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Research Article

Modelling of phase change for Two-Phase Refrigerant Flow inside Capillary Tube under Adiabatic Conditions

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Abstract

In the present study, phase change of refrigerant flow through capillary tube under adiabatic conditions has been studied based on computational fluid dynamics technique. Eulerian multiphase flow Homogeneous equilibrium model along with thermal phase change based on mass transfer mechanism was used for simulation of refrigerant flow through adiabatic straight capillary tube. The effect of various design parameter such condensation pressure, capillary tube length and capillary tube diameter on the flashing inception point has been discussed numerically. The numerical model based on finite volume method using $K-\varepsilon$ turbulence model gives the behavior of refrigerant properties such as field of pressure, temperature, dryness fraction, void fraction and velocity along the distance of capillary tube which helps in the understanding of beginning of vaporization phenomenon. The present numerical model has been validated with the others models and a good agreement are obtained which can be lead to depend up on ANSYS CFX 16.1 in design and optimization of capillary tube of refrigeration industry.

Keywords: *ANSYS CFX, CFD, flashing inception point.*

1. Introduction

Capillary tubes are one of the most important components of the vapor compression refrigeration industry with capacity below 10 KW. Capillary tube is a long hollow pipe with inner diameter 0.5-2 mm and length (1-6) m (Zareh, M. *et al,* 2014). Despite of the simplicity in the design of capillary tube but the flow phenomenon take place inside it is really complex. Refrigerant leaves the condenser as a single phase sub-cooled liquid state and expands before enters the evaporator into mixture of two phase flow. This transition from single phase into two phase known as flashing flow. Unlike of pool boiling or flow boiling where vaporization takes place due to heat flux applied from external source, the vaporization occurs in capillary tube under adiabatic conditions due to frictional pressure drop below the vaporization pressure (Lin, S. *et al,* 1991). The point where the first vapour bubble form known as flashing inception point. Post the flashing inception point, two phase region will be dominated. Due to importance of phase change it had been studied by various researchers. Li *et.al.* investigated experimentally the flashing flow phenomenon of refrigerant R12 inside capillary tubes with length 150 cm and diameters ranging from 0.66 – 1.17 mm. The pressure and temperature distributed along the capillary tube were measured. The temperature at the inlet of capillary tube was varied from 290-326 °K, pressure was varied from 630-1320 kPa, inlet sub-cooling was varied from 0-290 °K. It obtained that as the tube diameter of capillary tube increases, metastable length will decreases.

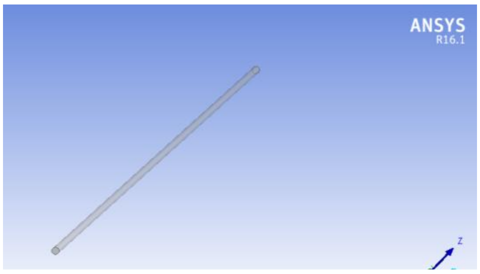

Fig.1 Capillary tube model

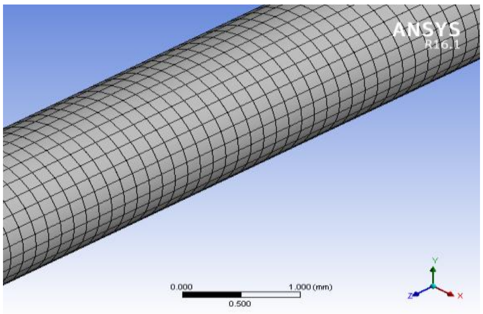

Fig.2 Mesh of Capillary tube

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The increasing of refrigerant mass flow rate leads to increases of under pressure of vaporization. Under pressure of vaporization will decreases as inlet sub-cooling increasing. It obtained also that back pressure did not have any effect on flashing inception point. Bansel, Rupasinghe presented homogeneous flow model in order to study the performance of capillary tube of small vapor compression refrigeration systems. Their model based on conservation of mass, energy and momentum of fluid which are solved by writing code in FORTRAN77 program through iterative procedure and Simpson rule. The model used REFPROP where Carnahan-Starling-DeSantis equation of state in order to calculate properties of refrigerant.

Ingle, *et al.* presented a homogeneous equilibrium approach to model the flashing phenomenon along with the cavitation model based on mechanism of transfer of mass through capillary tubes for systems of refrigeration. This model gave the field of pressure, temperature and dryness fraction along capillary tubes. The mass, energy and momentum of fluid equations solved using multiphase mixture model, realizable k epsilon turbulent model with scalable wall function treatment had been used which is available in ANSYS FLUENT V15.0. The mass transfer model proposed by Zwart-Gerber-Belamri had been used in the source term. They conclude that homogeneous model can be used to design capillary tubes for refrigeration systems. Prajapati, Y.K. *et al.* presented numerical simulation of refrigerant flow through adiabatic capillary tube using R134a as a working fluid. ANSYS FLUENT Version 12 based on finite volume method using volume of fluid. k omega as a turbulent model used in CFD Simulation. A source term had been incorporated in the governing equations to model mass transfer from liquid phase to vapor phase during the flashing of liquid refrigerant. The mass transfer model proposed by Lee had been used in the source term. investigated experimentally the metastable flow through capillary tubes with pure propellants R134A and R600 and propellant-oil mixtures. A large number of experiments were carried out to verify the influence of inlet sub-cooling, internal diameter, mass flow rate and inlet pressure on the under pressure of vaporization. The results showed that the mass flow rate and sub-cooling degree are the two most important parameters affecting the under pressure of vaporization. Oil presence increases the metastable liquid region retarding flashing flow inception of mixture compared with pure propellant R134A.

The exact location of bubble formation has been indicated. Zareh, M., *et al.* simulated two phase refrigerant flow using drift flux model for adiabatic straight and helical capillary tubes. The model validation was done with measured data for refrigerants R134a, R12 and R22. Mass flow through the helically coiled tube with coil diameter equals to 40 mm was compared with straight capillary tube. Reduction in the length of helically coiled capillary tubes was analyzed for the same mass flow under different coil diameters.

In this paper, flow of refrigerant flow inside capillary tube studied numerically. ANSYS CFX 16.1 based on finite volume method using Eulerian-Eulerian multiphase flow model considering the homogeneous flow model between phases along with thermal phase change based on mass transfer mechanism used to simulate the phase change phenomenon of refrigerant flow through capillary tube under adiabatic conditions.

2. CFD Simulation part

Flashing flow of refrigerant flow through adiabatic capillary tube is simulated using commercial CFD code ANSYS CFX version 16.1 based on finite volume method using $k-\varepsilon$ turbulence model along with Eulerian-Eulerian model considering the homogeneousity between phases to solve the governing equations.

2.1 Mesh Generation

The partial differential equations of fluid flow are not amenable to analytical solution except for very simple cases. Therefore, in order to analyze fluid flows, flow domain are split into smaller domains called elements cells and the collection of all elements are known as numerical grid or mesh. The governing equations are solved in side each of these portions of the domain.

2.2 Governing equations

The homogeneous equilibrium model is based up on the conservations equations of mass, energy and momentum of fluid as well as the void fraction equation.

For homogeneous two phase flow model, the density of mixed (liquid-vapour) flow can be predicted using the following expression.

$$\rho_{tp} = \sum_{i=1}^{i=n} x_i \rho_i = \rho_g + (1-x)\rho_f$$

For homogeneous two phase flow model, the formula of calculating two phase (liquid-vapour) viscosity is taken as an empirical equation as a function of dryness fraction (x) inmpleminated in ANSYS CFX 16.1

$$\mu_{tp} = \sum_{i=1}^{i=n} x_i \mu_i = \mu_g + (1-x)\mu_f$$

1. Conservation of mass

$$\frac{\partial}{\partial t}(\rho_{tp}) + \nabla.(\rho_{tp}U_{tp}) = 0$$

2.2. Conservation of momentum

$$\frac{\partial}{\partial t}(\rho_{tp}U_{tp}) + \nabla.\left(\rho_{tp}U_{tp} * U_{tp} - \mu(\nabla U_{tp} + (\nabla U_{tp})^T)\right) = S_M - \nabla p$$

S_M is the surface tension interphase of two phase flow.

2.2.3 Conservation of energy

$$\frac{\partial}{\partial t}(\rho E) + \nabla.\left(U(\rho E + p)\right) = \nabla.\left(k_{eff}\nabla T\right) + S_h$$

Where,

$$k_{eff} = \sum_{i=1}^{i=n} x_i k_i = k_g + (1-x)k_f$$

$$E = \frac{\sum_{i=1}^{i=n} x_i \rho_i E_i}{\sum_{i=1}^{i=n} x_i \rho_i}$$

2.2.4 Conservation of volume fraction

$$\sum_{i=1}^{i=n} x_i = 1$$

$$(\frac{\partial}{\partial t}(x_v \rho_v) + \nabla.(x_v \rho_v U)) = \sum_{\alpha=1}^{N_P} \Gamma_{fv}$$

Where Γ_{fv} are source term of mass transfer from one phase to another due to phase change of some amount of refrigerant in liquid state into vapour.

2.3 Turbulence Model

On the basis of inlet boundary conditions such as inlet pressure, temperature and mass flow rate of refrigerant inside capillary tube, the flow will be turbulent. In the present numerical simulation, $k-\varepsilon$ turbulent model will be used for better accuracy at the cost of less computational time.

2.4 Boundary Conditions

What distinguishes how a fluid flow in a case from another case depends solely on the boundary condition. The treatment of boundary conditions are thus of paramount importance in numerical simulations. Improper boundary conditions treatment may cause significant discrepancies in predicted results. Boundary conditions may be classified into:

- Inlet/outlet conditions
- Walls

The capillary tube wall specified as frictional adiabatic wall, and the content of the capillary tube as refrigerant. The boundary conditions specified for this case are as given in Table (1).

Table 1: Boundary conditions

Zone	Parameter
Upstream conditions	• Inlet pressure • Inlet temperature • Inlet dryness fraction specified 1 for sub-cooled liquid
Downstream conditions	• Exit pressure
Wall	• Adiabatic frictional wall

3. Results and Discussion

The experimental and theoretical investigation results are illustrated in the present section, which include the results obtained for pressure and temperature data points for different capillaries.

Figure (3) shows the pressure distribution along the capillary tube. the results shows in single phase region(region I), the pressure of refrigerant drop linearly due to internal wall frictional losses while it drop suddenly and non-linearly in the two-phase region (region II). Figure (4) shows the temperature distribution along the straight capillary tube. Due to adiabatic conditions, the temperature remain constant in the single phase region till the flashing inception point where it will start to decrease because phase change (vaporization phenomenon) required latent heat of vaporization taken from liquid. In this two-phase temperature will be drop continuously decreasing till the end of the capillary tube. Figure (5) represents Dryness fraction distribution along capillary tube, it may be observed that in single phase region the value is zero but with the inception of vapor it start to increasing till the end of the pipe which mean that phase change happened in the capillary tube. Figure (6) explains the void fraction along the capillary tube. It can be seen that it slightly remain zero in sub-cooled single phase region but in the two-phase zone it starts to increases. Figure (7) represents the velocity of the refrigerant along the centerline of the pipe, it observed that that velocity in the single phase region is constant but with the inception of vapor and increasing of void fraction velocity keeps increasing in the two-phase region. This is due to fact the mass flow rate is constant and density reduced due to vapor formation which leads for increasing of velocity of refrigerant according to the continuity equation.

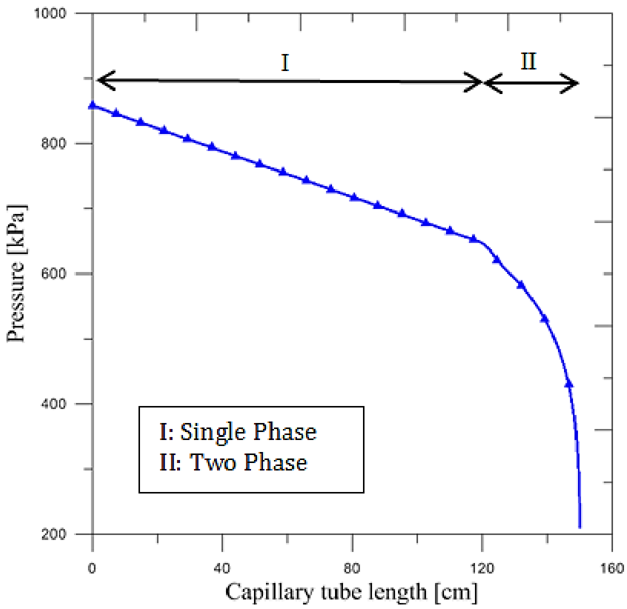

Fig.3 Pressure distribution of refrigerant flow through straight capillary tube under adiabatic conditions

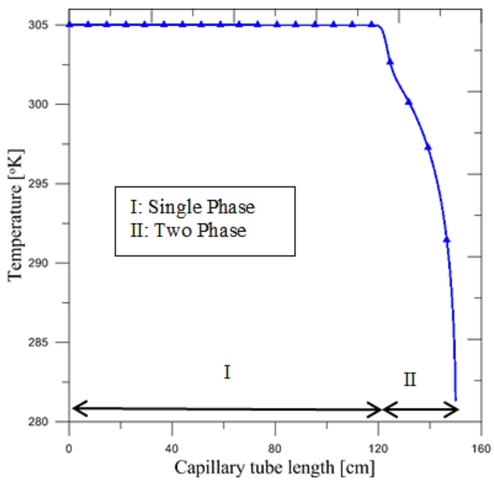

Fig.4 Temperature distribution of refrigerant flow through straight capillary tube under adiabatic conditions

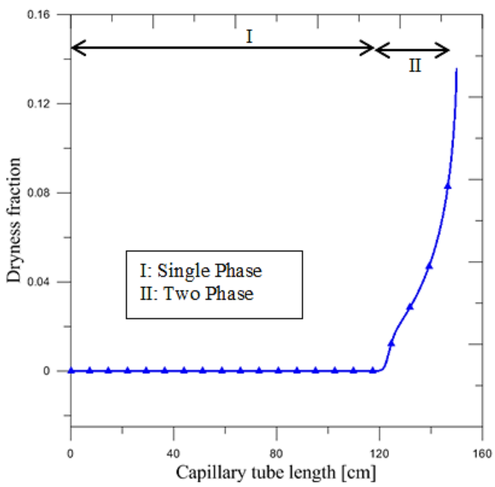

Fig.5 Dryness fraction distribution of refrigerant flow through straight capillary tube under adiabatic conditions

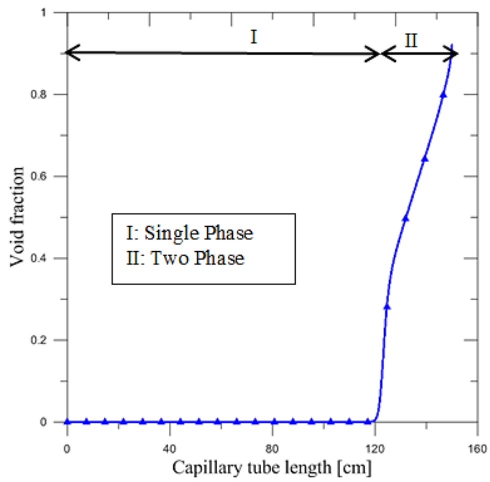

Fig.6 Void fraction distribution of refrigerant flow through straight capillary tube under adiabatic conditions

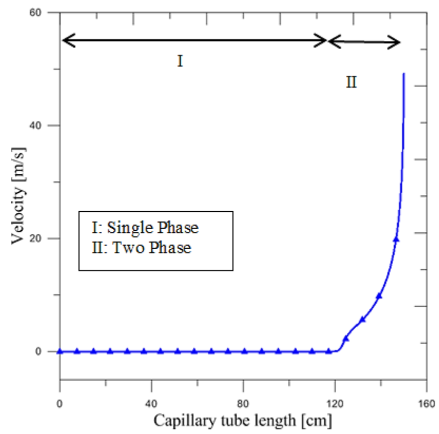

Fig.7 Velocity distribution of refrigerant flow through straight t capillary tube under adiabatic conditions

Figures (8),(9) and (10) represent the field of pressure, temperature and dryness fraction respectively of refrigerant flow through adiabatic straight capillary tube under different diameters. It can be seen for all capillary tubes diameters that pressure behavior is linear in the single phase region and temperature remain constant due to adiabatic while dryness fraction equals to zero because the working fluid in sub-cooled liquid up to the flashing inception point, the pressure and temperature drop nonlinearly while the dryness fraction increases rapidly due to formation of vapor bubbles. As the diameter increases, single phase length will increase and flashing inception point will retard towards capillary tube exit which delay the occurrence of vaporization. Also under the same inlet conditions as the diameter increases, the total length of capillary tube will increases and hence the pressure drop will increases as the length of capillary tube increases where when the length increases from 90 cm to 200 cm, the pressure drop from 4900 kPa into 2100 kPa. As well as temperature decreases more and more as the length increases where when the length increases from 900 cm to 200 cm, the temperature decreases from 296 k to 284.5 k. The physical reason is that as the length increases, the friction effect of internal wall will increases which leads to make a drop in pressure and temperature.

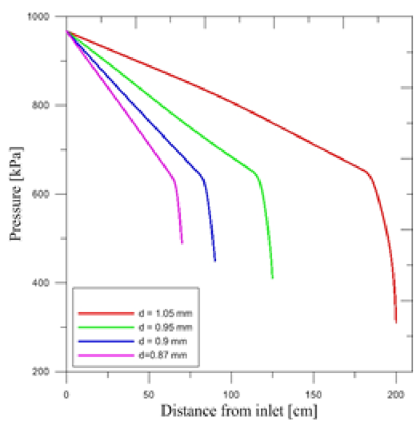

Fig.8 Pressure distribution of refrigerant flow inside straight capillary tube under adiabatic conditions for different diameters

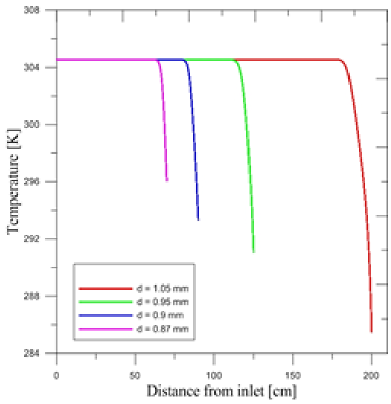

Fig.9 Temperature distribution of refrigerant flow inside straight capillary tube under adiabatic conditions for different diameters

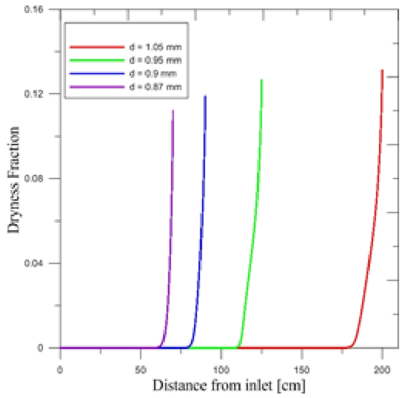

Fig.10 Pressure distribution of refrigerant flow inside straight capillary tube under adiabatic conditions for different diameters

Figure (11) represents the variation of pressure with dryness fraction of refrigerant flow through straight capillary tube. It can be seen that relation is inversely after the flashing point where the dryness fraction value starts to increase after the pressure of refrigerant reduces to 650 kPa due to formation of bubbles which required to absorb latent heat of vaporization from liquid which reduces its temperature and increasing of dryness fraction as in figure (12).

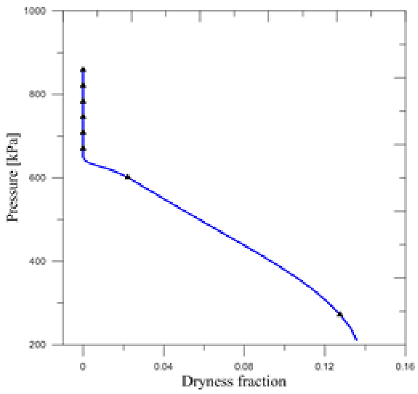

Fig.11 Variation of pressure with dryness fraction of refrigerant flow inside straight capillary tube under adiabatic conditions

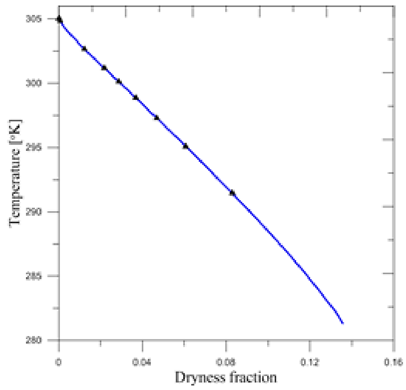

Fig.12 Variation of temperature with dryness fraction of refrigerant flow inside straight capillary tube under adiabatic conditions

The drop in temperature means there is drop in pressure because the relation between them is direct. Starting of vaporization lead to decreases the density and this will increasing the refrigerant velocity as in figure (13) where the relation between velocity and dryness fraction is direct.

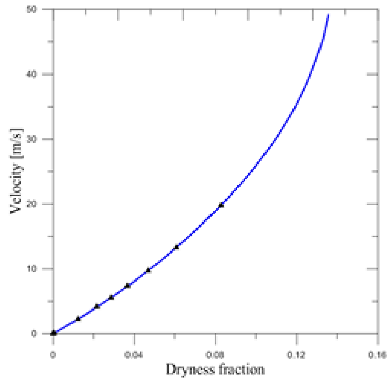

Fig.13 Variation of velocity with dryness fraction of refrigerant flow inside straight

Figure (14) show a comparison CFX model of the distribution of pressure along the capillary tube with measured data of Li *et.al* and with numerical data of Ingle *et.al* using ANSYS FLUENT 15. Again a good agreement is obtained.

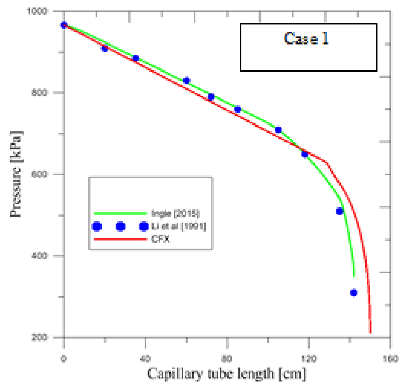

Fig.14 A Comparison of present numerical model with Ingle *et.al* and experimental data points of Li *et al*

Figure (15) show a comparison of the distribution of pressure along the capillary tube predicted by present CFD model [CFX] with measured data of Li *et.al* and with numerical data of M.Zareh *et.al* based on drift flux model. A good agreement is obtained. The data tables used in the CFD simulation are presented in table 2.

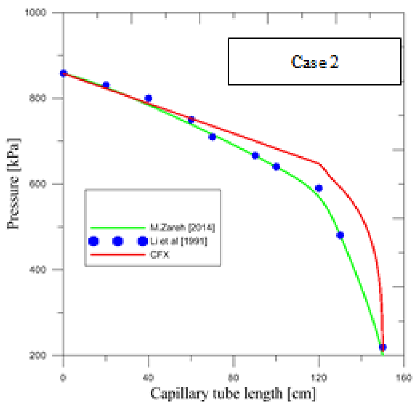

Fig.15 A Comparison of present numerical model with drift flux model and experimental data points of Li *et al*

Table 2 Test Flow conditions for refrigerant

Case Study	P_{in} [kPa]	T_{in}[°K]	D [mm]	ε/D
Case 1	967	304.4	1.17	$3.0303*10^{-3}$
Case 2	858	304	0.66	$2.991*10^{-3}$

Conclusions

1) Using of Eulerian-Eulerian multiphase homogeneous model coded in ANSYS CFX 16.1 to simulation of phase change of refrigerant flow capillary tubes.
2) Effect of various design parameters on metastable region had been studied.
3) The diameter is the most important parameter in the beginning of phase change
4) The present model based on finite volume method and k-epsilon as a turbulent model coded in commercial CFD software (ANSYS CFX16.1).
5) CFX have the ability to predict field of pressure, temperature, velocity and dryness fraction along the capillary tube.
6) The numerical model solves the resulting set of algebraic equations in an iterative way.
7) ANSYS CFX 16.1 can be used in the design of capillary tube in refrigeration and air conditioner systems.

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