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Flow characteristics of adiabatic capillary tube using R-12 as a refrigerant by mathematical modeling and CFD analysis

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Abstract - **The intent of the present study is to study the behavior of counter flow solar air heaters and to compare their performance with the conventional solar air heaters under different set of conditions, obtained by changing the various governing parameters like air mass flow rate, inlet air temperature, spacing between top cover and absorber plate and intensity of solar radiation. Four types of solar air heaters have been taken into consideration i.e. single glazing solar air heater, double glazing solar air heater, counter flow solar air heater and counter flow with porous matrix solar air heater. The problem have been solved by the Finite Difference Method. It has been found that the counter flow solar air heater is more efficient than the conventional solar air heaters. The efficiency of counter flow with porous matrix solar air heater is highest among all four types of solar air heaters which are been taken into consideration.**

Keywords - Adiabatic, straight capillary, Refrigerant R-12, Properties

1. INTRODUCTION

Capillary tubes have been investigated in detail for many decades. A capillary tube is a common expansion device used in small sized refrigeration and air-conditioning systems. A capillary tube is a constant area expansion device used in a vapor-compression refrigeration system located between the condenser and the evaporator and whose function is to reduce the high pressure in the condenser to low pressure in the evaporator. The capillary tube expansion devices are widely used in refrigeration equipment, especially in small units such as household refrigerators, freezers and small air conditioners. Its simplicity is the most important reason to continue using it instead of other expansion devices. Capillaries substitute for more expensive and complex thermostatic valves. For instance, capillary tubes are used in some complex cooling systems for particle detectors installed. Nevertheless, one can find other reasons for their use in highly specialized cooling circuits.

In fact the flow through capillary tube is actually adiabatic not an isenthalpic. As the name suggests the adiabatic capillary tubes are one in which there is no heat transfer with the surroundings or the walls of the capillary tube are thermally insulated. On the basis of geometrical shape the capillary tubes can be classified as under 1) straight capillary tube 2) coiled capillary tube. As the flow through the capillary tube is adiabatic, the enthalpy of refrigerant remains constant till the flashing occurs. As a result of flashing, a part of enthalpy is used to increase the kinetic energy of the refrigerant. Therefore, as the vaporization progresses the enthalpy of refrigerant falls in the two-phase flow region of the capillary tube.

2. LITERATURE REVIEW

Bansal and Rupasinghe [2] has also developed an empirical model for sizing capillary tubes. capillary tube is dependent on five primary variables, namely the capillary tube inner diameter, the mass flow rate of the refrigerant in the capillary tube, the pressure difference between high side and low side, the refrigerant subcooling at capillary inlet and the relative roughness of the capillary tube material. Bansal and Rupasinghe [3] have presented a homogeneous two-phase flow model, CAPIL, which is designed to study the performance of adiabatic capillary tubes in small vapour compression refrigeration systems, in particular household refrigerators and freezers. Wongwises et al. [11] presented theoretical comparison of the flow characteristics of many pairs of Refrigerants flowing through adiabatic capillary tubes. The two-phase flow model developed was based on homogeneous flow assumption. Two-phase friction factor was determined from Colebrook correlation [4]. Wongwises and Pirompak [10] have studied the flow characteristics of pure refrigerants and refrigerant mixtures in adiabatic capillary tubes and this paper provides the results of simulations using an adiabatic capillary tube as a refrigerant control device in refrigerating systems. The developed model can be considered as an effective tool of capillary tubes' design and optimization for systems using newer alternative refrigerants. The model is validated by comparing with the experimental data of Li et al. and Mikol [8] for R12 and Melo et al. [7] for R134a. Zhang and Ding [12] based on approximate analytic solutions of adiabatic capillary tube is valuable for theoretical analysis and engineering calculation. In this work, two kinds of approximate analytic solutions of adiabatic capillary tube have been developed. Akure et al. [1] has discussed the effects of various geometries of capillary tubes, the effects of pitches of both helical and serpentine-coiled capillary tubes on the performance of a vapor compression refrigeration system. Several capillary tubes of equal lengths (2.03 m) and varying pitches, coiled diameters and serpentine heights were used. Both inlet and outlet pressure and temperature of the test section (capillary tube) were measured and used to estimate the coefficient of performance (COP) of the system. Khan et al. [5] have also developed a numerical model flow through an adiabatic spiral capillary tube. An analytical model has been developed to predict the length of adiabatic capillary tubes used in domestic refrigerators and low-capacity residential air conditioners. McAdams et al. [6] viscosity correlation has been used to evaluate the two-phase viscosity of the expanding refrigerant in the latter part of the capillary tube. The simulation results are validated with the experimental findings of previous researchers. The performance of the above two geometries of adiabatic capillary tube is compared, and it is established that for the same state of refrigerants at the inlet and exit of the adiabatic capillary, spiral capillary is found to have a shorter length.

3.1 Finite Difference Formulation

The technique of Finite Difference Methods is used to solve differential equations numerically. In this method physical domain is converted to computational domain by dividing it into a number of linear elements. Following steps describe the procedure of solving differential equation.

a. By applying the laws of conservation of mass, momentum and energy mass we develop the Governing differential equations
b. Convert a given differential equations into difference equations Using finite difference approximation.

The finite difference approximations using Taylor Series

$$f(x_0+\Delta x) = f(x_0) + \Delta x f^{'}(x) + \frac{\Delta x^2}{2!} f^{''}(x) + \ldots\ldots. \tag{3.1}$$

$$f(x_0-\Delta x) = f(x_0) - \Delta x f^{'}(x) + \frac{\Delta x^2}{2!} f^{''}(x) + \ldots\ldots \tag{3.2}$$

Approximation for first Derivative (forward difference formulation)

$$f^{'}(x_0) = \frac{f(x_0+\Delta x) - f(x_0)}{\Delta x} - f^{''}(x) \tag{3.3}$$

$$f^{'}(x_0) = \frac{f(x_0+\Delta x) - f(x_0)}{\Delta x} - 0(\Delta x)$$

$$f_i \approx \frac{f_{i+1} - f_i}{\Delta x}$$

Backward difference formulation

$$f^{'}(x_0) = \frac{f(x) - f(x_0-\Delta x)}{\Delta x} + f''(x).\frac{\Delta x}{2}$$

$$f_i^{'} = \frac{f_i - f_{i-1}}{\Delta x} + 0(\Delta x)$$, $0(\Delta x)$ higher order terms

$$f_i^{'} \approx \frac{f_i - f_{i-1}}{\Delta x} \quad \text{having an order of accuracy } 0(\Delta x) \tag{3.4}$$

Central difference formulation

$$f(x_0+\Delta x)-f(x_0-\Delta x)=2\Delta x f^{'}(x_0)+2\frac{\Delta x^3}{3!}f^{'''}(x_0)$$

$$f^{'}(x_0)=\frac{f(x_0+\Delta x)-f(x_0-\Delta x)}{2\Delta x}-\frac{\Delta x^2}{3}f^{'''}(x_0) \tag{3.5}$$

$f_i^{'} \approx \frac{f_{i+1}-f_{i-1}}{2\Delta x}$, having an order of accuracy $0(\Delta x)$

Approximation for second derivative

Central difference formulation from equation (3.1) and (3.2) we get

$$f(x_0+\Delta x)+f(x_0-\Delta x)=2f(x_0)+2\frac{\Delta x^2}{2!}f^{''}(x_0)+........ \tag{3.6}$$

$$f^{''}(x_0)\approx\frac{f(x_0+\Delta x)-2f(x_0)+f(x_0-\Delta x)}{\Delta x^2}-0(h^2) \tag{3.7}$$

$$f_i^{''}=\frac{f_{i+1}-2f_i+f_{i-1}}{\Delta x^2} \tag{3.8}$$

3.2 Mathematical Modeling

Initially, a generalized mathematical model has been developed for straight capillary tube and for other geometries like helical and spiral capillary tubes the necessary modifications have been made in the developed model for the flow through a straight capillary tube.

The mathematical modeling of the capillary tubes has been carried out by applying mass, momentum and energy conservation equations on the capillary tube of required geometry. For the purpose of analysis, the physical domain has been converted to computational domain, as shown in Figure.3.1. The refrigerant from condenser enters the capillary tube at section 1 in a sub cooled liquid state. Due to sudden contraction at the capillary tube inlet, the refrigerant pressure is dropped and state point 2 is reached. Subsequently, a single phase liquid flow in the capillary tube is established. Since the flow of refrigerant through the capillary tube is adiabatic, the temperature of the flowing liquid refrigerant remains constant. The pressure inside the capillary tube drops linearly as long as the flow is in liquid state. When the refrigerant pressure drops up to point 3 i.e., the saturation pressure, at that point two-phase flow set up in the capillary tube. In the two-phase region of the capillary tube, the temperature and pressure of refrigerant starts falling rapidly till the evaporator pressure or the choking point 4 is attained.

3.2.1 Mass Balance

Application of continuity equation results into the following

$$m=\rho AV \quad \text{or} \quad G=\frac{m}{A}=\rho V \tag{3.9}$$

3.2.2 Momentum Balance

On applying the principle of momentum conservation or the Second law of thermodynamics

$$P.A-(P+dP).A-\tau_w(\pi d)dL=mdV \tag{3.10}$$

On simplification, Equation 3.10 reduces to

$$-dP=\frac{f}{2d}\rho V^2 dL+\rho VdV \tag{3.11}$$

Taking log both sides of equation 3.9 after solving we get

$$-\frac{dV}{V}=\frac{d\rho}{\rho} \tag{3.12}$$

Equation 3.11 reduces to

$$dL = \frac{2d}{f}\left(\frac{\rho dP}{G^2} - \frac{d\rho}{\rho}\right) \tag{3.13}$$

3.2.3 Energy Balance

On applying the steady flow energy equation on the element to get

$$\delta \mathrm{q} - \delta \mathrm{w} = \mathrm{dh} + \mathrm{VdV} + \mathrm{gdZ} \tag{3.14}$$

Single phase liquid region

$$L_{sp} = \frac{d}{f_{sp}}\left(\frac{2}{\rho V^2}\left(P_2 - P_3\right)\right) = \frac{2d\rho\left(P_2 - P_3\right)}{fG^2} \tag{3.15}$$

Pressure loss due to entrance effects

$$P_1 - p_2 = k\frac{\rho V^2}{2} \tag{3.16}$$

where k is the entrance loss coefficient, taken as 1.5

From Equations 3.15 and 3.16

$$L_{sp} = \frac{d}{f_{sp}}\left[\frac{2\rho}{G^2}\left(P_1 - P_3\right) - k\right] \tag{3.17}$$

3.3 Two-phase region

$$m = \frac{V_3 A}{V_3} = \frac{V_4 A}{V_4} \tag{3.18}$$

Applying steady flow energy equation, with no external work, heat transfer and potential energy, between sections 3 and 4

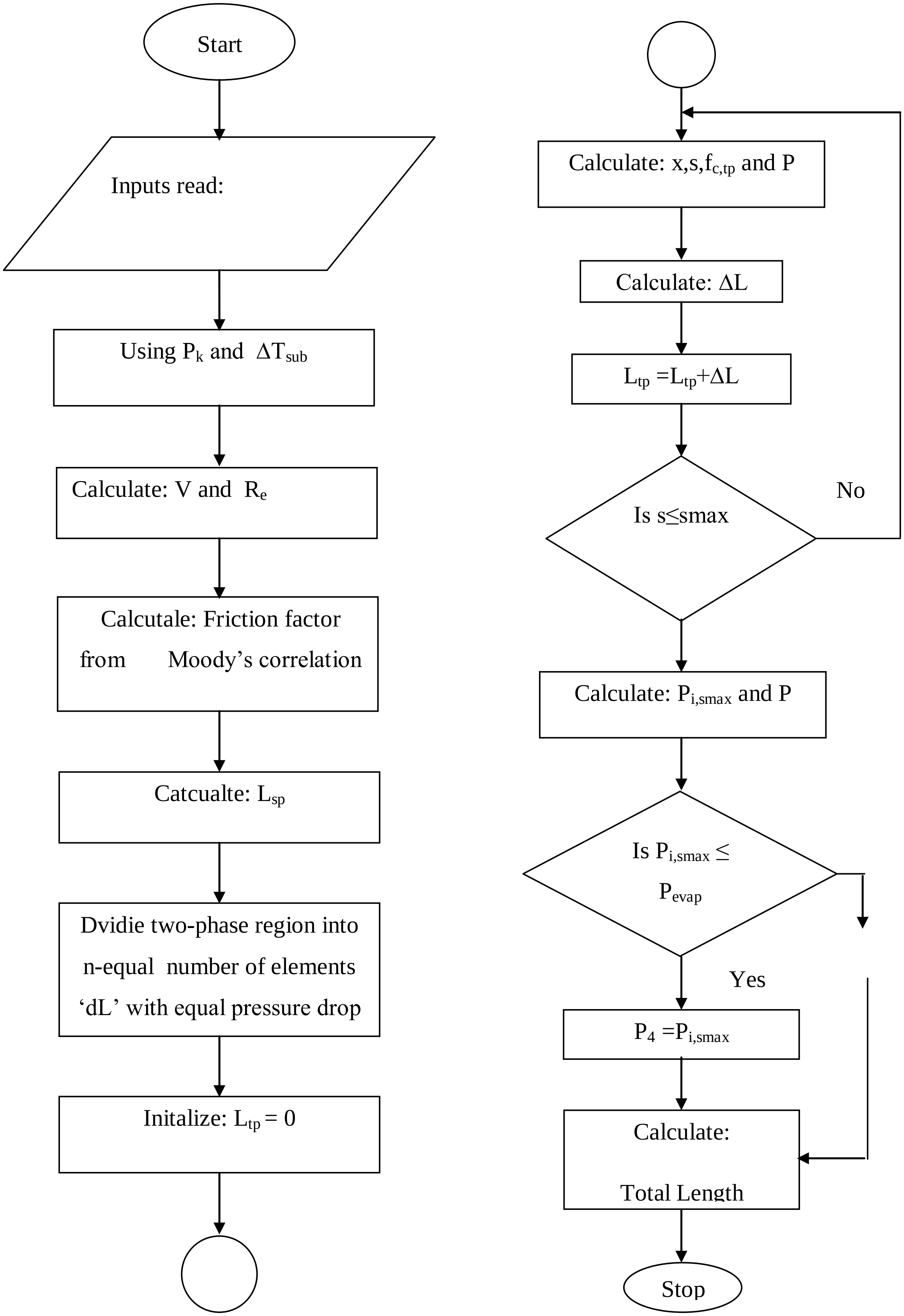
$$h_3 + \frac{V_3^2}{2} = h_f + x.h_{fg} + \frac{G^2}{2}\left(v_f + x.h_{fg}\right)^2 \tag{3.19}$$

Equation 3.19 is quadratic in x and the quality x can be expressed as

$$x = \frac{-h_{fg} - G^2 v_f v_{fg} + \sqrt{\left(G^2 v_f v_{fg}\right)^2 - 2G^2 v_{fg}^2\left(\frac{G^2 v_f^2}{2} - h_4 + \frac{v_3}{2} + h_f\right)}}{G^2 v_{fg}^2} \tag{3.20}$$

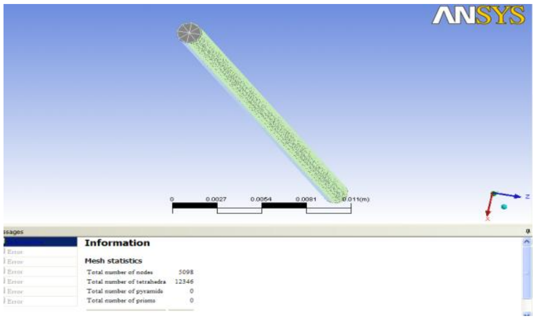
The two-phase friction factor f_{tp} can be calculated using Moody’s correlation [9]. The Reynolds number in two-phase region has to be determined by

$$\mathrm{Re}_{tp} = \frac{Vd}{\mu_{tp} v_{tp}} \tag{3.21}$$


Start
Inputs read:
Using P_k and ΔT_sub
Calculate: V and R_e
Calcutale: Friction factor from Moody’s correlation
Catcualte: L_sp
Dvidie two-phase region into n-equal number of elements ‘dL’ with equal pressure drop
Initalize: L_tp = 0
Calculate: x,s,f_c,tp and P
Calculate: ΔL
L_tp =L_tp+ΔL
Is s≤smax
No
Calculate: P_i,smax and P
Is P_i,smax ≤ P_evap
Yes
P_4 =P_i,smax
Calculate: Total Length
Stop

3.4 ANSYS CFX Solution Methodology

In order to use simulation techniques developed, a physical model is used in Pro/E. After creation of the physical model, file is saved in *.iges format.



Information

Mesh statistics

Total number of nodes	5098
Total number of tetrahedra	12346
Total number of pyramids	0
Total number of prisms	0

Figure 3.4 Straight capillary tube model

Figure 3.5 Meshing

Now open the ANSYS Workbench and open the meshing module for creation of CFX mesh. Set the physical preference as CFD and mesh method as CFX. Import the geometry in the ANSYS Workbench, by clicking on the tab geometry and from this tab select from file. A new window CFX mesh is opened. Now set the default body spacing and default face spacing as the size of the capillary tube used is small reduce the size of default body spacing and default face spacing. The meshing is done by iterative process. If a very fine mesh is created then more calculation work is to be done by the processor. Generate the volume mesh by clicking on generate volume mesh. file is saved in *.gtm or *.cmdb.

After creation of CFX mesh, open ANSYS CFX module. In the ANSYS CFX open CFX-Pre and from the file menu select new simulation and set the simulation type as general. By right click on the mesh, select import mesh and window display as shown in figure

Figure 3.6 Import mesh

Add the material by selecting tab material and then select import from library select materials-redkw.ccl. A list of refrigerant opened, now select R12Rkvl. As in the capillary tube there are two flow regions i.e. single phase and two phase. So we have to select R12Rkv which is suitable for single phase and two phase flow. Now click on default domain tab and insert the boundary conditions as inlet. Inlet in default domain tab is opened in this, icon select the inlet boundary from the model and after that fill the boundary details as static pressure at the inlet and temperature at the inlet. Similarly create the outlet boundary and fill the details and then click on apply these settings.

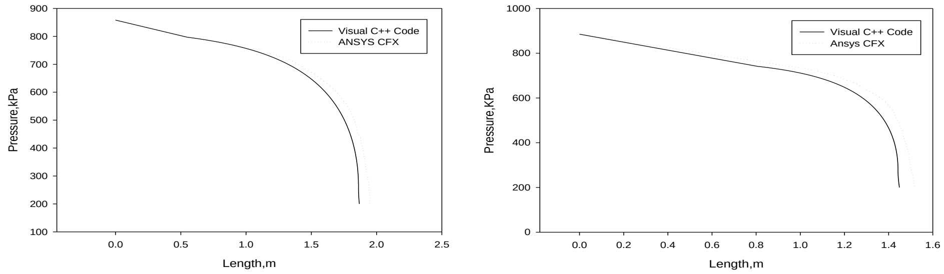
After that select default domain default tab and select the wall as ANSYS CFX creates the wall adiabatic by default and the model acting as a working fluid.

Now solve the model with solver and the results are obtained through CFX-Post.

4.1 Straight Capillary Tube

S.No.	Input Parameters	Case 1	Case 2
1	Refrigerant Used	R12	R12
2	Mass flow rate	15.66 kg/h	21.23 kg/h
3	Dia of Capillary Tube	1.17 mm	1.41 mm
4	Roughness Ratio	0.003	0.000384
5	Capillary Tube Inlet Pressure	885 kPa	858 kPa
6	Capillary Tube Inlet Temperature	303K	305.8K

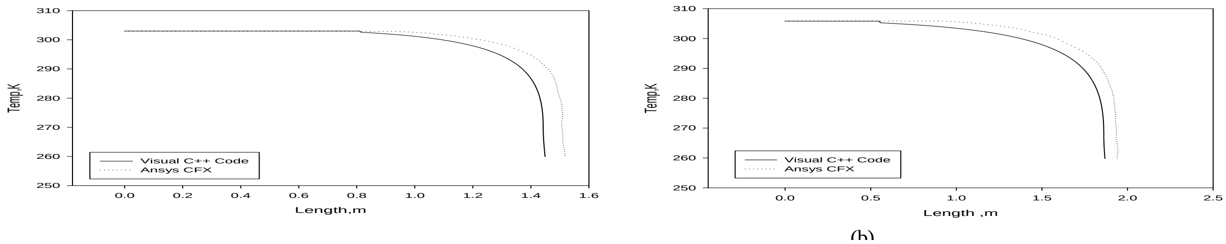
Table 4.1 shows the input parameters used for the R-12 to find the length of the straight adiabatic capillary tube and to further study the effect of fluid properties such as pressure, temperature, density, viscosity, specific volume, reynolds number and dryness fraction on length.



(a) (b)

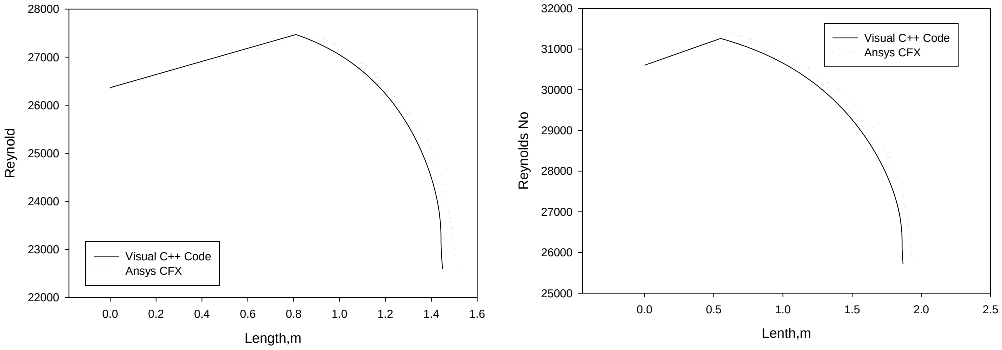
Figure 4.1 Pressure and length plot for proposed model and ANSYS CFX

Figure 4.1 has been drawn to compare the proposed model with the ANSYS CFX module to study the flow characteristics for R12 refrigerant inside the straight capillary tube. The length of the proposed model for case 1 is 1.4491m and with ANSYS CFX is 1.519 m. The result obtained from the proposed model under predicts the capillary length as compared to ANSYS CFX for the flow of R-12. . The length of the proposed model for case 2 is 1.867 m and with ANSYS CFX is 1.9490 m. The result obtained from the proposed model under predicts the capillary length as compared to ANSYS CFX Hence, the proposed model is in good agreement with the ANSYS CFX. As the refrigerant in liquid state enters in the straight capillary tube its pressure drops linearly. As the refrigerant enters in the two phase region there is sharp decrease in pressure and temperature this is due to cumulative effect of friction pressure drop and acceleration pressure drop, which leads to more vaporization of the fluid into the two phase region.



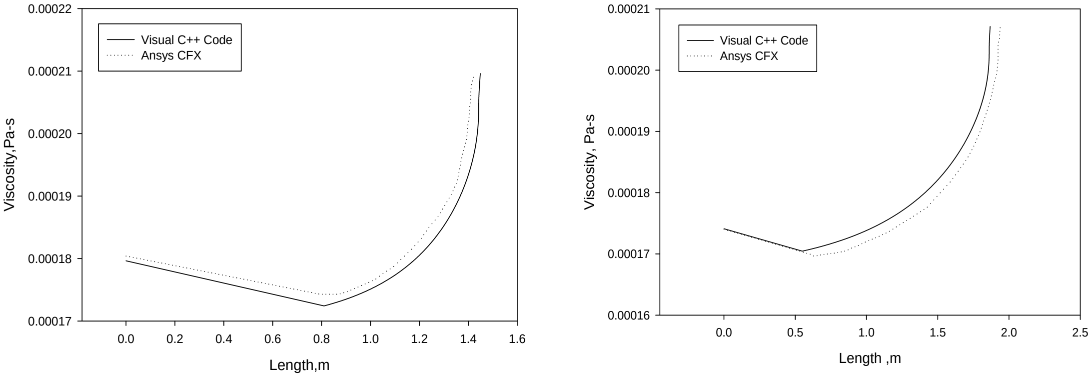
(b)

Figure 4.2 Temperature and length plot for proposed model with ANSYS CFX



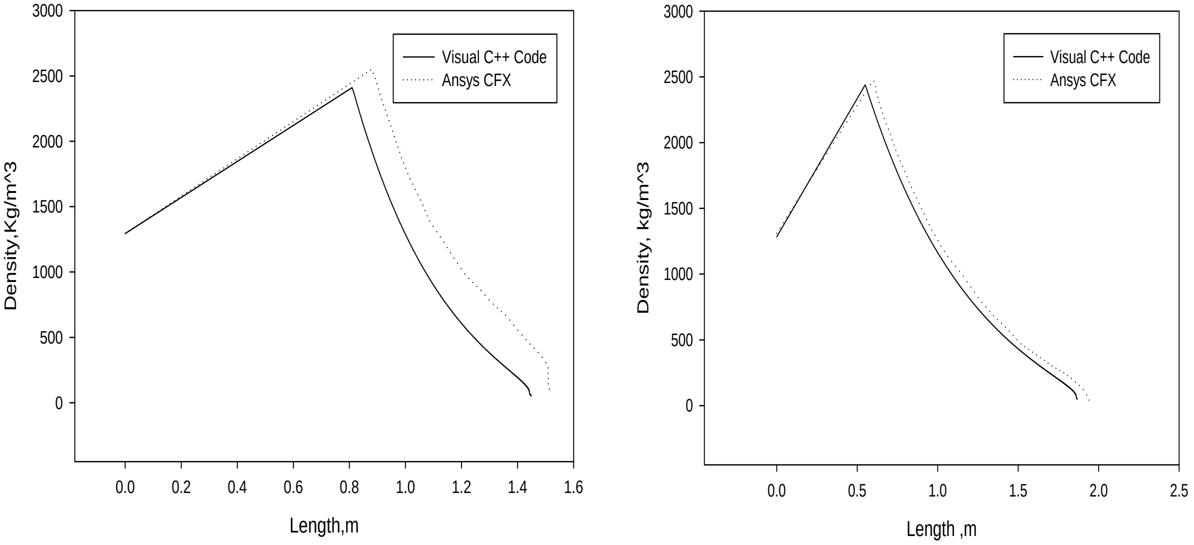
(a) (b)

Figure 4.3 Reynolds number and length plot for proposed model with ANSYS CFX



(a) (b)

Figure 4.4 Viscosity and length plot for proposed model with ANSYS CFX



(a) (b)

Figure 4.5 Density and length plot for proposed model with ANSYS CFX

4.2 Conclusion Remarks

The following conclusion can be drawn

- The mathematical model for straight adiabatic capillary tube has been developed by using the law of conservation of mass momentum and energy and the model is capable of predicting the capillary tube length for a given mass flow rate.
- Similar model is obtained in the ANSYS CFX and the results are found to be in fair agreement

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