWP refrigerants; condensation heat transfer; R-513A; R-1234yf; R-1234ze(E)

### 1. Introduction

In recent years, the use of energy systems including refrigeration and air conditioning systems is gradually increasing due to the advancement of technology and improvement of living standards, and energy supply and demand and environmental problems are emerging as important issues. Among the energy systems, the environmental impact of the refrigeration and air conditioning systems is the global warming effect that occurs in generating the working fluids of the system and power required for the system operation. The global warming is highly affected by air-conditioning, refrigeration and heat pump systems which account 700 million metric tons of CO<sub>2</sub> equivalent direct (7%–19%) and indirect emissions (74%) per year [1]. Therefore, it is very important to increase the energy efficiency of the system, and use eco-friendly alternative refrigerants such as carbon dioxide and HFO refrigerants with a small global warming potential [2–3]. Heat exchangers in air conditioning and heat pump applications play an important role on system efficiency and physical size. Finned round tube or flat tube heat exchangers are widely used for the evaporators and condensers in residential air-conditioning and heat pump systems. To investigate the overall performance of the finned tube heat exchangers, tube-side heat transfer and pressure drop characteristics as well as air-side performance should be investigated simultaneously. Several investigators [4–10] conducted investigations on two phase thermal and hydraulic performance in smooth and enhanced tubes. Kim and Shin [5, 6] investigated experimentally evaporation and condensation heat transfer characteristics using R-22 and R-410A in 9.52mm OD smooth and microfin tubes. They found that average evaporation and condensation heat transfer coefficients of R-410A for microfin tubes were 1.86–3.27 and 1.7–3.19 larger than those of smooth tubes, respectively. And they also reported that the evaporating heat transfer coefficients for R-410A were 97–129% of R-22 when compared to R-22 at the same test conditions. Due to the EU Regulation No 517/2014, the refrigerant R-134a is already banned in mobile air-conditioning and household refrigerator-freezer systems and will be also prohibited for commercial refrigerator-freezers from 2022 [7]. Hence studies to find low-GWP alternative refrigerants for R-134a have attracted to prevent negative effects on climate change by many researchers. Table 1 and Fig. 1 show general properties and vapor pressures of R-134a compared to alternative refrigerants R-1234yf, R-1234ze(E), and R-513A. GWP values of R-1234yf and R-1234ze(E) are significantly lower than R-134a. However, R-1234yf and R-1234ze(E) are mildly flammable and classified as A2L. R-1234ze(E) has a lower saturation pressure than R-134a (75% of R-134a at a saturation temperature of 35°C), so it the design of the system requires to be modified and the pressure drop is relatively

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Table 1. General properties of R-134a alternative refrigerants

	R-134a	R-513A	R-1234yf	R-1234ze(E)
Chemical Formula	CF <sub>3</sub> CH <sub>2</sub> F	R-1234yf/134a (56/44 wt %)	CH <sub>2</sub> CF <sub>2</sub> CF <sub>3</sub>	C <sub>3</sub> H <sub>2</sub> F <sub>4</sub>
Molar mass [g/mol]	102	108	114	114
ODP	0	0	0	0
GWP	1430	573	4	6
Flammability	A1	A1	A2L	A2L
NBP[°C]	-26	-29	-29	-19
T <sub>c</sub> [°C]	101	96.5	94.7	109.4
P <sub>c</sub> [kPa]	4059	3648	3381	3632
qv* [kJ/m <sup>3</sup> ]	7293	7373	6891	5608

\* Volumetric capacity calculated at the condensing temperature of 35°C

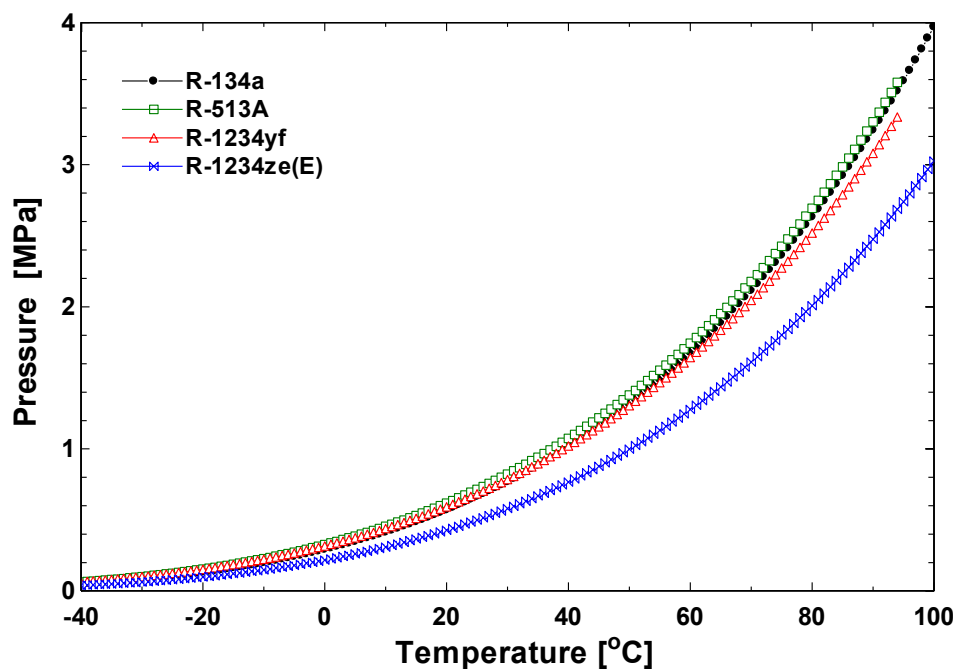


Fig. 1. Saturation vapor pressures for R-134a alternative refrigerants

high. R-513A refrigerant is an azeotropic mixture with a mass ratio of R-1234yf and R-134a of 56 to 44, and its GWP value is slightly higher at 573, but it is not flammable and has an advantage that is very similar to R-134a in thermodynamic properties. Yang et al. [8] and Diani et al. [9] conducted experimental studies on condensation heat transfer of R-1234yf and R-1234ze refrigerants in small diameter microfin tubes, respectively. Diani et al. [10] investigated condensation heat transfer of R-513A at the saturation temperatures of 30 and 40 °C in the range of 100-1000 kg/m<sup>2</sup>s mass fluxes inside 3.5 mm ID smooth and microfin tubes.

In this study, condensation heat transfer and pressure drop characteristics in a 9.52 mm OD microfin tube are experimentally performed for R-513A, R-1234yf, R-1234ze(E), and R-134a at a condensation temperature of 35°C in the range of 100–440 kg/m<sup>2</sup>s mass fluxes. The correlation equation of the heat transfer coefficient for the annular space of the test section is obtained using the Wilson plot, and the condensation test results of the refrigerant R-513A are compared with those of R-134a, R-1234yf and R-1234ze(E).

## 2. Experiments

### 2.1 Experimental facility

A schematic diagram of the experimental facility is shown in Fig. 1. The facility consists of one refrigerant loop and two water loops. The refrigerant loop is designed to measure the mean heat transfer coefficient of refrigerant condensing inside a micro fin tube. It is mainly composed of a gear pump, a pre-heater, a test section, a heat exchanger and a receiver tank. Refrigerant in liquid state is pumped from the bottom of the receiver tank to the preheater where it is heated up until it reaches a state of superheated vapour. With the preheater, it is possible to control the refrigerant superheat when it enters the test section. The refrigerant enters the test section in superheated vapor state and leaves in subcooled liquid. The test section with a length of 2 m as shown in Fig. 2 consists of a simple tube-in-tube counter flow heat exchanger. The refrigerant inside the inner tube condenses and the water that flows in the annular duct between the two tubes is heated. Chiller 1 (6) is designed to control the conditions of the water entering the test section. After the test section, the refrigerant enters the plate heat exchanger as a subcooled liquid. The role of the plate heat exchanger is to control the system pressure. Chiller 2 (7) controls water temperature and flow rate at the inlet of the plate heat exchanger.

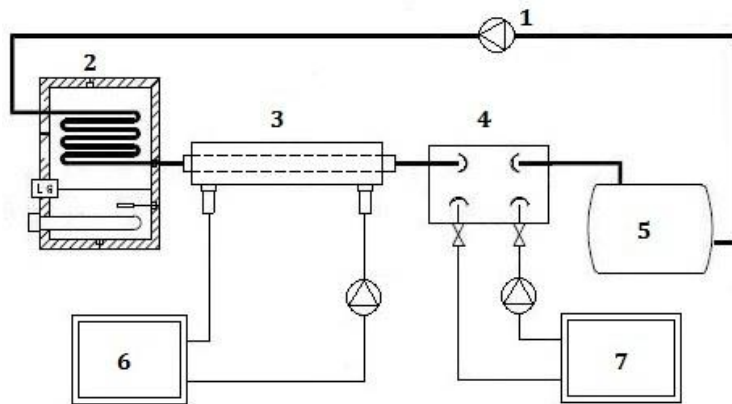


Fig. 2. Schematic diagram of experimental facility (1. Refrigeration pump, 2. Preheater, 3. Test section, 4. Plate heat exchanger, 5. Receiver tank, 6. Chiller1, 7. Chiller2)

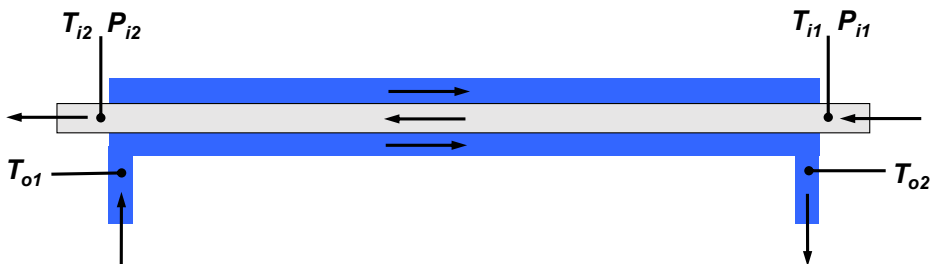


Fig. 3. Schematics of test section

The refrigerant pump (1) is a positive displacement gear pump with the maximum flow of 100 kg/h liquid refrigerant. Special attention is given to the refrigerant inlet pressure and temperature conditions to ensure that the refrigerant's pressure is higher than its vapor pressure at any point in the pump and avoid any bubble

formation within the pump. For that reason, the refrigerant's pressure and temperature is measured at the suction line to ensure that the refrigerant remain in liquid state. The pre-heater (2) is an insulated tank that contains a coil of the main loop refrigerant on the top, electrical resistances on the bottom and a low-pressure fluid; its role is to heat up the liquid refrigerant to a superheated vapor state. The electrical resistor heaters heat the low-pressure refrigerant which evaporates on the bottom of the tank. Then, low-pressure refrigerant vapor condensates on the surface of the main refrigerant loop coil on the top of the tank. The test section (3) can be described as a simple tube in a tube heat exchanger. It consists of an inner grooved tube mounted inside an outer shell tube, so that the refrigerant flows counter-current through the inner tube, with the cooling water around it. Refrigerant condensates in the test section under fully controlled conditions. The pressure and temperature are measured at the inlet and outlet of the test section. Both inlet and outlet state of the refrigerant are single phase, thus the inlet-outlet specific enthalpies can be determined using thermodynamic data. The condensation heat capacity is calculated as the product of the mass flow and the differential enthalpy. The plate heat exchanger (4) role is to control the refrigerants pressure; this is accomplished by heating or cooling the refrigerant loop with water as a secondary mean. The heating or cooling rates at the plate heat exchanger are small in order to accomplish a high precision pressure regulation. The water flow rate and temperature are controlled. The receiver tank (5) contains refrigerant in both liquid and vapor state at the bottom and top respectively. The refrigerant outlet is located on the bottom of the receiver tank so that only liquid refrigerant is pumped.

## 2.2 Experimental methods and conditions

The test conditions are described in Table 2. The condensation experiments are conducted at the saturation temperature of 35 °C for the mass flux of 100-440 kg/m<sup>2</sup>s with R-134a, R-513A, R-1234yf and R-1234ze(E). The inlet superheat and outlet subcooling of condenser are 5 and 2 °C, respectively. The refrigerant flow is regulated by controlling the input power of the variable speed magnetic gear pump. The test conditions and data to be collected were monitored throughout the test, and data sets were recorded and averaged over 10 min after test conditions reached steady state. Before the condensation experiment, a series of water-to-water experiments are first performed to find the correlation of the heat transfer coefficient of the annular space. Water to water test data are collected with increasing the water flow rate of the annular space from 200 to 800 kg/h in increments of 100 kg/h. The tested microfin tube has 60 fins with fin height of 0.25 mm, an apex angle of 60°, and bottom wall thickness of 0.35mm.

Table 2. Test conditions

Refrigerants	R-134a, R-513A, R-1234yf, R-1234ze(E)
Condensing temp. [°C]	35
Mass flux [kg/m <sup>2</sup> s]	100-440
Degree of superheat/subcooling [°C]	5/2

## 2.3 Data reduction

Condensation heat transfer coefficients can be calculated using the following equations

$$\frac{1}{U_o A_o} = \frac{1}{h_i A_i} + R_w + \frac{1}{h_o A_o} \quad (1)$$

Where  $U_o A_o$  is the overall heat transfer coefficient.  $R_w$  is the thermal conduct resistance of the tube wall and it can be neglected because the tube material is copper and the thickness of the tube wall is very thin.

$$Q = U_o A_o LMTD \quad (2)$$

Where  $Q$  is the heat transfer rate of the test section and the arithmetic mean of tube- ( $Q_i$ ) and annular-side ( $Q_o$ ) heat transfer rates that obtained from the following equations

$$Q = \frac{Q_i + Q_o}{2} \quad (3)$$

$$Q_i = m_i c_p (T_{i1} - T_{i2}) \quad (4)$$

$$Q_o = m_o c_p (T_{o2} - T_{o1}) \quad (5)$$

And the  $LMTD$  is the log mean temperature difference which is defined as

$$LMTD = \frac{(T_{i2} - T_{o1}) - (T_{i1} - T_{o2})}{\ln \left( \frac{T_{i2} - T_{o1}}{T_{i1} - T_{o2}} \right)} \quad (6)$$

If the heat resistance ( $1/h_o A_o$ ) of the annular space is known from Eq. (1), the heat transfer coefficient ( $h_i$ ) in the tube can be obtained from the heat resistance ( $1/h_i A_i$ ) in the tube. Refrigerant properties were calculated using NIST REFPROP [11].

### 3. Results and discussion

Figs. 4 and 5 show the Wilson plot and the correlation equation for obtaining the heat transfer coefficient of the annular space with variation of water flow rate of 200-800 kg/h, respectively. As shown in Fig. 4, the total thermal resistance value ( $1/U_o A_o$ ) of the test section is well expressed as a function of the tube-side thermal resistance ( $1/h_i A_i$ ). The total thermal resistance value decreases with the increase of the flow rate of the annular space at the same flow rate in the tube-side, because the heat transfer coefficient of the annular flow path increases with the increase of the flow rate. The refrigerant-side heat transfer coefficients are calculated from Eq. (1) using correlation of  $1/h_o A_o$  from Fig. 5.

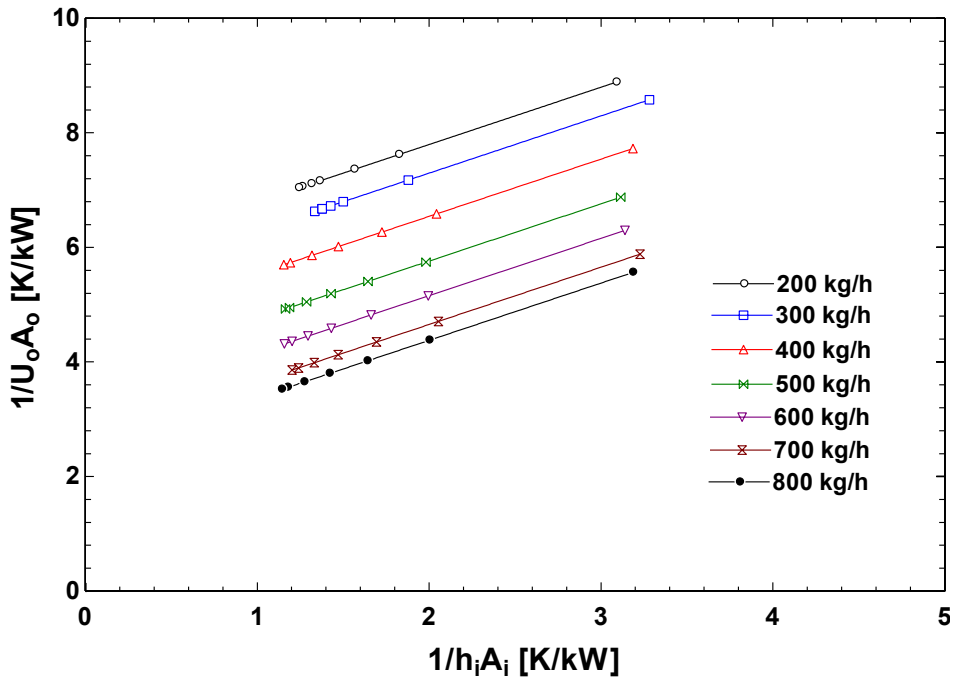


Fig. 4. Wilson plot with variation of annular-side mass flow rate

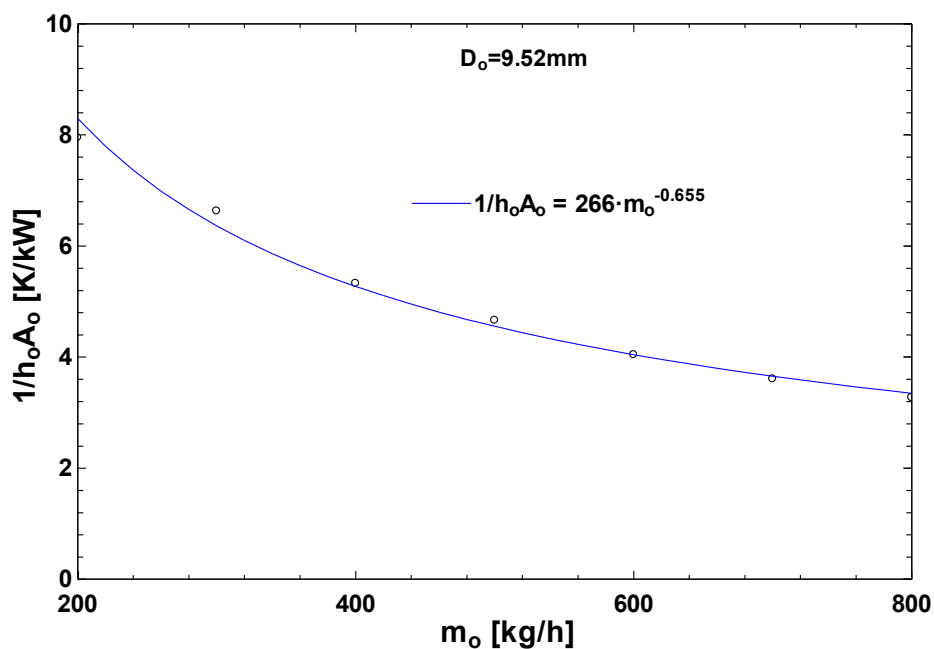


Fig. 5. Heat transfer coefficient for annular side as function of water mass flow rate

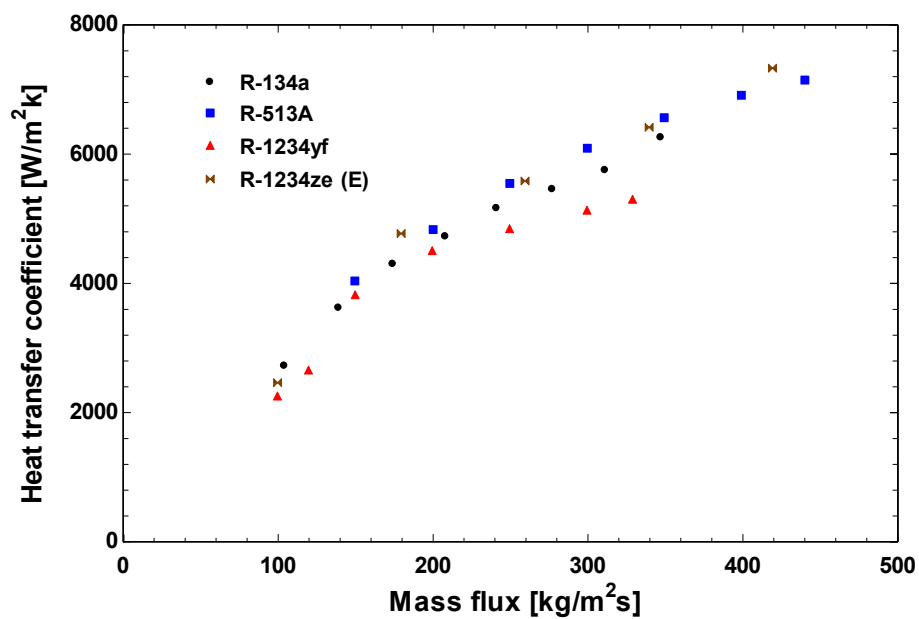


Fig. 6. Heat transfer coefficient for refrigerant side with variation of refrigerant's mass flux

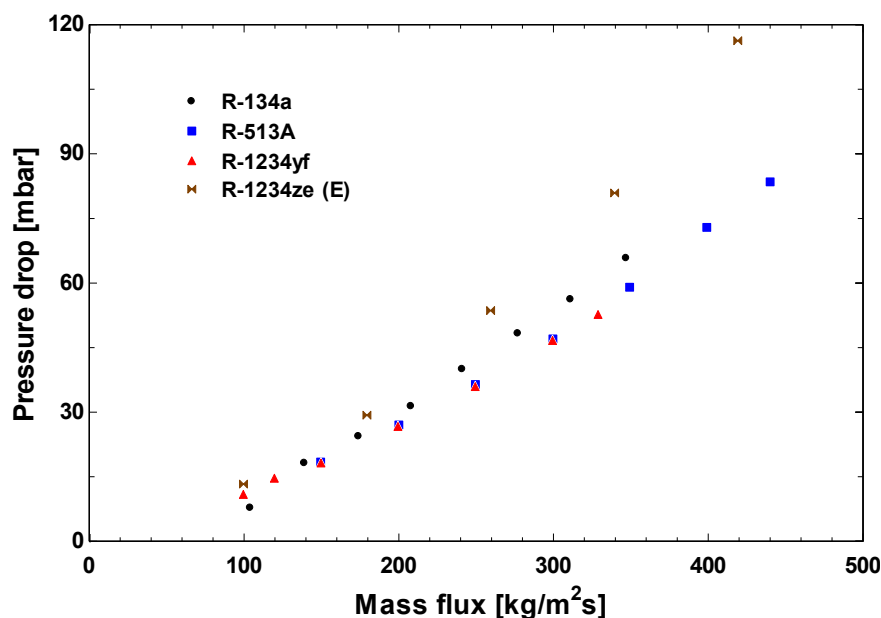


Fig. 7. Pressure drops with variation of refrigerant mass flux

Table 3 Thermodynamic and transport properties of R-134a alternative refrigerants [11]

Properties [Units]	Refrigerants			
	R-134a	R-513A	R-1234yf	R-1234ze(E)
Saturation temperature [°C]	35	35	35	35
Saturation pressure [kPa]	887	941	895	667
Latent heat [kJ/kg]	168	147	137	159
Liquid viscosity [μPa-s]	172	147	135	168
Vapor viscosity [μPa-s]	12.1	12.0	12.0	12.8
Liquid thermal conductivity [mW/m-K]	76.9	66.3	60.5	70.9
Vapor thermal conductivity [mW/m-K]	14.9	15.1	14.9	14.5
Liquid density [kg/m³]	1167	1095	1054	1129
Vapor density [kg/m³]	43.4	50.2	50.3	35.3
Liquid specific heat [J/kg-K]	1471	1464	1443	1422
Vapor specific heat [J/kg-K]	1103	1131	1124	1023
Liquid Prandtl number [ - ]	3.29	3.23	3.23	3.37
Vapor Prandtl number [ - ]	0.90	0.90	0.90	0.91
Surface tension [mN/m]	6.74	5.47	4.97	7.56
Reduced pressure [ - ]	0.18	0.26	0.26	0.18

Figs. 6 and 7 present average heat transfer coefficients and pressure drops at the condensing temperature of 35°C in ranging of 100–440 kg/m<sup>2</sup>s mass flux, respectively. The heat transfer coefficients of the test refrigerants including R-513A increase with the refrigerant mass flux as expected, and all four refrigerants have similar heat transfer coefficient values at low mass flux. However as the mass flux increases, the heat transfer coefficient of R-513A has a similar value to that of R-1234ze(E), while it is about 10% higher than that of R-134a. The heat transfer coefficient of R-1234yf represents the lowest value among the test refrigerants, and the difference in heat transfer coefficient with other refrigerants becomes larger as mass flux increases. Table 3 presents the major thermodynamic and transport properties of R-134a alternative refrigerants. These properties are attributed to the higher R-513A and R-1234ze(E) heat transfer coefficients and lower R-1234yf heat transfer coefficient compared to R-134a [12,13]. The pressure drops for all test refrigerants are increased with mass flux as expected as shown in Fig. 7. The pressure drops of R-513A and R-1234yf are smaller than that of R-134a when the mass fluxes are larger than 150 kg/m<sup>2</sup>s, while the pressure drops of R-1234ze(E) are

relatively higher than that of R-134a. This is partly due to the higher vapor viscosity of R-1234ze(E) compared to R-134a as shown in Table 3.

#### 4. Conclusion

The present study has been conducted to investigate two-phase condensation heat transfer and pressure drop characteristics in a horizontal 9.52 mm OD microfin tube with refrigerant R-513A. The experimental results are compared with those of R-134a, R-1234yf and R-1234ze. The findings of the present study have been listed below.

- The average condensation heat transfer coefficients of R-513A and R-1234ze (E) are similar to that of R-134a in the lower range of tested mass fluxes (100-150 kg/m<sup>2</sup>s). As mass flux increases, the heat transfer coefficients of R-513A and R-1234ze (E) become higher than that of R-134a.
- The average condensation heat transfer coefficients of R-1234yf is lower than that of R-134a for the full range of tested mass fluxes.
- The pressure drop of R-513A is similar to R-1234yf and lower compared to that of R-134a
- R-1234ze(E) pressure drops are higher compared to that of R-134a.

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