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Effect of Condenser Temperature on the Flow of Refrigerant R134a and its Alternative through a Capillary Tube

Kamlendra Singh Rajput[1], Prof. R.C Gupta[2]
[1]Research Scholar, M.E (Heat Power Engineering), [2]Associate Professor, Department of Mechanical Engineering, Jabalpur Engineering College, Gokalpur, Jabalpur (M.P.)- 482011, India

Abstract: After the Kyoto protocol, it's become a need to investigate substitute for a commonly used refrigerant R134a. For this purpose, thermophysical properties of refrigerant like R1234yf and R152a are compared with R134a, along with that analytical performance comparison of R134a and its substitute is done for adiabatic straight capillary. This analysis proves that R1234yf and R152a are considered as a substitute of R134a and gives two more important results. Firstly, it shows that R1234yf works well in the given temperature range for given input whereas R152a results in choked flow for same given input. Secondly, it shows R1234yf requires longer tube length whereas R152a requires shorter tube length as compared to R134a. This paper also shows that, with increase in condenser temperature, properties of the refrigerant flowing through a capillary tube like; evaporator temperature, dryness fraction and velocity increases whereas change in pressure per unit length decreases.
Keywords: Capillary tube, Mathematical model, R134a, Alternatives, Comparison.

I. INTRODUCTION

A typical refrigeration and air conditioning system consists of a compressor, evaporator, condenser and expansion devices. Capillary tubes have been extensively used as the expansion device for the past few decades. Now a day electronic expansion valves and / or short tube orifices are considered as future expansion devices for somewhat large size air- conditioners heat pump.

R134a has been used mostly as the working fluid in domestic refrigerator, mobile air conditioning due to its excellent properties and fit for combining with various materials. R134a have zero ozone depletion potential but Global warming potential value above than that provided in Kyoto protocol, thus there is a need to find out the alternatives for R134a. For this purpose, thermophysical properties of refrigerant like R1234yf and R152a are compared with R134a along with that performance comparison of R134a and its substitute is done for adiabatic straight capillary to find out whether these refrigerant are considered as a replacement for R134a in near future or not. After searching the validity of alternatives for R134a, study continues to find out the effect of condenser temperature on the flow of refrigerant flowing through a capillary tube.

II. PROPERTY COMPARISION

For being a suitable replacement for R134a, refrigerant R152a and R1234yf should have similar thermodynamic properties. Table 1 below shows the comparison between properties of R134a, R152a and R1234yf.

Table 1: Thermodynamic properties for various refrigerants.

Thermodynamic Property	R134a	R1234yf	R152a
Chemical Formula	CH2FCF3	CF3CF=CH2	CHF2CH3
Molar Mass (kg/kmol)	102.03	114.04	66.051
Boiling Point at 1 atm (K)	247.08	243.7	249.127
Critical Temperature(K)	374.21	367.85	386.411
Critical Pressure(MPa)	4.06	3.38	4.51675
Auto Ignition Temperature(K)	–	678	727
GWP	1430	4	124
ODP	0	0	0
Safety Group	A1	A2L	A2

R152a and R1234yf have almost similar critical temperature and critical pressure as that of R134a. Whereas the molar mass of R152a is approximately half than that of R134a and for R1234yf it is also similar. The GWP of R1234yf is 04 and of R152a is 124 which is very less as compare to GWP of R134a.If we talk about safety group both R1234yf and R152a are of slightly flammable nature but of low toxicity. This comparison shows that R1234yf and R152a can be considered as an alternative for R134a.

Nomenclature	
A=Cross-sectional area of inside of tube, m^2	v = Specific volume, m^3/kg
D=Diameter of tube, m	v_f = Specific volume of saturated liquid, m^3/kg
f = Friction factor, dimensionless	v_g = Specific volume of saturated vapour, m^3/kg
h = Enthalpy, KJ/Kg	V = Velocity of refrigerant, m/s
h_f = Enthalpy of saturated liquid, KJ/Kg	W= Mass rate of flow, kg/s
h_g = Enthalpy of saturated vapour, KJ/Kg	x = Fraction of vapour in mixture of liquid and vapour
ΔL = length of increment, m	μ = Viscosity, Pa.s
P = Pressure, MPa	μ_f = Viscosity of saturated liquid, Pa.s
Re = Reynolds number	μ_g = Viscosity of saturated vapour, Pa.s

III. CAPILLARY TUBE MATHEMATICAL MODELING

Initially, a generalized mathematical model has been developed for straight capillary tube. The fundamental equations applicable to the control volume bounded by point 1 and 2 in fig. (3.1) are (1) conservation of mass, (2) conservation of energy, and (3) conservation of momentum.

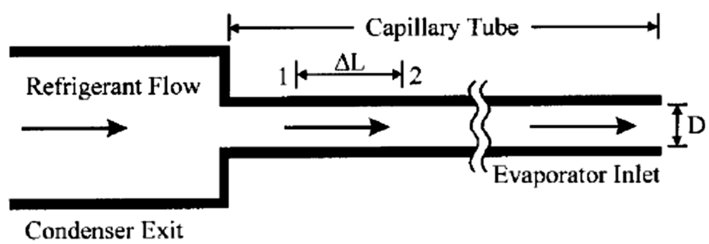

Figure 3.1 :- Incremental length of capillary tube.[2] et.al Jung

The equation for conservation of mass states that

$$W = V_1A/v_1 = V_2A/v_2 \quad (1)$$

$$W/A = V_1/v_1 = V_2/v_2 \quad (2)$$

And W/A will be constant throughout the length of the capillary tube. The statement of conservation of energy is

$$1000\, h_1 + V_1^2/2 = 1000\, h_2 + V_2^2/2 \quad (3)$$

Which assumes negligible heat transfer in and out of the tube.

The momentum equation in words states that the difference in forces applied to the element because of drag and pressure difference on opposite ends of the element equals that needed to accelerate the fluid

$$[(p_1 - p_2) - f(\Delta L/D)\,(V^2/2v)]\, A = W(V_2 - V_1) \quad (4)$$

As the refrigerant flows through the capillary tube, its pressure and saturation temperature progressively drop and the fraction of vapor x continuously increases. At any point

$$h = h_f\,(1-x) + h_g\, x \quad (5)$$

and

$$v = v_f\,(1-x) + v_g\, x \quad (6)$$

In Eq. (4) V, v , and f all change as the refrigerant flows from point 1 to point 2 but some simplification results from Eq .(2) which shows that V/v is constant so that

$$f(\Delta L/D)\,(V^2/2v) = f(\Delta L/D)\,(V/2)\,(W/A) \quad (7)$$

In the calculation the V used in Eq. (7) will be the mean velocity

$$V_m = (V_1+V_2)/2 \quad (8)$$

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Since expressing the friction factor f for the two phase flow is complex, we shall use friction factor to predict the performance of capillary tube given by Stocker's

$$f = 0.33/Re^{0.25} \quad (9)$$

The viscosity of the two-phase refrigerant at a given position in the tube is a function of the vapor fraction x.
viscosity of the two-phase can be calculated by same formula used Stocker's

$$\mu = \mu_f (1-x) + \mu_g x \quad (10)$$

The mean friction factor fm applicable to the increment of length
1-2 is

$$f_m = (f_1+f_2)/2 \quad (11)$$

A. Calculating The Length Of An Increment

The essence of analytical calculation method is to determine the length of the increment 1-2 in Fig. (A) for a given reduction in saturation temperature of the refrigerant. The flow rate and all the conditions at point 1 are known, and for an arbitrarily selected temperature at point 2 the remaining conditions at point 2 and the ΔL will be computed in the following specific steps.

1) Select t_2 .
2) Compute p_2 , h_{f2} , h_{g2} , v_{f2} , and v_{g2}, all of which are function of t_2 .
3) Combine the continuity equation (2) and the energy equation (3)

$$1000h_2 + (v_2^2/2)(W/A)^2 = 1000h_1 + V_1^2/2 \quad (12)$$

Substitute Eqs. (5) and (6) into Eq. (12)

$$1000h_{f2}+1000(h_{g2} -h_{f2})\, x+[v_{f2}+(v_{g2}-v_{f2})\, x]^2/2(W/A)^2 = 1000h_1 + V_1^2 /2 \quad (13)$$

Everything in Eq.(13) is known except x , which can be solved by the quadratic equation

$$x = [-b \pm \sqrt{(b^2-4ac)}]/(2a) \quad (14)$$

where

$a = (v_{g2}-v_{f2})2(W/A)^2(1/2)$

$b = 1000(h_{g2}-h_{f2}) + v_{f2} (v_{g2}-v_{f2}) (W/A)^2$

$c = 1000(h_{f2}-h_1) + (W/A)^2 (1/2) v_{f2}^2 – V_1^2 /2$

4) With the value of x known, h_2, v_2, and V_2 can be computed.
5) Compute the Reynolds number at point 2 using the viscosity from Eq. (10) , the friction factor at point 2 from Eq. (9) , and the mean friction factor for the increment from Eq. (11).
6) Finally, substitute Eq. (7) and Eq. (8) into Eq. (4) to solve for ΔL.

IV. VALIDATION OF MATHEMATICAL MODEL

This mathematical model is validated with mathematical model used by wongwises[1] in his research work. This is done by plotting graphs and comparing results under similar input parameters as used by wongwises[1] .For this validation, Refrigerant R134a is used and subjected to following input conditions T_{in} =23.4^{0}C,P_{in} = 0.717 Mpa,D= 0.66m,m=0.8443g/s. Output obtained from both the models are compared on graph .This comparison of models show similar trends on graph and have approximately similar results.

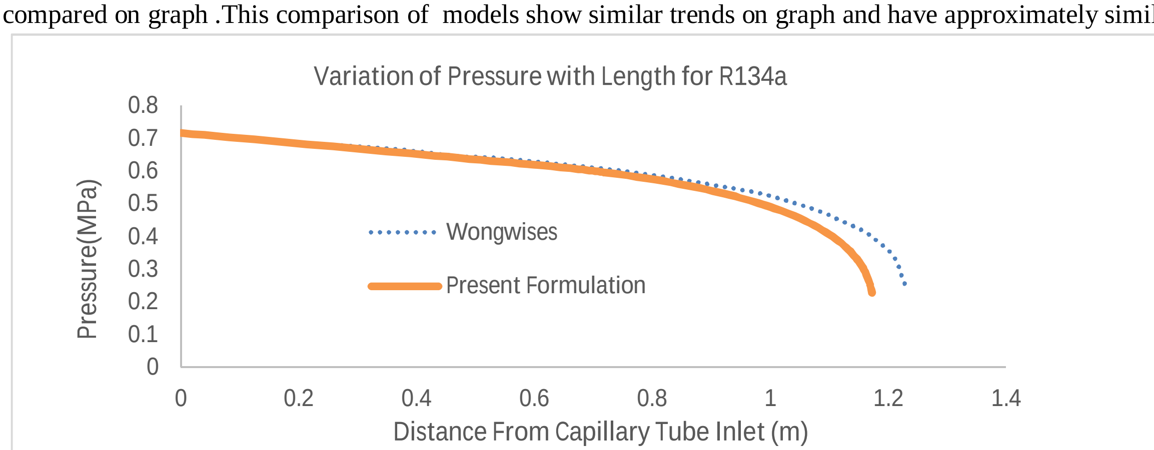

Figure 4.1 :- Variation of pressure with length for R134a

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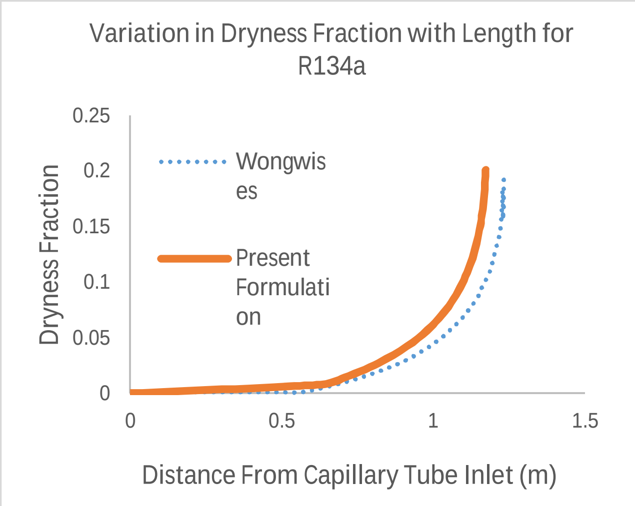

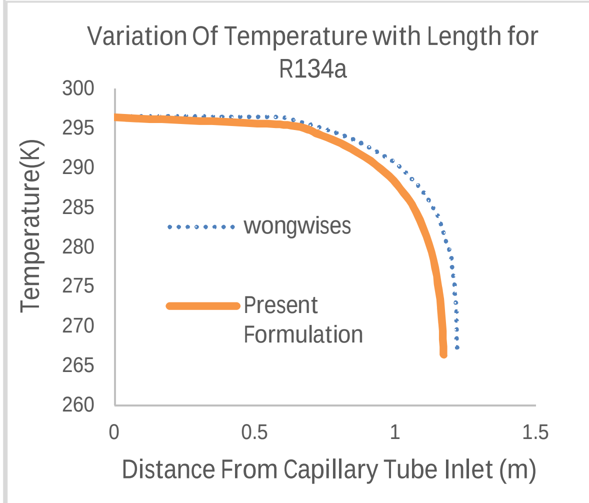

Figure 4.2 :- Variation of dryness fraction with length for R134a. Figure 4.3:- Variation of temperature with length for R134a.

V. PERFORMANCE COMPARISION

Performances of R1234yf and R152a is compared with the performance of R134a for a typical Indian situation where condenser temperature is about 45°C, diameter of capillary is taken as 0.66 mm, mass flow of refrigerant is fixed to 0.8443g/s and problem is solved up to chocked flow condition.

Graph shown below gives a correct idea about the behavior of these refrigerants for particular condition. If we talk about pressure variation then it is from 1.153 to 0.247 MPa for R1234yf, 1.0368 to 0.273 MPa for R152a and 1.159 to 0.2433 MPa for R134a.This drop in pressure is almost similar for R1234yf, R152a and R134a.Temperature variation graph shows that R1234yf is suitable to use up to 266K, R134a is suitable to use up to 268K and R152a is up to 274K. Dryness fraction is 0.423 for R1234yf ,0.347 for R134a and 0.257 for R152a at exit of a capillary tube. Velocity profile is almost similar for all three refrigerants. In this study one thing is important to note that, for above written pressure and temperature drop length of capillary required for R1234yf is 2.87 m, R134a is 1.67m and for R152a is 1.07m. This shows that R1234yf requires 72% longer tube length and R152a requires 36% shorter tube length as compared to R134a.

One thing is clear from the performance comparison that these refrigerants R1234yf and R152a can be considered as a substitute of R134a since all three refrigerants follow almost similar trends and also within a range.

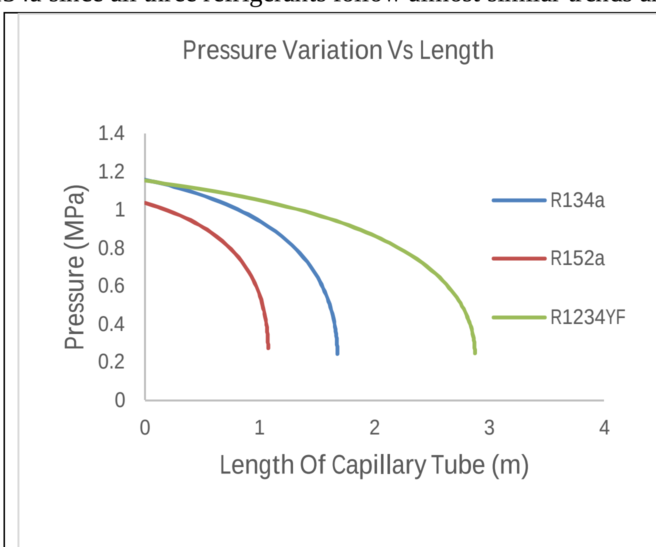

Figure 5.1: - Variation of pressure with length for R134a, R152a and R1234yf.

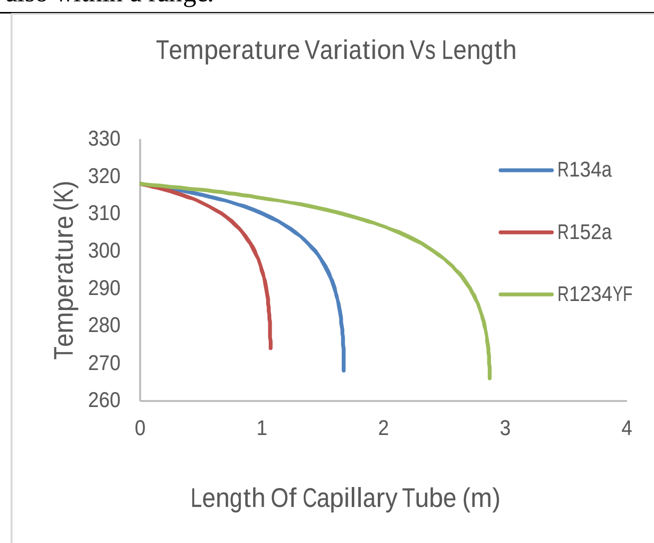

Figure 5.2: - Variation of temperature with length for R134a, R152a and R1234yf.

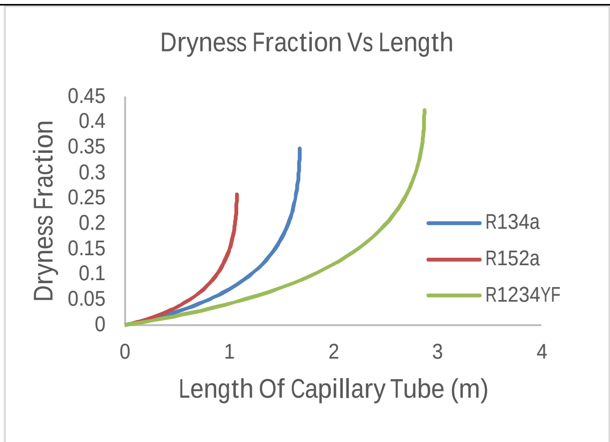

Figure 5.3: - Variation of dryness fraction with length for R134a, R152a and R1234yf.

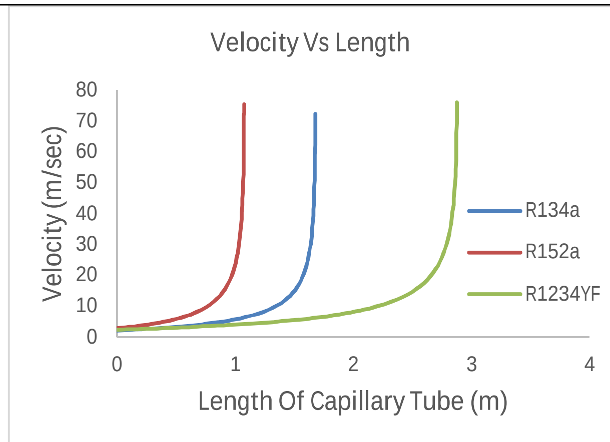

Figure 5.4 :- Variation of velocity with length for R134a,R152a and R1234yf.

VI. EFFECT OF CONDENSOR TEMPERATURE

For finding out the effect of condenser temperature on the flow of refrigerant through a capillary tube, refrigerants R134a and its alternative R1234yf and R152a are used. These refrigerants are tested for condenser temperature of 50,45 and 40 ^{o}C in a capillary tube of diameter 0.66mm, mass flow rate through a capillary is fixed to 0.8443 g/s and problem is solved up to chocked flow condition.

A. *Effect of condenser temperature on pressure variation*

When R134a is tested for condenser temperature of 50 ^{o}C we get pressure drop from 1.3179 to 0.252 Mpa and takes a capillary length of 2.015m,for 45 ^{o}C pressure drop is from 1.159 to 0.243 Mpa and takes a capillary length of 1.67m .Now it is finally tested for 40 ^{o}C this shows drop in pressure from 1.016 to 0.234 Mpa and takes length of 1.38m.These results shows that for each 5 ^{o}C rise in condenser temperature change in pressure per unit length decreases with 3-4%.Similar trend is shown in graph below for R152a and R1234yf.From this we will say that change in pressure per unit length decreases with increase in condenser temperature. This effect results in larger tube length for similar pressure drop.

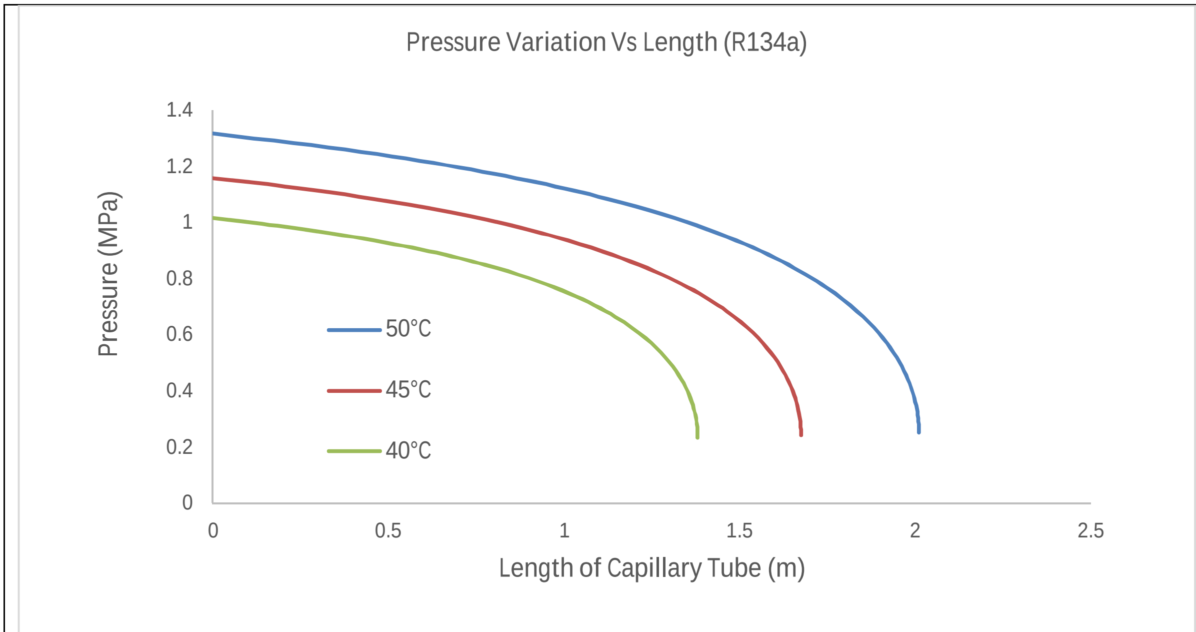

Figure 6.1.1 :- Variation of pressure with length for condenser temperatures of 50,45 and 40^{0}C for R134a.

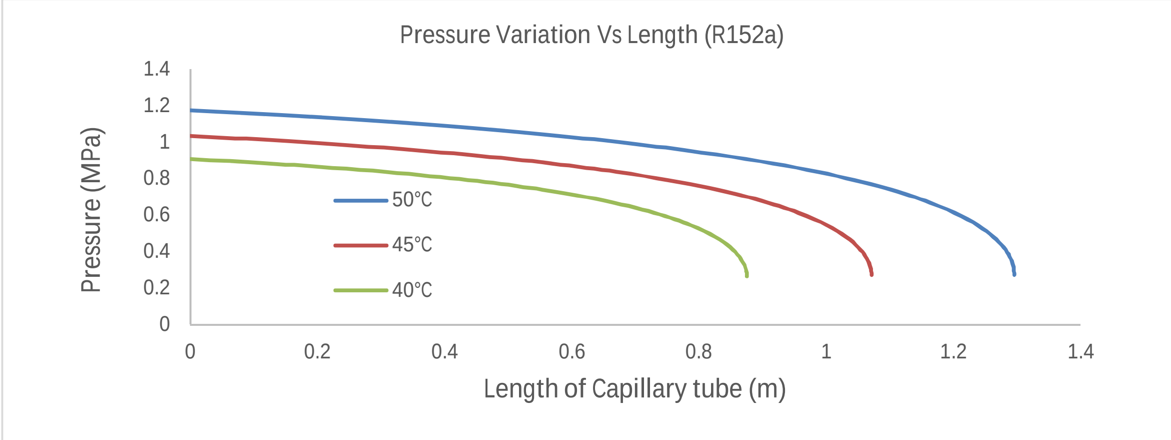

Figure 6.1.2 :- Variation of pressure with length for condenser temperatures of 50,45 and 40^{0}C for R152a.

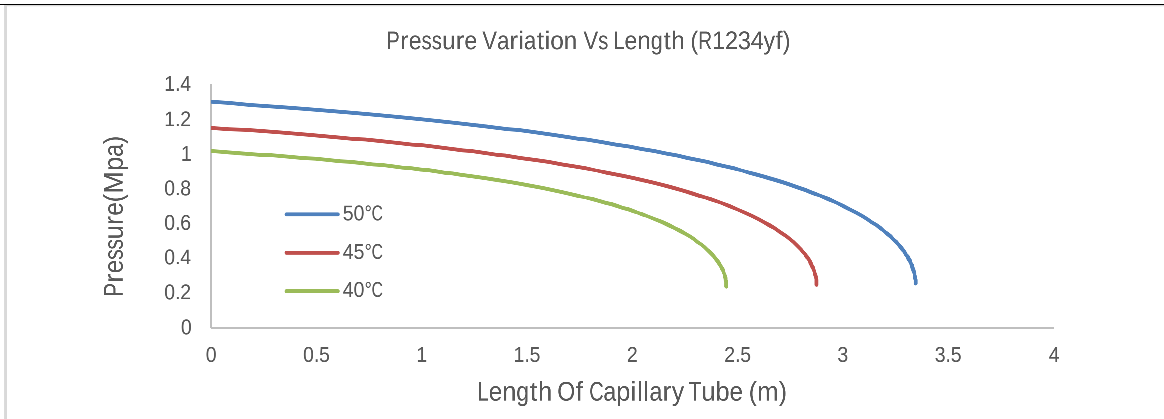

Figure 6.1.3 :- Variation of pressure with length for condenser temperatures of 50,45 and 40^{0}C for R1234yf.

B. Effect Of Condenser Temperature On Temperature Variation

When R134a is tested for condenser temperature of 50 ^{o}C we get temperature drop upto -4 ^{o}C, for 45^o C temperature drop upto -5 ^{o}C. Now it is finally tested for 40 ^{o}C this shows temperature drop upto -6 ^{o}C.This shows that every 5 ^{o}C rise in condenser temperature decreases 1^{o}C drop in temperature at exit of a capillary for R134a. These results shows that for each 5^{o}C rise in condenser temperature increases the evaporator temperature by 1^{o}C. Similar trend is shown in graph below for R152a and R1234yf.From this we will say that temperature at exit of a capillary decreases minutely with increase in condenser temperature. This effect somehow bounds the capillary to be used for more temperature at exit of a capillary tube.

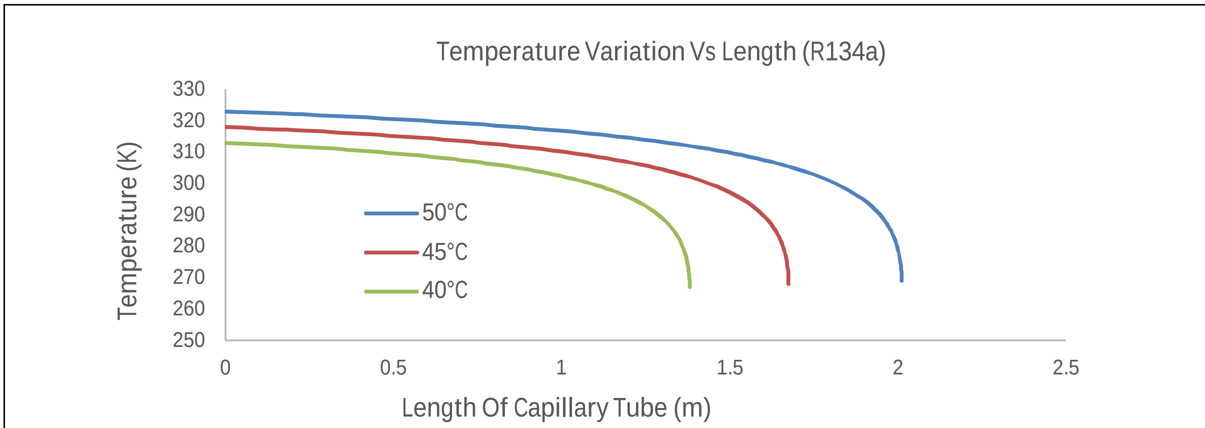

Figure 6.2.1 :- Variation of temperature with length for condenser temperatures of 50,45 and 40^{0}C for R134a.

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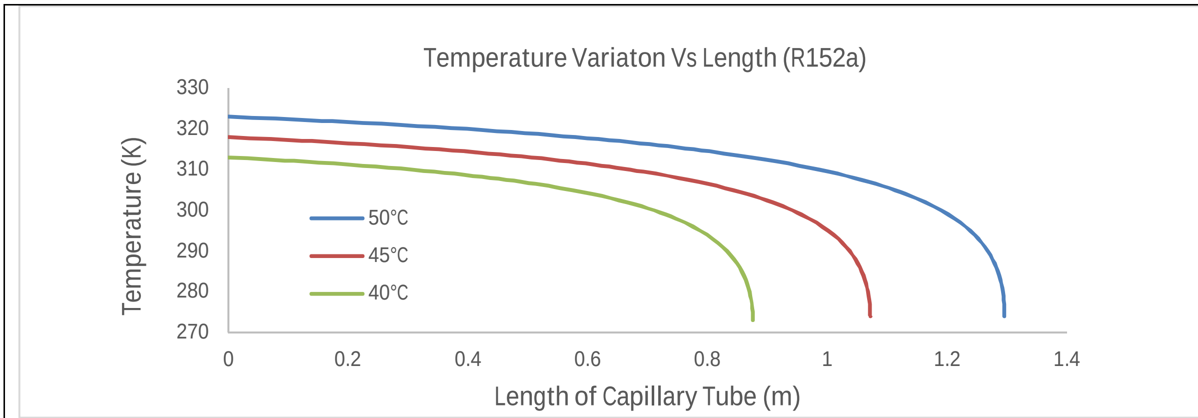

Figure 6.2.2 :- Variation of temperature with length for condenser temperatures of 50,45 and 40^{0}C for R152a.

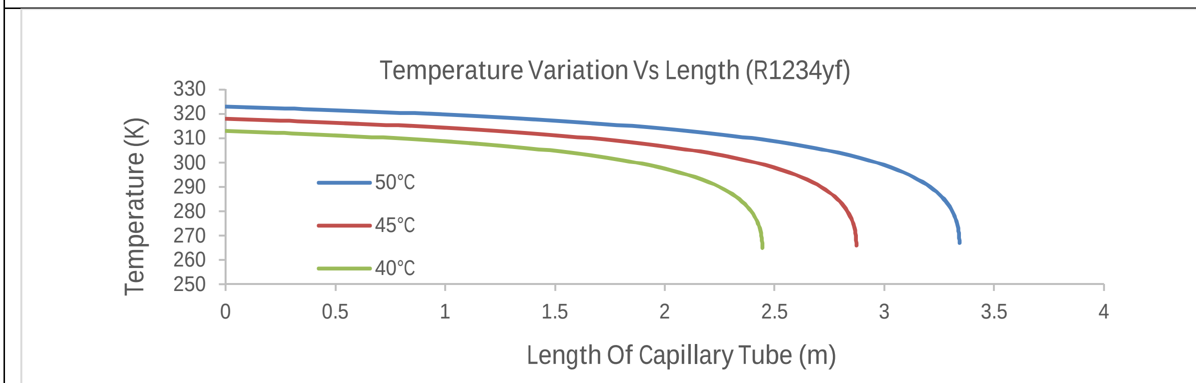

Figure 6.2.3 :- Variation of temperature with length for condenser temperatures of 50,45 and 40^{0}C for R1234yf.

C. Effect Of Condenser Temperature On Dryness Fraction

When R134a is tested for condenser temperature of 50 ^{o}C we get dryness fraction of 0.380 at exit of an capillary tube, for 45 ^{o}C dryness fraction is 0.347 . Now it is finally tested for 40 ^{o}C this shows dryness fraction of 0.316.These results shows that for each 5^{o}C rise in condenser temperature dryness fraction increases at exit of an capillary by 9-10%. Similar trend is shown in graph below for R152a and R1234yf.From this we will say that dryness fraction increases at exit of a capillary with increase in condenser temperature. This is also an undesirable effect because we want minimum amount of dryness fraction at exit because it reduces the amount of useful refrigerant at exit of a capillary tube.

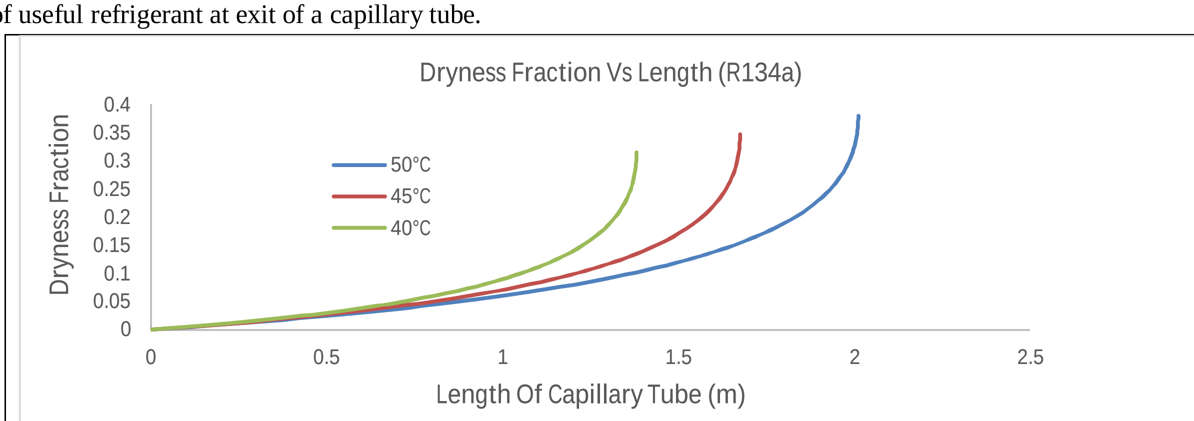

Figure 6.3.1 :- Variation of dryness fraction with length for condenser temperatures of 50,45 and 40^{0}C for R134a.

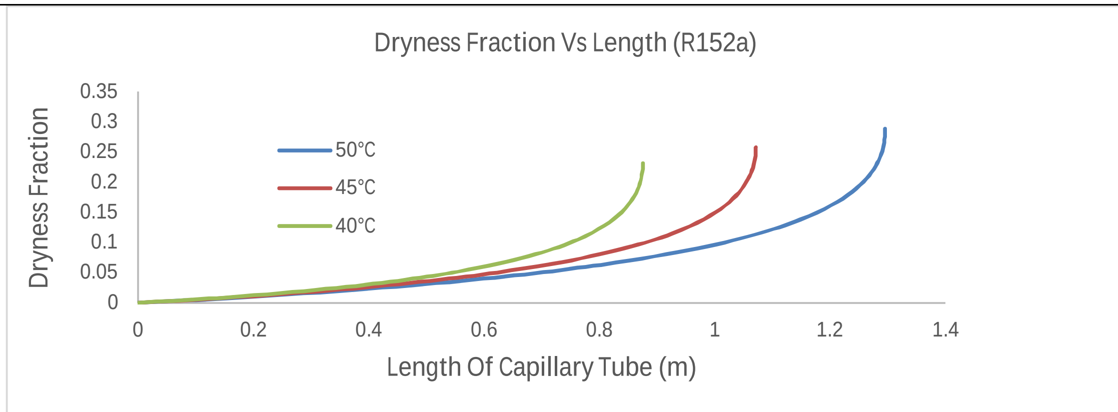

Figure 6.3.2 :- Variation of dryness fraction with length for condenser temperatures of 50,45 and 40^{0}C for R152a.

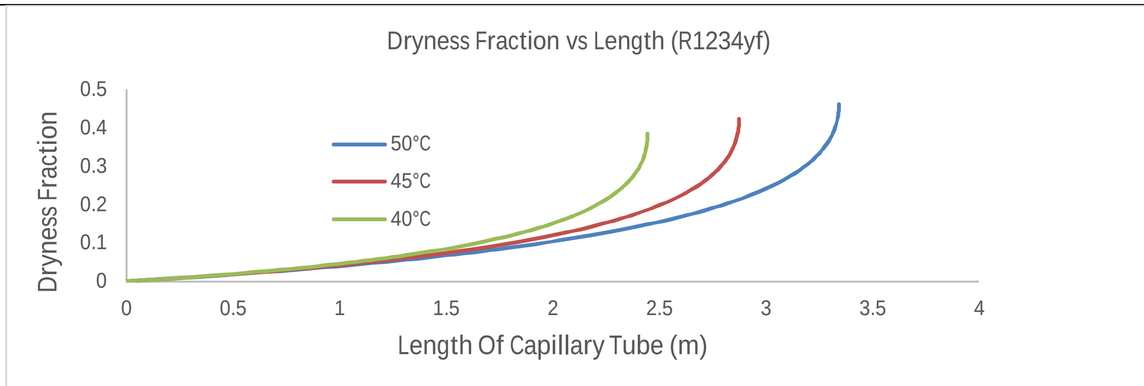

Figure 6.3.3 :- Variation of dryness fraction with length for condenser temperatures of 50,45 and 40^{0}C for R1234yf.

D. Effect Of Condenser Temperature On Velocity

When R134a is tested for condenser temperature of 50 ^{o}C we get velocity of 76.212m/sec at exit of a capillary tube, for 45 ^{o}C velocity is 72.346 m/sec. Now it is finally tested for 40 ^{o}C this shows velocity of 68.3105 m/sec. These results shows that for each 5^{o}C rise in condenser temperature velocity increases at exit of a capillary by 5-6%. Similar trend is shown in graph below for R152a and R1234yf.From this we will say that velocity increases at exit of a capillary with increase in condenser temperature. This increase in velocity results in acceleration pressure drop which ultimately supports the flashing phenomena which is also undesirable.

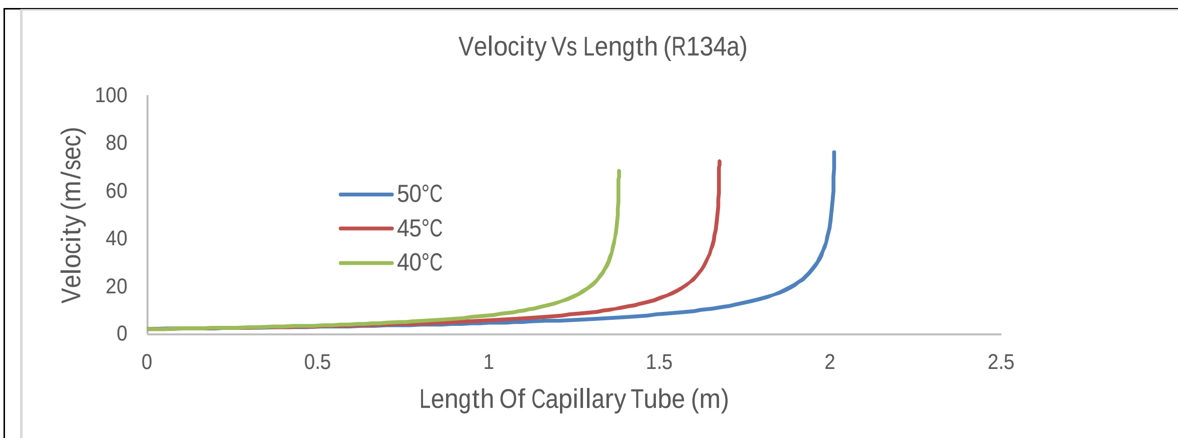

Figure 6.4.1 :- Variation of velocity with length for condenser temperatures of 50,45 and 40^{0}C for R134a.

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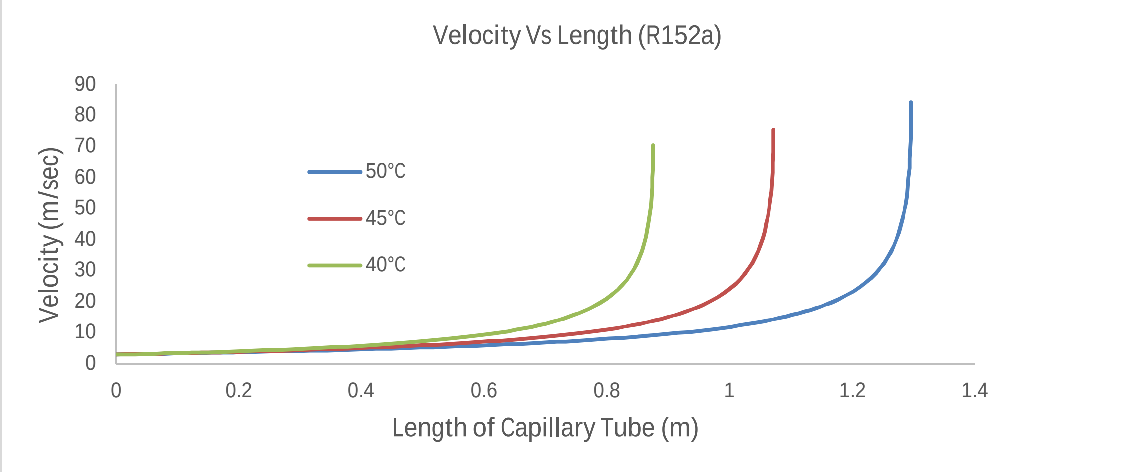

Figure 6.4.2 :- Variation of velocity with length for condenser temperatures of 50,45 and 40^{0}C for R152a.

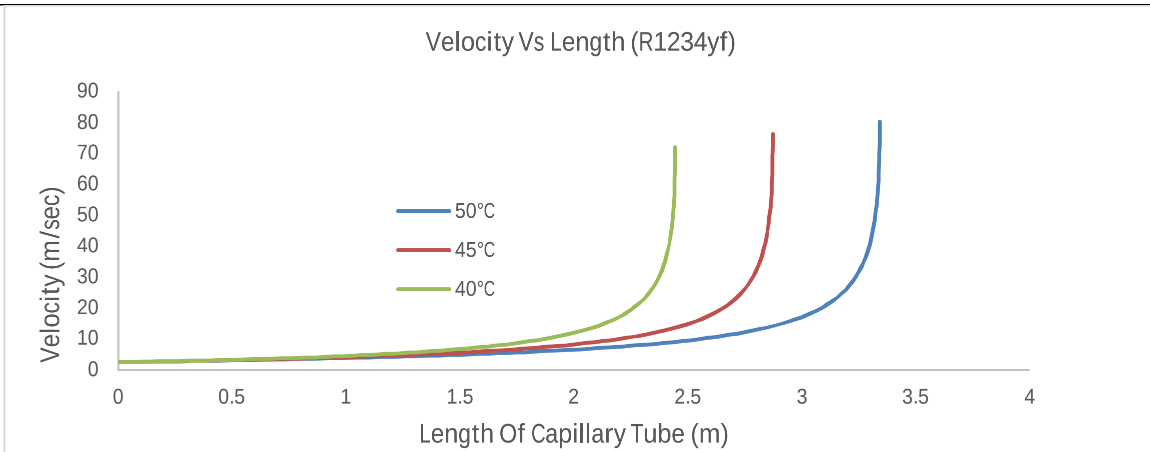

Figure 6.4.3 :- Variation of velocity with length for condenser temperatures of 50,45 and 40^{0}C for R1234yf.

VII. CONCLUSION

In present study, thermophysical properties of refrigerants like R1234yf and R152a are compared with R134a. This investigation shows that R1234yf and R152a have almost similar properties like R134a and have very low GWP that is 4 for R1234yf and 124 for R152a which is less compared to 1432 GWP of R132a.This shows that these refrigerants are considered as a substitute for R134a.After this Investigation, performance comparison of these refrigerants are done in adiabatic straight capillary to check there feasibility as substitute. This performance comparison shows that these substitutes have almost similar graphs and trend whether it is for temperature, pressure, dryness fraction and velocity. Whatever difference we obtain in a graphs are negligible and can be ignored in a first view. But if we have to choose between R1234yf and R152a for best substitute, then following points are to be considered obtained from analysis-

1) R1234yf works well in given temperature range for given input whereas R152a results in chocked flow for same given inp
2) R1234yf requires 72% longer tube length and R152a requires 36% shorter tube length as compared to R134a.

After finding the alternatives, effect of condenser temperature is evaluated for these refrigerants on properties like pressure drop, temperature variation, dryness fraction and velocity which gives following important points-

a) Change in pressure per unit length decreases with increase in condenser temperature.
b) For R134a, each 5^{0}C rise in condenser temperature increases the evaporator temperature by 1^{0}C.This shows temperature at exit of a capillary increases minutely with increase in condenser temperature.
c) Dryness fraction increases at exit of a capillary with increase in condenser temperature. For R134a, each 5 ^{o}C rise in condenser temperature, dryness fraction increases at exit of a capillary by 9-10%.
d) Velocity increases at exit of a capillary with increase in condenser temperature.

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