CFD ANALYSIS OF TWO PHASE FLOW INSIDE A HORIZONTAL PIPE

A major project submitted in partial fulfillment of the
Requirement for the award of a degree in

MASTERS OF TECHNOLOGY
IN
THERMAL ENGINEERING

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CERTIFICATE

*This is to certify that the thesis entitled, **"CFD ANALYSIS OF TWO PHASE FLOW INSIDE A HORIZONTAL PIPE"** submitted by **Mayank Kumar** in partial fulfillment of the requirements for the award of Master of Technology Degree in **Mechanical Engineering** with specialization in **Thermal Engineering** at the **Delhi Technological University** is an authentic work carried out by him under my supervision and guidance.*

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any degree or diploma.

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CANDIDATE DECLARATION

I hereby declare that the work which is being presented in this project report entitled, ***"CFD ANALYSIS OF TWO PHASE FLOW INSIDE A HORIZONTAL PIPE"*** *submitted as major project towards the fulfillment of the requirements for the award of the degree of* ***Master of Technology*** *with specialization in* ***Thermal Engineering, D.T.U. Delhi****, is an authentic record of my own work carried out under the supervision of* ***Dr. Rajesh Kumar*** *Mechanical Engineering Department, at Delhi technological university, Delhi.*

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any degree or diploma.

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ABSTRACT

The present research is endeavored on the estimation of total frictional pressure drop inside a smooth horizontal pipe for two-phase flow of refrigerant R410a under adiabatic condition at a given saturated temperature of 40 °C (i.e. for condensing flow of refrigerant) at different quality of vapour and at two different mass fluxes of 350 kg/m^2*s and 1055 kg/m*^{2}*s by using CFD modeling. Analysis results are then compared with homogeneous and separation flow models of multiphase flows as explained in literature and chapter 3 of this report.*

The analysis of single phase flows and the two-phase flows through different components and fittings is essential for the regulation and application of few heat transfer devices such as condensers, evaporators, and some heat exchangers needed in refrigeration and air conditioning units. For all these, single-phase flow may emerge as superheated vapors in the evaporator and condenser or as sub cooled liquid in the condenser, but still the two-phase flow is the dominant part of these coils. In drafting of such components, the calculation of pressure gradient is also as necessary as the heat transfer coefficient.

The results of CFD analysis found satisfactory closure to the Chisholm correlation at low mass flux with 07.96 % of average deviation from CFD analysis results and for higher mass flux CFD results are best predicted by Muller Steinhagen - Heck Correlation with 04.04% average deviation from the CFD analysis results but the results for Lockhart-Martinelli and Gronnerud Correlations are deviated largely in both the cases.

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ABBREVIATIONS & ACRONYMS

$\dot{m}$	*Mass flow rate, kg/s*
A	*Flow area,* m^2
g	*Acceleration due to gravity,* m/s^2
τ_w	*wall shear stress, MPa*
x	*Volume fraction*
G	*Mass flux,* kg/m^2*-s*
f_{TP}	*Two phase friction factor*
d	*Diameter of pipe, m*
L	*Length of pipe, m*
Re	*Reynolds number*
f_v	*Friction factor for vapour phase*
f_l	*Friction factor for liquid phase*
F_r	*Froude number*
We	*Weber number*
T_s	*Saturation temperature, ℃*

Greek Symbols

ρ	*Density, kg/m^3*
μ	*Dynamic viscosity, kg/ms*
ϕ	*Two Phase pressure multiplier*

Subscripts

l	*liquid*
v	*vapour*
f	*fluid*
W	*wall*
d	*diameter*
TP	*Two-phase*
F_r	*Froude number*
L-M	*Lockhart-Martinelli*
M-S-H	*Muller Steinhagen and Heck*
GR	*Gronnerud*
H-M	*Homogeneous Model*

Chapter-1

Introduction

1.1. Fundamentals of two-phase flow

Two-phase flow indicates the concurrent flow of two phases isolated from one another by distinct consolidates. Somewhat one of the phases need to be a fluid, may be either liquid or gas. The other phase may either be a fluid or solid particles drooping in the flow. A Two-phase flow is an appropriate case of multiphase flow. Two-phase flow consists the following: Liquid-solid flows, Liquid-liquid flows, Gas-solid flows, and Gas-liquid flows amid them Gas-liquid flows are presumably the most significant mode of two-phase flow, and used extensively in industrial applications. In such flows, the pressure drop and the rates of heat and mass transfer are robustly persuade by the flow dynasty that are regulated by the related flow rates and the size of component that imports the fluid mixture.

The analysis of single phase flows and the two-phase flows through different components and fittings is essential for the regulation and application of few heat transfer devices such as condensers, evaporators, and some heat exchangers needed in refrigeration and air conditioning units. For all these, single-phase flow may emerge as superheated vapors in the evaporator and condenser or as sub cooled liquid in the condenser, but still the two-phase flow is the dominant part of these coils. In drafting of such components, the calculation of pressure gradient is also as necessary as the heat transfer coefficient.

In air conditioning and refrigeration systems, the pressure gradient must be restricted to the certain predetermined design value. For example if there is high pressure drop in the suction line of a compressor, the volumetric efficiency will be noticeably reduced and more energy will be consumed by the compressor. Hence pressure gradient must be under certain limit for satisfactorily working of compressor. Moreover, prediction of total fall in pressure helps to predict the pumping load needed by these heat transfer equipments.

The conclusive examination of two phase flows are more sophisticated substantially than the single phase flow. Two phase flow abide by all primitive postulates of fluid mechanics. In addition to the conventional conservation equations, two phase flows are also influenced by interfacial tension forces, the momentum transfer between the liquid and vapor phases in the flow and the wetting characteristics of phases. In two phase flows there is no clear relationship between the wall shear stress in single and two phase flow, so, data required about interfacial tension, Moreover, Estimation of void fraction is necessary. Due to these effects, the physiology of two phase flow arrangements differs for different geometries of tubes or channels and their direction.

1.2. Aim of modeling a two-phase flow

The aim of two-phase flow modeling is to study and predict all the primitive parameters involved in two phase flows. It consists of following four primitive parameters which are most significant to predict the behavior of two phase flow pattern.

1. **To Presume the flow dynasty** - usually significant in the petroleum industry to study the clogging phenomena appears in pipelines that arise due to the slug flow of petroleum during transportation.

2. **To Presume the heat transfer** – usually significant in refrigeration and air conditioning systems to evaluate the performance of various heat transfer devices such as condensers and evaporators.

3. **To Presume the pressure gradient** - significant in entire two-phase flows as total fall in pressure helps to predict the pumping power required by the equipment.

4. **To Presage the phase change** – significant in all heat transfer applications.

Usually, Envision of all these parameters i.e. flow dynasty, heat transfer, pressure gradient and change of phase are necessary during research under two-phase flows as all these appears simultaneously in a two phase flow. Among all these parameters the investigation of heat transfer coefficient and pressure gradient is most important as these two parameters predominantly influence the flow behavior.

1.3. Methods for analyzing two-phase Flow

1) Homogeneous models

The fundamental presumption of the homogeneous flow model is that the two phases move at equal velocities and mix together and therefore can be considered as a quasi-single phase having average fluid properties like average density and average viscosity by different correlations depending on mass quality. It is the simplest model to estimate the characteristics and the nature of the two phases. This model works more suitable for two-phase flow adjacent to the critical point, where the fluctuation in the properties of the liquid and vapor are inconsequential, or when the mass flow per unit area is very high so that the flow dynasty is either bubbly or misty.

2) Separated flow models

The separated flow models are most widely used models for the study of two phase frictional pressure gradient with a convenient level of intricacy because these models are based on some correlations developed as consequence of experimental results. It resolves each phase individually and develops separate conservation equations for each individual phase. The separated flow model presumes that each phase exhibits distinct properties and flows at different velocity. These models are preferred especially for slug flow, annular flow and stratified flow. This model gives more accurate and precise results for frictional pressure drop which is significant as design point of view.

3) Eulerian-Multi-fluid models

In these models each individual phase described by its own conservation equations and these equations represents the interrelationship between these phases. Multi-fluid models are apparently more refined than separated-flow models as two-phase multipliers are not required, and may or may not be forced to describe the correlation between single phase and two-phase.

- **NOTE** - The progress of all these models depends apparently on two aspects. First, knowledge about flow-dynasty is necessary to solve each individual phase solely. Second, requirement of precise models at the interface between phases for mass, momentum and energy transfer.

4) Drift flux model

These models are modified homogeneous models and very much similar to the separated flow models but much simpler than separated flow models. In these models relative motion between the two phases are considered rather than individual motion of each phase and two phases are considered as a single phase rather than two different phase. These models are preferred when motion between two phases are firmly coalesced and are not preferred for chocked flow and sound wave promulgation.

An important consideration regarding drift flux model is that it requires limited number of equations for the formulation of two phase flow and hence analysis carried out with limited numbers of flowing parameters. This model is based on approximate simulation but due its severity and suitability over broad span it is relevant for complex engineering systems.

5) Computational fluid dynamic (CFD) models

CFD is a branch of fluid science that employs two dimensional or three dimensional numerical simulation and algorithm technique to explain and evaluate the problems related to the fluid flow. It requires fundamental model equations to adumbrate the frictional pressure gradient, flow dynasty, heat transfer, flow rates, void fraction, slip velocities, etc.

The two phase simulation by using computation fluid dynamic technique can be done by using following two approaches:

a) Euler-Lagrange approach

This approach is sometimes called as discrete phase model. This approach has its significant in those flow dynasties where volume fraction between two phases differs greatly. In this approach large numbers of particles or droplets are injected over the primary phase and then the effect of each particle or droplet on primary phase is estimated by particle or droplets tracking techniques. This approach is suitable when volume fraction is low for secondary dispersed phase.

b) Euler-Euler approach

In this approach both phases are considered as transfusing continuum and the dispersed phase equalized for each control volume and each phase regulated by analogous conservation equations. For this approach modeling is required for phase interaction, and the turbulent dispersion of particles colliding with the wall. This approach is suitable when volume fraction is high enough and varies widely for dispersed phase.

In ANSYS FLUENT following three models are available based on Euler-Euler approach:

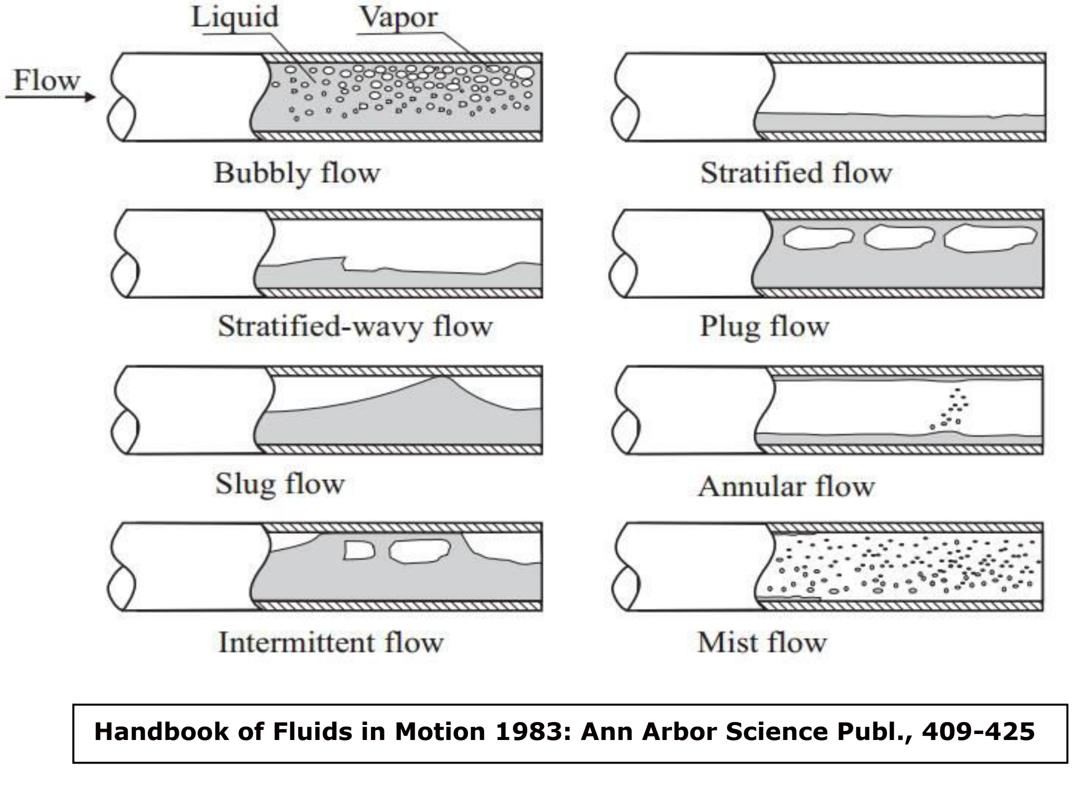
- Volume of Fluid (VOF) Model
- Eulerian Mixture Model
- Eulerian Multiphase Model

- **NOTE:** Selection of modeling approach is based on available data and the accuracy required.

1.4. Flow Patterns of two-Phase flow inside Horizontal Pipes

The prediction of flow pattern is an important aspect while examine two phase flows because for two phase flows, the pressure drop and the coefficient of heat transfer usually associated with the provincial flow arrangement of the fluid.

The two-phase flow dynasty in horizontal pipes is different than the flow dynasty in vertical pipes because in vertical pipes gravity acts parallel and opposite to the flow direction whereas in horizontal pipes gravity acts in perpendicular direction to the flow. Hence the study of flow dynasty in horizontal two phase flow is more typical than the flow dynasty in vertical two-phase flow, as due to gravity effect flow is non-axisymmetric. Flow dynasties for two-phase flows are categorized as follow:



Handbook of Fluids in Motion 1983: Ann Arbor Science Publ., 409-425

Fig. 1.1: Flow Dynasty in horizontal two-phase flow

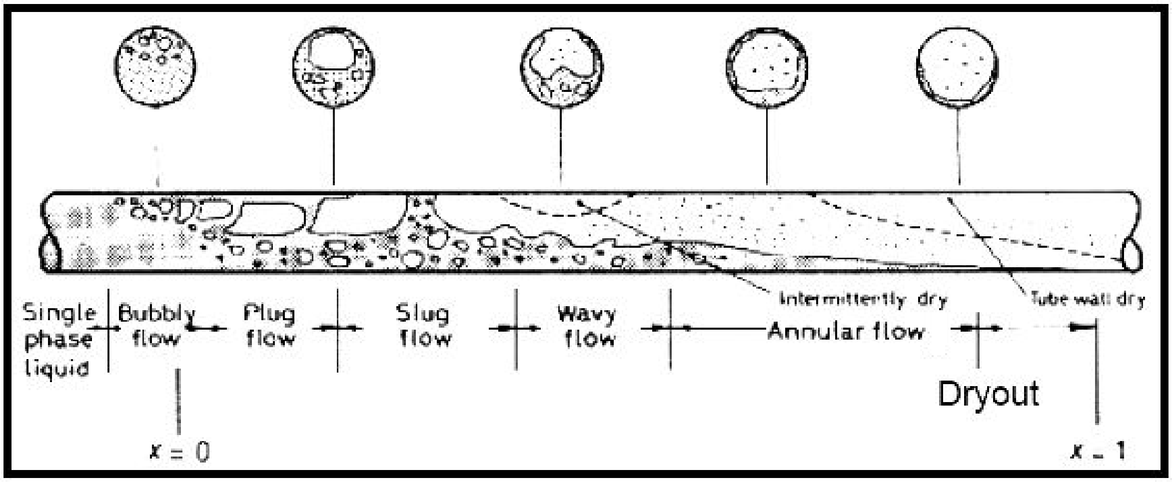


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Fig. 1.2: Illustration of two phase flow Patterns occurring in horizontal pipe

- **Dispersed bubble flow**. In continuous flow field vapors are emerge as recognizable bubbles in steady liquid phase. Due to buoyancy effect these bubble tends to rise to the top of liquid phase and are more stable when the flow velocity is high.
- **Plug flow**. It is similar to dispersed bubble flow, only differs in the quality of two phase mixture. It contains more vapors or bubbles which seem to be in the shape of plug which remains at the top of liquid phase due to buoyancy effect.
- **Stratified flow**. In this flow dynasty quality of two phase mixture is much high and contains large amount of vapors or bubbles moving with relatively low velocities. In this case also vapors or bubbles flow at the top whereas liquid phase at the bottom of flow field.
- **Stratified wavy flow**. As the velocity of bubbles rises in the stratified flows, then due to the shear stress between liquid and vapor phase crest developed on the top surface of the liquid phase and result in the evolution of waves on the liquid-vapor interface.

- **Slug flow**. In this flow the flow velocities are much high due to which amplitude of waves may increase and the crests can appear over the entire pipe length which results in the formation of a link that separating the slugs from each other. However, a considerable liquid phase prevails and due to buoyancy force it pulled toward the bottom of the flow field but still a thin layer of liquid may exist at the top of the flow field.
- **Annular-dispersed flow**. In this case the liquid layer flows adjacent to the interior surface of the pipe and the vapor flows in the central core
- **Mist Flow**. In this flow vapor velocities very high so that all the liquid phase stripped from the surface of the pipe and liquids droplets are entrained in the vapor flow.

1.5. Two-phase pressure drops: Importance

A reliable presumption of two-phase pressure gradient is an importance aspect in the design and escalation of various energy related engineering systems such as chemical, pharmaceutical, petroleum, food, nuclear, refrigeration and air conditioning systems.

Let us take an example of compressors; if there is high pressure drop in the suction line of a compressor, the volumetric efficiency will be noticeably reduced and more energy will be consumed by the compressor. Hence pressure gradient must be under certain limit for satisfactorily working of compressor. Moreover, prediction of total fall in pressure helps to predict the pumping load needed by these heat transfer equipments.

Hence, accurate presumption of pressure gradient is a significant aspect of robust design and escalation of such systems.

The prime cause of the pressure drop in a system is the variation in potential energy and kinetic energy of the fluid and the presence of friction at the pipe walls. Thus the total pressure gradient is the summation of static pressure gradient due to change in potential energy, momentum pressure gradient due to change in kinetic energy and the frictional pressure gradient due to presence of friction at the pipe walls.

$$\boxed{\Delta p_{total} = \Delta p_{static} + \Delta p_{mom} + \Delta p_{frict}}$$

For a horizontal tube, static pressure gradient remains zero because each section of horizontal pipe exists at same datum.

1.6. Objectives of Work

- The main aim of the work is to calculate the local frictional pressure drop inside horizontal pipe of 8.6 mm diameter and 1500 mm long by using two dimensional computational fluid dynamics technique for condensing flow of refrigerant R410a at a saturation temperature of 40 °C and at two different mass fluxes of 350 kg/m^2s and 1055 kg/m^2s under adiabatic condition for different quality of vapour refrigerant.
- To compare the result of CFD analysis with the pressure drop calculated by homogeneous and separated flow correlations and to plot a graph to display the relative variation of pressure drop among the CFD analysis, homogeneous models and separated flow models.

1.7. Organization of thesis

This thesis comprises of six chapters excluding references:

- **Chapter 1** gives the brief introduction of two-phase flows, Goals of Two-phase Flow Modeling, Approaches to two-phase flow modeling, Two-Phase Flow Patterns in Horizontal Tubes, Importance of the study of pressure drop in two-phase flows and the objective of work.

- In **chapter 2**, a brief review of literature has been taken which is related to the thesis topic and the present research work.

- **Chapter 3** deals with the introduction of problem with its governing equations and boundary conditions.

- In **chapter 4** CFD modeling of the problem has been done.

- **Chapter 5** deals with the results and its discussions for this research work at all the considered boundary conditions.
- **Chapter 6** gives the conclusion and scope of future work.

Chapter-2

Literature Review

2.1. Literature Survey

A considerable amount of work has been done to analyze the two-phase pressure drops in horizontal, vertical pipe and return bent by several authors in the open literature. The research in the arena of two phase frictional pressure drop was began in 1940 and still having scope for further research in this field.

The prediction of frictional pressure drops in a pipe is primarily based on two principal types of models in two phase flow: the homogeneous model and the separated flow model. The basic presumption of the homogeneous flow model is that the two phases move at equal velocities and mix together and therefore can be considered as a single phase having average fluid properties depending upon mass quality. This model works more suitable for two-phase flow adjacent to the critical point, where the fluctuation in the properties of the liquid and vapor are inconsequential, or when the mass flow per unit area is very high so that the flow dynasty is either bubbly or misty. On the other hand the Separated Flow Model considers each phase individually and formulates independent mass, momentum and energy balance equations for either of them. The separated flow model presumes that each phase exhibits distinct properties and flows at different velocity. In comparison with the homogeneous model, the separated flow model has been adopted more widely, because it gives a better prognosis of flow behavior with a convenient level of intricacy.

The separated flow model was first developed by **Lockhart and Martinelli et al. [1]** in 1949 in which they presented pressure drop data for the simultaneous flow of air and liquids inclusive of benzene, kerosene, water and different oils in pipes of varying diameter. The Lockhart and Martinelli method is one of the simplest methods to evaluate the frictional pressure drops in pipes for all type of flow regime with relatively low accuracy and highly conservative values.

The further work in the field of two phase frictional pressure drop was carried by many researchers among them few important researches are as below:

Chisholm. D. et al. [2] in 1967 established equations in terms of Lockhart and Martinelli correlation during the flow of gas-liquid or vapour-liquid mixture and compared the theoretically developed data with the previous treatments by allowing the interfacial shear stress between two phases.

Isbin et al. [3] studied two phase frictional pressure drop for steam water mixture in pipes of two different diameters maintained at different pressure with varying steam flow rate and different quality of mixture. Data based on this study was then compared with the standard correlations and developed new restricted correlation that depends upon the pressure, flow rate and the mass quality.

Baroczy et al. [4] in 1965 presented a correlation for liquid fraction data of liquid mercury-nitrogen and water-air in which liquid fraction was assumed be a function of Martinelli Modulus, liquid to gas viscosity and density ratio.

Beggs and Brill et al. [5] in 1973 predicted pressure drop and liquid holdup occurring during two phase gas liquid flow in pipes. They used air and water as two phase fluids with varying flow rate for pipes of different size. Experiment for all flow patterns was initially performed on horizontal pipe and then performed at different inclination so that effect of angle on holdup and pressure drop could be observed.

Friedel et al. [6] in 1979 proposed correlation for two phase friction pressure drop by utilizing two phase multiplier. The correlation was based on average homogeneous density based on vapour quality. This correlation is recommended when liquid to gas viscosity ratio is less than the mass flux of 1000 kg/m^2-s.

Gronnerud [7] proposed correlation especially for refrigerant applicable for intermittent and stratified wavy flow

Müller-steinhagen and Heck [8] presented correlation for frictional pressure drop for two phase annular flow that was a practical intercalate between all liquid and all vapour flow

Ould-Didi, Kattan and Thome [9] studied experimental pressure gradient for R-134a, R-123, R-402A, R-404A and R-502 at varying mass flux and vapour quality and compared result with standard correlation and finally mapped the best correlations for corresponding Annular flow, Intermittent flow and Stratified-Wavy flow.

Moreno Quiben and Thome [10] introduced new results based on flow pattern for R-410A and R-134a and compared to R-22 refrigerant for the flow boiling pressure drop at different experimental conditions in a smooth horizontal pipe. **Moreno Quiben [11]** in 2005 carried further research for evaporative flow in horizontal pipe to study the pressure gradient experimentally and analytically.

Christophe Vallée [12] studied stratified two phase flow inside two rectangular horizontal channel allowing co-current flow of air and water. Work was performed for slug flow and the test section was made by acrylic glass so that optical techniques for study may be applied easily. Analysis was performed on CFD under atmospheric condition and the results were then compared with the earlier experimental results. His work showed that CFD can be used as an important tool in the analysis of frictional pressure drop in a pipe.

Duckler et al. [13] to propose a correlation for two-phase friction pressure drop based on similarity analysis by using data bank consisting of short tube laboratory and long tube oil field data in their work. More than (20,000) experimental measurements have been taken.

Cicchitti et al. [14] worked on steam water system and predicted pressure drop experimentally and finally developed a correlation based on experimental result.

Cavallini et al. [15] studied pressure drop characteristics of a 1.4 mm hydraulic diameter multiport mini-channel tube during adiabatic two-phase flow of R236ea, R134a and R410A at 40 °C saturation temperature, corresponding to a reduced pressure of 0.096, 0.25 and 0.49, respectively.

Pierre et al. [16] derived expression to estimate total pressure drop as well as to estimate coefficient of heat transfer for evaporative flow of refrigerant inside horizontal tubes.

Wang et al. [17] investigated the frictional pressure gradient of both R-22 and R-407C in a 7.92 mm tube. The mass flux ranged from 100 kg/m^-s to 300 kg/m^-s. Among the two fluids, R-407C had a 45% smaller frictional pressure gradient at the highest mass flux while both fluids exhibited a similar frictional pressure gradient at the lower mass flux. Wang et al. (1996) stated that while both frictional pressure gradients were proportional to the mass flux raised to the power of 2.45, the large differences in the frictional pressure gradients at the high mass flux might be attributed to a difference in flow patterns. This work exemplifies the importance of predicting the flow regime and basing pressure drop correlations on the individual flow mechanisms.

The influence of return bend on the frictional performance of R-410A and R-22 in a 5-mm diameter tube with a curvature ratio of 6.63 was examined by **Wang [18]** in 2003 in which he signified the effect of mass flux on flow pattern.

Hence, it has been found out from the literature that the frictional pressure gradient predicted by the separation flow model is comparable with those computed by Fluent, with a small variation in results. Hence, we can assuredly employ CFD modeling for the prediction of frictional pressure drop in a horizontal smooth pipe for the flow of refrigerant R410a.

Chapter-3

Problem Formulation

3.1. Problem Description:

The main aim of the problem is to calculate the local frictional pressure drop inside horizontal pipe of 8.6 mm diameter and 1500 mm long by using two dimensional computational fluid dynamics technique for condensing flow of refrigerant R410a at a saturation temperature of 40 °C and at two different mass fluxes of 350 kg/m^{2}s and 1055 kg/m^{2}s under adiabatic condition for different quality of vapour refrigerant.

The result is then compared with the pressure drop calculated by homogeneous and separated flow model correlations and graph is plotted to display the relative variation of pressure drop among the CFD analysis, homogeneous models and separated flow models.

3.2. Homogeneous model and Governing Equations

A homogeneous two phase flow model is primarily a special subset of separated flow model. The fundamental presumption of the homogeneous flow model is that the two phases move at equal velocities and mix together and therefore can be considered as a quasi-single phase having average fluid properties depending on mass quality. It consists of following basic equations:

$$\text{Continuity Equation: } \dot{m} = \overline{\rho}\, A\, \overline{u}$$

$$\text{Momentum Equation: } -Adp - d\overline{F} - A\overline{\rho}gdz = \dot{m}d\overline{u}$$

Where,

$$d\overline{F} = \tau_W(Pdz)$$

$d\overline{F}$ is the total wall shear force acting over inner surface of pipe having surface area equal to pdz and shear stress equal to $\tau_{w.}$

The average fluid properties for quasi single phase fluid are given by following models.

For average fluid density:

$$\frac{1}{\overline{\rho}} = \left[\frac{x}{\rho_v} + \left(\frac{1-x}{\rho_l}\right)\right]$$

For average fluid viscosity we have following three models:

a) McAdams Homogeneous viscosity model,

$$\frac{1}{\overline{\mu}} = \left[\frac{x}{\mu_v} + \left(\frac{1-x}{\mu_l}\right)\right]$$

Where, μ_v and μ_l are vapour and liquid viscosity of mixture respectively and x is dryness fraction.

b) Cicchitti Homogeneous viscosity model,

$$\overline{\mu} = x\mu_v + (1-x)\mu_l$$

c) Duckler Homogeneous viscosity model,

$$\frac{1}{\overline{\mu}} = \overline{\rho}\left[\frac{x\mu_v}{\rho_v} + \frac{(1-x)\mu_l}{\rho_l}\right]$$

Now, Total frictional pressure drop based on homogeneous flow model is given by:

$$\Delta P = \frac{2f_{TP}G^2L}{\bar{\rho}d}$$

Where,

G is the total mass flux in Kg/m^2-s

L is the total length of pipe in meter (m)

d is the diameter of pipe in meter (m)

f_{TP} is the two phase friction factor

f_{TP} can be calculated by using Blasius equation given by,

$$f_{TP} = 0.079\left[\frac{Gd}{\bar{\mu}}\right]^{-0.25}$$

3.3. Separated flow model and Governing Equations:

The separated flow models are most widely used models for the study of two phase frictional pressure gradient with a convenient level of intricacy because these models are based on some correlations developed as consequence of experimental results. It resolves each phase individually and develops separate conservation equations for each individual phase. The separated flow model presumes that each phase exhibits distinct properties and flows at different velocity. These models are preferred especially for slug flow, annular flow and stratified flow. This model gives more accurate and precise results for frictional pressure drop which is significant as design point of view.

1. **Lockhart-Martinelli correlation:** It is one of the simplest methods to evaluate the frictional pressure drops in pipes for all type of flow dynasty with relatively low accuracy and highly conservative values. Calculation of following parameters are required to calculate the total frictional pressure drop through this correlation:

   1. Mass flux calculation :

   $$G = \frac{\dot{m}}{A}$$

   $$\dot{m} = \overline{\rho}\, A\, \overline{u}$$

   2. Reynolds's number:

   $$Re = \frac{G(1-x)d}{\overline{\mu}}$$

   3. Friction factor for smooth pipe based on Blasius equations:

   $$f_f = 0.079\, Re^{-0.25}$$

4. Liquid and vapour pressure drop :

$$-\left(\frac{dP_f}{dL}\right)_l = 4f_{fl}\frac{G^2}{2d\rho_l}$$

$$-\left(\frac{dP_f}{dL}\right)_v = 4f_{fv}\frac{G^2}{2d\rho_v}$$

5. X parameter :

$$X = \sqrt{\frac{\left(\frac{dP_f}{dL}\right)_l}{\left(\frac{dP_f}{dL}\right)_v}}$$

6. Two phase pressure gradient multiplier :

$$\phi_L^2 = 1 + \frac{C}{X} + \frac{1}{X^2}$$

Liquid	Vapour	C
Turbulent	Turbulent	20
Laminar	Turbulent	12
Turbulent	Laminar	10
Laminar	Laminar	5

7. friction pressure drop :

$$-\left(\frac{dP_f}{dL}\right)_{TP} = -\phi_L^2\left(\frac{dP_f}{dL}\right)_l$$

2. Chisholm Correlation :

Chisholm established equations in terms of Lockhart and Martinelli correlation during the flow of vapour-liquid mixture and compared the theoretically developed data with the previous treatments by allowing the interfacial shear stress between two phases. Chisholm correlation consists of following calculations:

1. Single phase Reynolds number :

$$Re = \frac{Gd}{\overline{\mu}}$$

2. Friction factor for smooth pipe based on Blasius equations:

$$f_f = 0.079\, Re^{-0.25}$$

3. Pressure gradients for liquid and vapour :

$$-\left(\frac{dP_f}{dL}\right)_l = 4f_f \frac{G^2}{2d\rho_l}$$

$$-\left(\frac{dP_f}{dL}\right)_v = 4f_f \frac{G^2}{2d\rho_v}$$

4. Y parameter :

$$Y = \sqrt{\frac{\left(\frac{dP_f}{dL}\right)_l}{\left(\frac{dP_f}{dL}\right)_v}}$$

5. B parameter :

For Y < 9.5; $B = \frac{24.9}{G^{0.5}}$

For 9.5 < Y < 28; $B = \frac{235.3}{(YG)^{0.5}}$

For Y > 28; $B = \frac{6788.5}{Y^2 G^{0.5}}$

6. Calculation of the two phase pressure gradient multiplier :

$$\phi_L^2 = 1 + (Y^2 - 1)\left[Bx^{\frac{1.75}{2}}(1-x)^{\frac{1.75}{2}} + x^{1.75}\right]$$

7. Calculation of the friction pressure gradient :

$$-\left(\frac{dP_f}{dL}\right)_{TP} = -\phi_L^2\left(\frac{dP_f}{dL}\right)_l$$

3. **Friedel Correlation:** This correlation is based on average homogeneous density based on vapour quality and is recommended when liquid to gas viscosity ratio is less than the mass flux of 1000 kg/m^2-s.

1. Calculation of two phase density :

$$\frac{1}{\bar{\rho}} = \left[\frac{x}{\rho_v} + \left(\frac{1-x}{\rho_l}\right)\right]$$

2. Calculation of parameters: E, F and H :

$$E = (1-x)^2 + x^2\left[\frac{\rho_l\, f_v}{\rho_v\, f_l}\right]$$

$$F = 3.24x^{0.78}(1-x)^{0.24}$$

$$H = \left(\frac{\rho_l}{\rho_v}\right)^{0.91}\left(\frac{\mu_v}{\mu_l}\right)^{0.19}\left(1-\frac{\mu_v}{\mu_l}\right)^{0.7}$$

3. Calculation of the two phase pressure gradient multiplier :

$$\phi_l^2 = E + \frac{FH}{Fr^{0.045}\,We^{0.035}}$$

Where,

$$Fr = \frac{G^2}{gd\,\overline{\rho}^2}$$

$$We = \frac{G^2 d}{\overline{\rho}\sigma}$$

4. Calculation of the friction pressure gradient :

$$-\left(\frac{dP_f}{dL}\right)_{TP} = -\phi_L^2\left(\frac{dP_f}{dL}\right)_l$$

4. **<u>Muller Steinhagen – Heck Correlation</u>:** This correlation was presented for frictional pressure drop for two phase annular flow that was a practical intercalate between all liquid and all vapour flow. This correlation consists of following calculations:

   1. Reynolds's number:

$$Re = \frac{G(1-x)d}{\overline{\mu}}$$

2. Friction factor for smooth pipe based on Blasius equations:

$$f_f = 0.079\, Re^{-0.25}$$

3. Liquid and vapour pressure drop :

$$A = -\left(\frac{dP_f}{dL}\right)_l = 4f_{fl}\frac{G^2}{2d\rho_l}$$

$$B = -\left(\frac{dP_f}{dL}\right)_v = 4f_{fv}\frac{G^2}{2d\rho_v}$$

4. G- parameter :

$$G = A + 2(B - A)x$$

5. Frictional Pressure gradient:

$$\left(\frac{dp}{dz}\right)_f = G(1-x)^{\frac{1}{3}} + Bx^3$$

5. <u>Gronnerud Correlation</u>: This correlation was developed especially for refrigerant applicable for intermittent and stratified wavy flow. Calculation of following parameters are required to calculate the total frictional pressure drop through this correlation:

1. Liquid Froude number:

$$Fr_l = \frac{G^2}{gd\,{\rho_l}^2}$$

2. Friction factor:

- If $Fr_l \geq 1$, $f_{fr} = 1$
- If $Fr_l \leq 1$, $f_{fr} = Fr_l^{0.3} + 0.0055\left(\ln\frac{1}{Fr_l}\right)^2$

3. Pressure drop based on Froude number:

$$\left(\frac{dp}{dz}\right)_{Fr} = f_{Fr}[x + 4(x^{1.8} - x^{10} + f_{Fr}^{0.5})]$$

4. Two-Phase Multiplier:

$$\phi_{gd} = 1 + \left(\frac{dp}{dz}\right)_{Fr} \left\{ \frac{\left(\frac{\rho_l}{\rho_v}\right)}{\left(\frac{\mu_l}{\mu_v}\right)^{0.25}} - 1 \right\}$$

5. Liquid Pressure Drop:

$$-\left(\frac{dP_f}{dL}\right)_l = 4f_{fl}\frac{G^2}{2d\rho_l}$$

6. Total Frictional Pressure Drop:

$$-\left(\frac{dP_f}{dL}\right)_{TP} = -\phi_{gd}\left(\frac{dP_f}{dL}\right)_l$$

Chapter- 4

CFD Modeling

4.1 Introduction

CFD is a branch of fluid science that employs two dimensional or three dimensional numerical simulation and algorithm technique to explain and evaluate the problems related to the fluid flow. It requires fundamental model equations to adumbrate the frictional pressure gradient, flow dynasty, heat transfer, flow rates, void fraction, slip velocities, etc.

CFD tool implements subjective and significant approach to presage the fluid flow dynasty by either setting up partial differential equations applied over mathematical models or by numerical methods using discretization and solution techniques or by using software tools consists of pre-processing, main solver and post processing utilities or by implementing combination of above techniques.

4.2 CFD Programming

The CFD programming consists of certain steps for the complete analysis of fluid flow system by using computational fluid dynamic technique. These steps must be followed in a specific order to achieve precise results.

CFD programming mainly consists of three elements viz. the pre-processor, the main solver, and the post-processor. All these elements itself consist of different procedures to complete the individual analysis of each element as shown in the given flow chart.

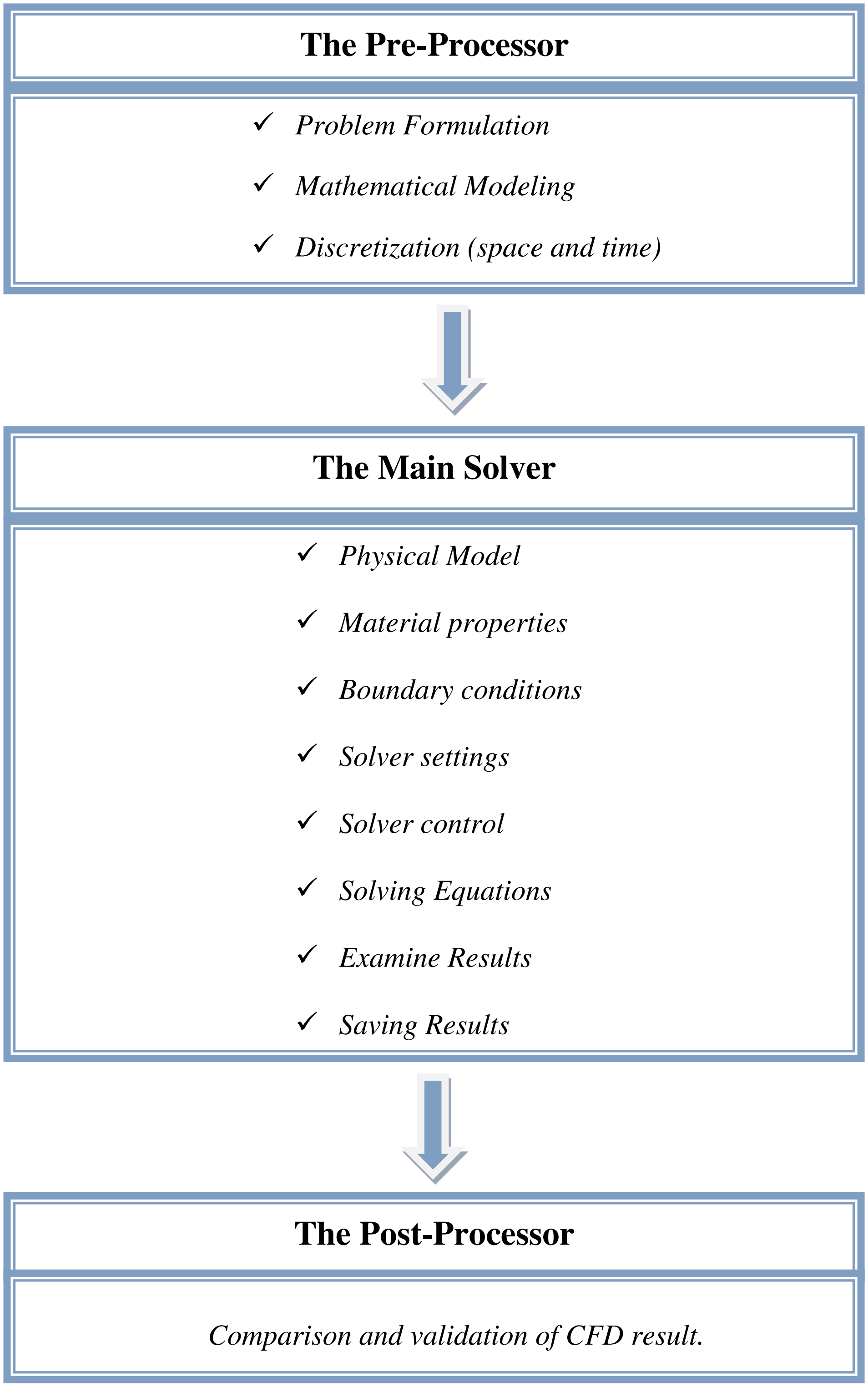


Fig 4.1: CFD Process Flow Chart

4.2.1 The Pre-Processor:

A standard fluid flow analysis using computational fluid dynamics technique primarily starts with pre-processing. The pre-processor delivers information of the flow problem to the computation fluid dynamic program by mean of user amiable interface and subsequently recalibrate this information into the form convenient to the main solver. This compilation of information is usually executed in step by step processes, which are as follows:

(a) **Problem Formulation:** In this process we clearly define the objective of the flow analysis and we explore the easiest way to achieve that objective among all alternative ways. In this process user gathers all the information about the flow problem by exploring the explanation of following questions:

- ✓ Which physical phenomenon is to be considered?
- ✓ Which geometry and flow domain is to be admitted?
- ✓ What is the type of flow (i.e. steady or unsteady, laminar or turbulent etc.)?
- ✓ What are the governing equations?
- ✓ What are the initial operating and boundary conditions?

(b) **Mathematical Modeling:** In this process firstly we establish a relevant flow model and define a reference frame as well as a computational flow domain. After that the forces acting over the fluid and the influence of these forces on the motion of fluid are analyzed. Based on that force analysis, conservation laws are formulated for mass, momentum and energy. All the physical or mathematical relationships between unknown parameters are then codified. Finally, initial operating and boundary conditions are then specified for that particular flow domain.

To reduce the computational effort in mathematical modeling we streamline the following optional factors:

- ✓ Figuring out symmetries in flow and predominant direction of flow.
- ✓ Omitting parameters having no or little impact on the results.
- ✓ Omitting very small fluctuations encountered during flow.
- ✓ Neglecting the results of previous mathematical or computational flow dynamic analysis.

(c) **Discretization:** It is the key process of computational fluid dynamic analysis. In this process structured or unstructured mesh is generated of desired shape and sizes that sheathing the flow domain. Properties like velocity, temperature and pressure are then calculated and formulated in the form of partial differential equations having infinite degrees of freedom. These partial differential equations are then discretized and transmuted in the form of algebraic equations having finite degrees of freedom. In this case solutions are determined at definable locations and at definite time interval (i.e. Space Discretization and Time Discretization respectively).

- ✓ **Space Discretization:** In this case spatial derivative of partial differential equation system is approximated in algebraic equations by taking finite differences, finite volume or finite element approach.
- ✓ **Time Discretization:** In this case temporal derivative of partial differential equation system is approximated in algebraic equations by taking implicit or explicit strategy. This is done by integrating universal discretized equations over a time step.

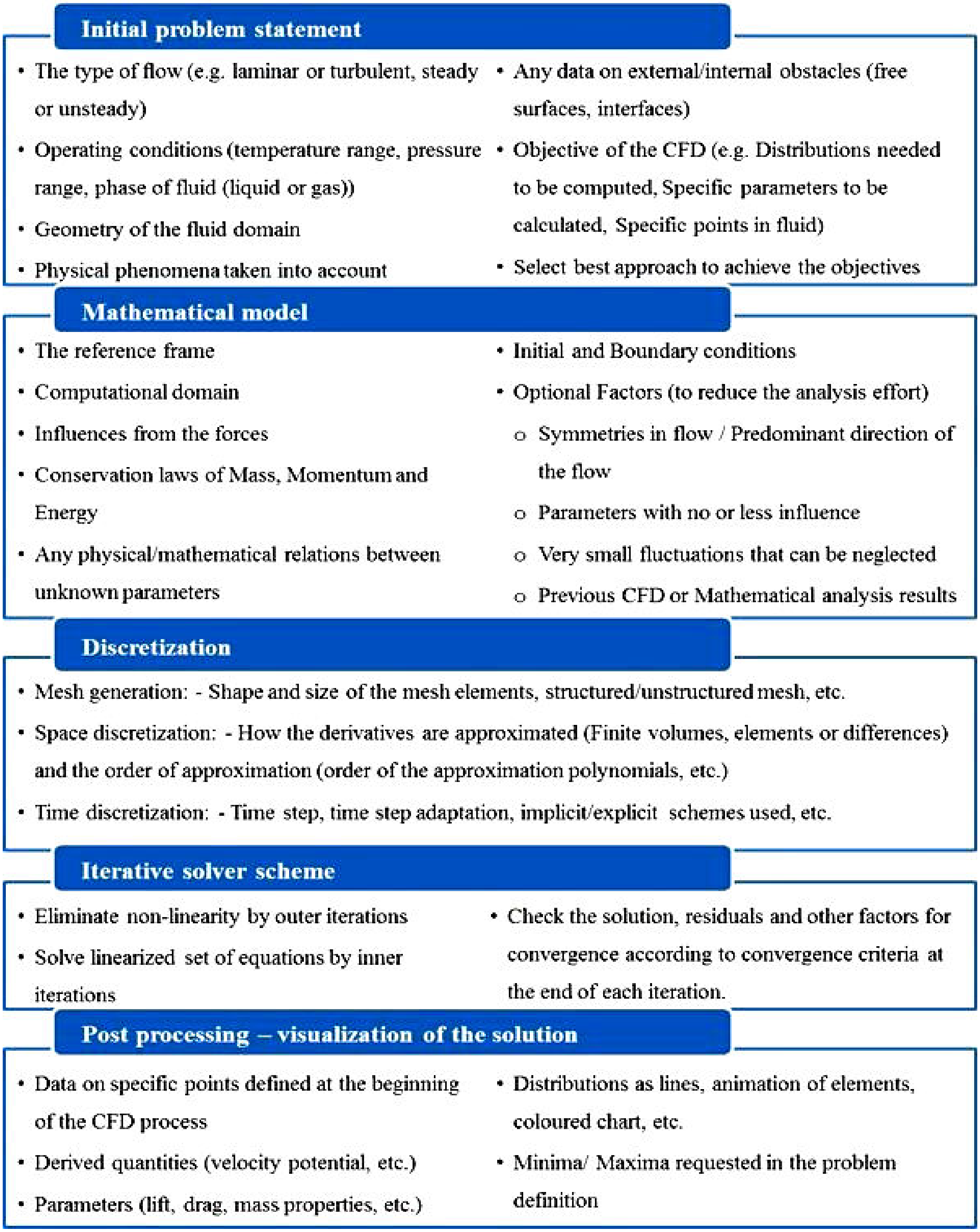
4.2.2 The Main Solver:

It is the central process of CFD programming in which transformed algebraic equations are solved to generate solution for the study of flow using computational fluid dynamic approach. It incorporates all the input parameters in the form of initial operating and boundary conditions and various algebraic expressions and solves them over the entire flow domain. It uses iterative method for initialization and computation of solution for flow field.

The main solver first establishes a relevant physical model then after selecting convenient model, it delineates the material properties, imposes boundary conditions, initializes solution and establishes a control over the solver till the solution generates.

4.2.3 The Post-processor:

It is the most important process of CFD simulation. The main work of post-processor is the comparison and validation of the solver results. The solution of CFD analysis must be validated by some experimental results or pre-determined data. The validation can also be performed by changing the grid size (i.e. using finer meshing) and again performing the analysis. If result remains same, it indicates analysis is accurate otherwise you need to perform analysis again using different operating parameters to retrieve valid results.



Initial problem statement

- The type of flow (e.g. laminar or turbulent, steady or unsteady)
- Operating conditions (temperature range, pressure range, phase of fluid (liquid or gas))
- Geometry of the fluid domain
- Physical phenomena taken into account
- Any data on external/internal obstacles (free surfaces, interfaces)
- Objective of the CFD (e.g. Distributions needed to be computed, Specific parameters to be calculated, Specific points in fluid)
- Select best approach to achieve the objectives

Mathematical model

- The reference frame
- Computational domain
- Influences from the forces
- Conservation laws of Mass, Momentum and Energy
- Any physical/mathematical relations between unknown parameters
- Initial and Boundary conditions
- Optional Factors (to reduce the analysis effort)
    - o Symmetries in flow / Predominant direction of the flow
    - o Parameters with no or less influence
    - o Very small fluctuations that can be neglected
    - o Previous CFD or Mathematical analysis results

Discretization

- Mesh generation: - Shape and size of the mesh elements, structured/unstructured mesh, etc.
- Space discretization: - How the derivatives are approximated (Finite volumes, elements or differences) and the order of approximation (order of the approximation polynomials, etc.)
- Time discretization: - Time step, time step adaptation, implicit/explicit schemes used, etc.

Iterative solver scheme

- Eliminate non-linearity by outer iterations
- Solve linearized set of equations by inner iterations
- Check the solution, residuals and other factors for convergence according to convergence criteria at the end of each iteration.

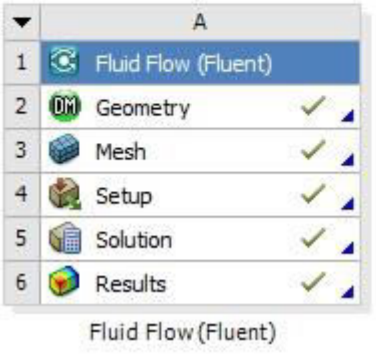
Post processing – visualization of the solution

- Data on specific points defined at the beginning of the CFD process
- Derived quantities (velocity potential, etc.)
- Parameters (lift, drag, mass properties, etc.)
- Distributions as lines, animation of elements, coloured chart, etc.
- Minima/ Maxima requested in the problem definition

Fig 4.2: Overview of the CFD modeling process

4.3 CFD Procedure

CFD analysis of flowing fluid using FLUENT is done in five stages such as:



	A	
1	Fluid Flow (Fluent)	
2	Geometry	✓
3	Mesh	✓
4	Setup	✓
5	Solution	✓
6	Results	✓

Fluid Flow (Fluent)

- ✓ Geometry Creation
- ✓ Mesh Generation
- ✓ Problem Setup
- ✓ Numerical Solution
- ✓ Numerical Result

4.3.1 Geometry Creation:

2-D geometry of straight horizontal pipe having diameter 8.6 mm and length 1500 mm has been created using design modeler of ANSYS 14.5 as shown in fig.4.3.

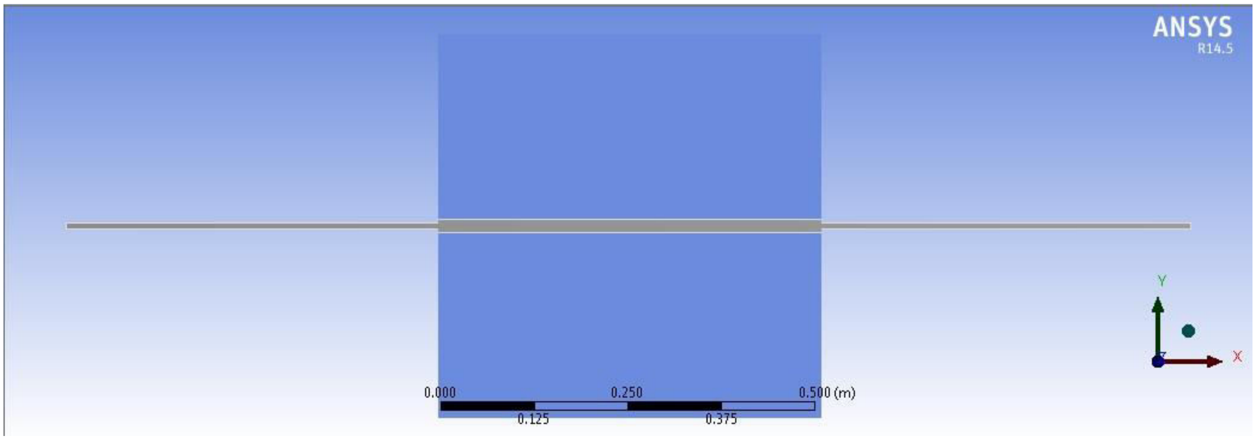


Fig.4.3: 2-D Geometry of horizontal pipe

Geometry can also be imported from other design software like AUTOCAD, PRO-E, CATIA, SOLIDWORKS, etc.`

4.3.2 Mesh Generation:

A fine mesh has been generated in ANSYS 14.5 as shown in fig.4.3. It depicts that the domain was mapped face meshed with rectangular cells.

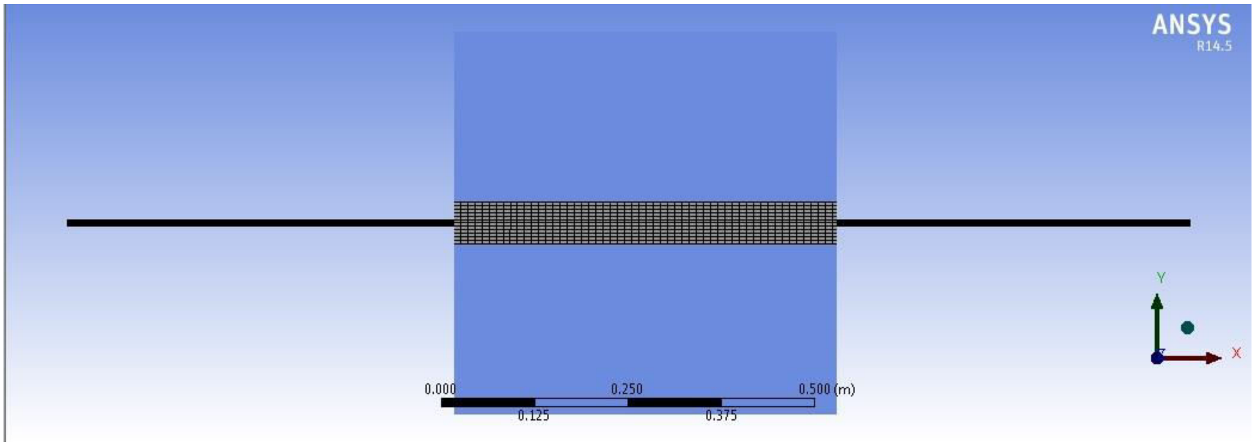


Fig.4.4: Meshed geometry of horizontal pipe

Geometry is meshed with 12072- quadrilateral cell zone, 23126 – 2-D interior face zones, 12 2-D velocity inlet and outflow faces and 2012 2-D wall faces with 13091 numbers of total nodes.

4.3.3 Problem Setup:

2-D planar pressure based solver was considered for steady conditions. Under model section multiphase mixture model with slip velocities, standard k-ε turbulence model with standard wall functions was selected.

Material taken for pipe was aluminum and R410a was taken as working fluid whose properties as added by user-defined database. Liquid R410a was taken as primary phase and vapour R410a was considered as secondary phase having a particular volume fraction.

Solver was arranged for a particular mass flow rate so that it cover entire flow field at velocity inlet and outflow condition was selected at outlet as fluid not left at atmospheric condition. At wall no slip condition was considered.

4.3.4 Numerical Solution:

Coupled scheme was selected and PRESTO! was selected under Pressure down list. First order upwind method was considered for discretization of momentum, turbulence K.E and turbulence dissipation rate.

4.3.5 Numerical Results:

In this section, the variation of pressure drop was obtained by using CFD analysis and for different homogeneous and separated flow models for R410a at different vapor quality and at two different mass fluxes at a given saturation temperature of 40°C which is discussed in detail in next chapter.

Chapter 5

Results and discussions

The present research is focused on the estimation of total frictional pressure drop inside a smooth horizontal pipe for two-phase flow of refrigerant R410a under adiabatic condition at a given saturation temperature of 40 °C (i.e. for condensing flow of refrigerant) at different quality of vapour and at two different mass fluxes. The results obtained from CFD analysis are then compared with the numerical study of pressure drop based on homogeneous and separated flow models.

5.1 Pressure Contour:

Figure 5.1 to 5.9 and figure 5.10 to 5.18 shows pressure contour for the two-phase flow of refrigerant R410a inside the smooth horizontal pipe at a mass flux of 350 kg/m^2-s and 1055 kg/m^2-s respectively. The flow behavior is turbulent and inlet velocity is taken as 2 m/s for both the phases so that it acts as a pseudo-single phase fluid.

The Pressure contours developed by CFD analysis using FLUENT-ANSYS 14.5 shows that there is a prominent deviation in the pressure gradient values evaluated for distinct quality of refrigerant i.e. at a different volume fraction at saturation temperature of T_s = 40°C and at two different mass fluxes of 350 kg/m^2-s and 1055 kg/m^2-s.

5.1.1 Pressure contours for mass flux of 350 kg/m^2-s at different vapour quality:

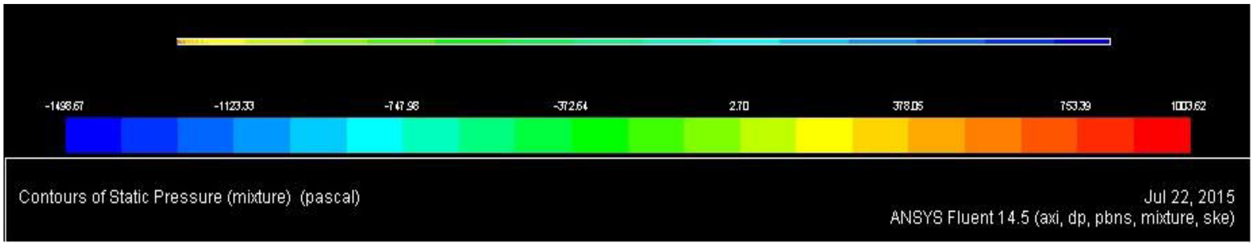


Fig.5.1. Pressure gradient for G=350 kg/m^{2}s at vapour quality of 10 %

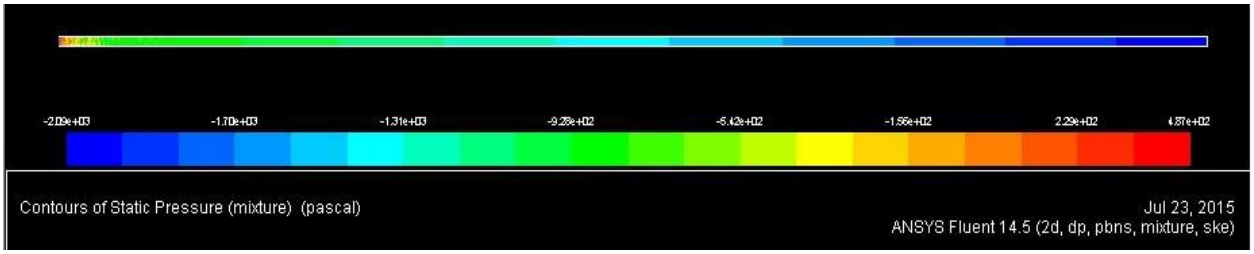


Fig.5.2. Pressure gradient for G=350 kg/m^{2}s at vapour quality of 20 %

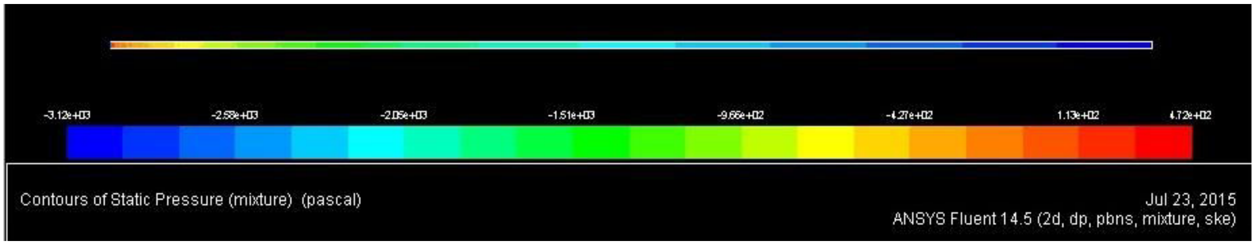


Fig.5.3. Pressure gradient for G=350 kg/m^{2}s at vapour quality of 30 %

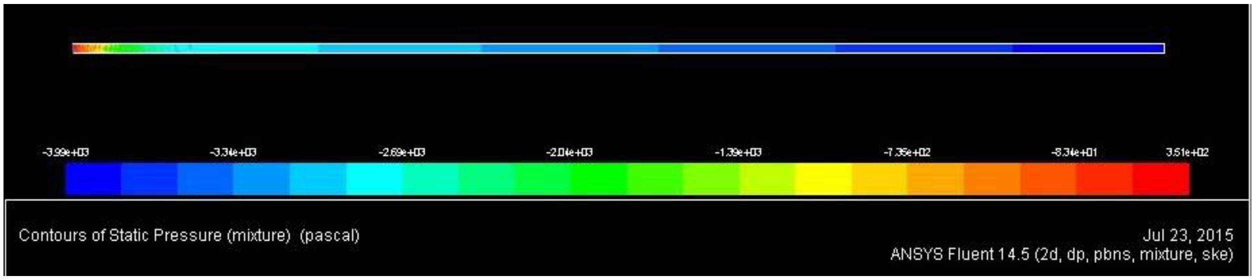


Fig.5.4. Pressure gradient for G=350 kg/m^{2}s at vapour quality of 40 %

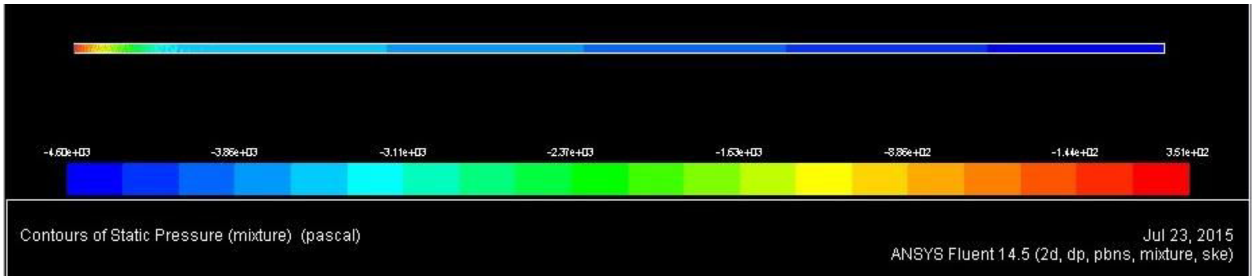


Fig.5.5. Pressure gradient for G=350 kg/m^{2}s at vapour quality of 50 %

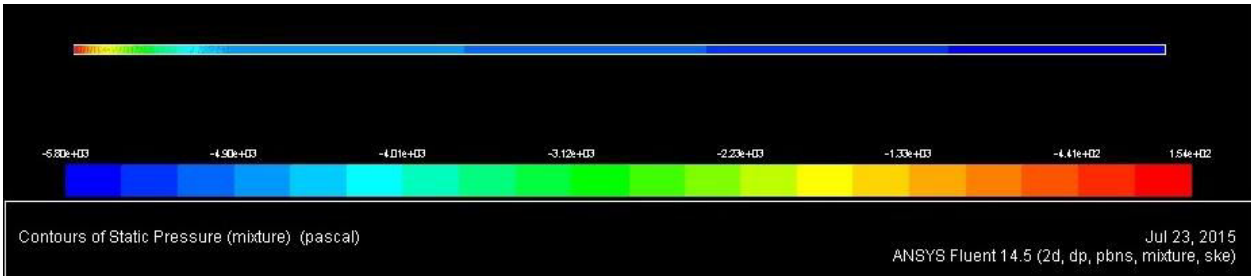


Fig.5.6. Pressure gradient for G=350 kg/m^{2}s at vapour quality of 60 %

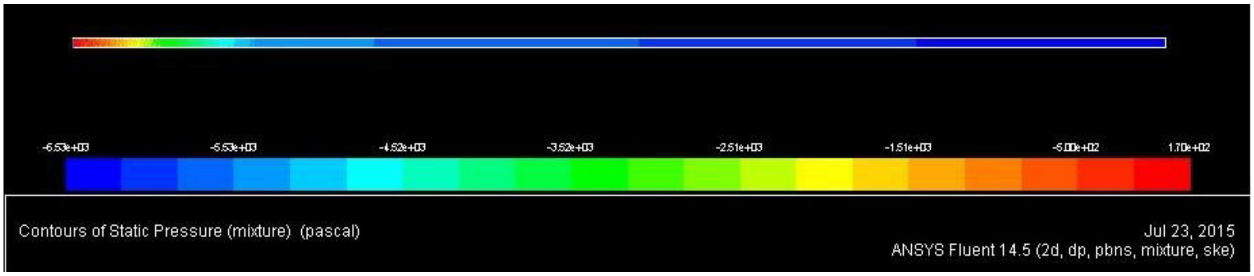


Fig.5.7. Pressure gradient for G=350 kg/m^{2}s at vapour quality of 70 %

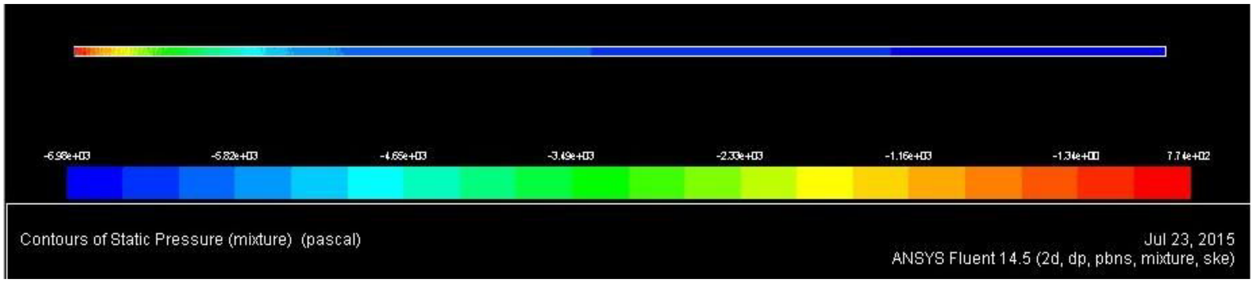


Fig.5.8. Pressure gradient for G=350 kg/m^{2}s at vapour quality of 80 %

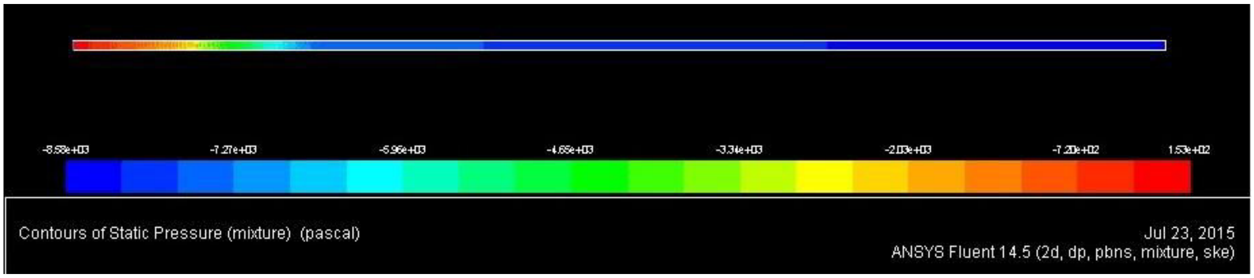


Fig.5.9. Pressure gradient for G=350 kg/m^{2}s at vapour quality of 90 %

5.1.2 Pressure contours for mass flux of 1055 kg/m^{2}s at different vapour quality:

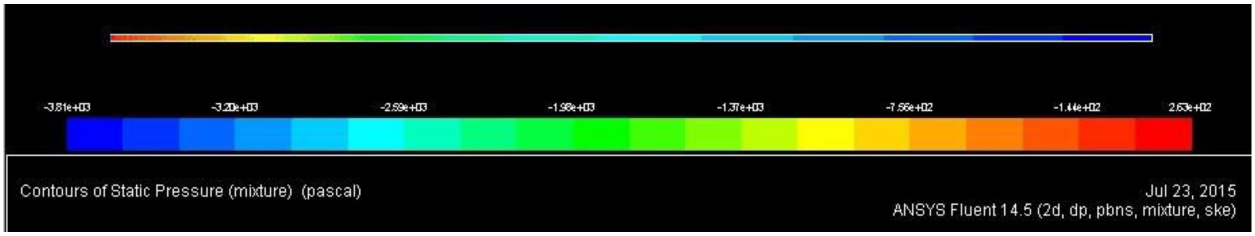


Fig.5.10. Pressure gradient for G=1055 kg/m^{2}s at vapour quality of 10 %

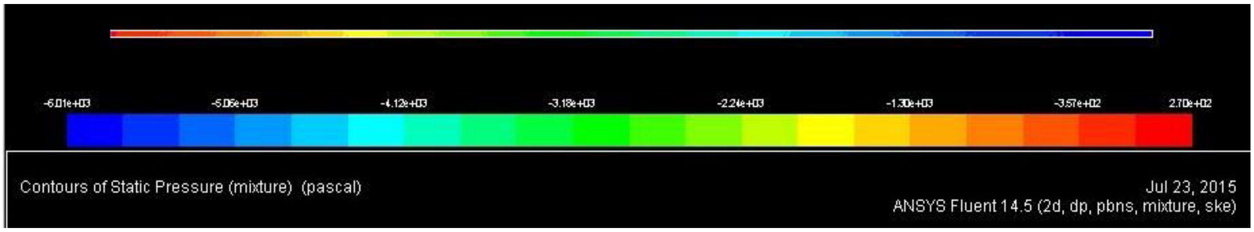


Fig.5.11. Pressure gradient for G=1055 kg/m^{2}s at vapour quality of 20 %

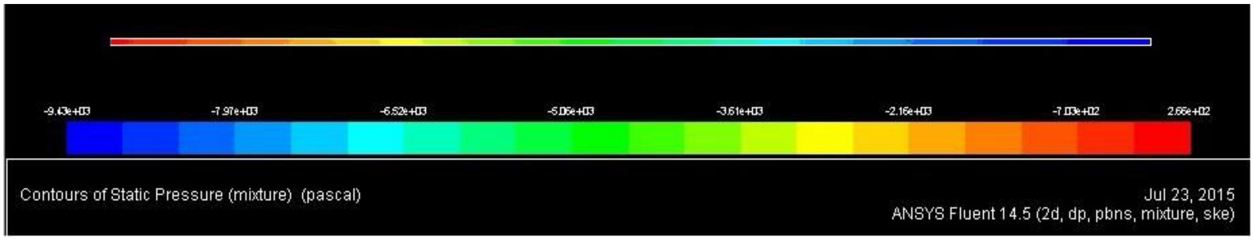


Fig.5.12. Pressure gradient for G=1055 kg/m^{2}s at vapour quality of 30 %

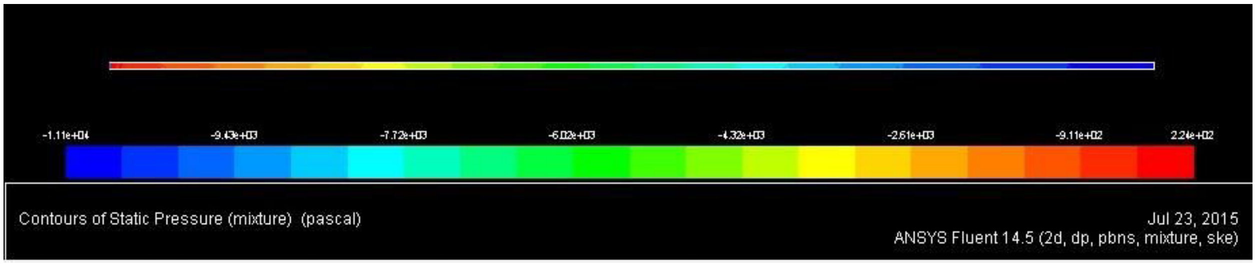


Fig.5.13. Pressure gradient for G=1055 kg/m^2s at vapour quality of 40 %

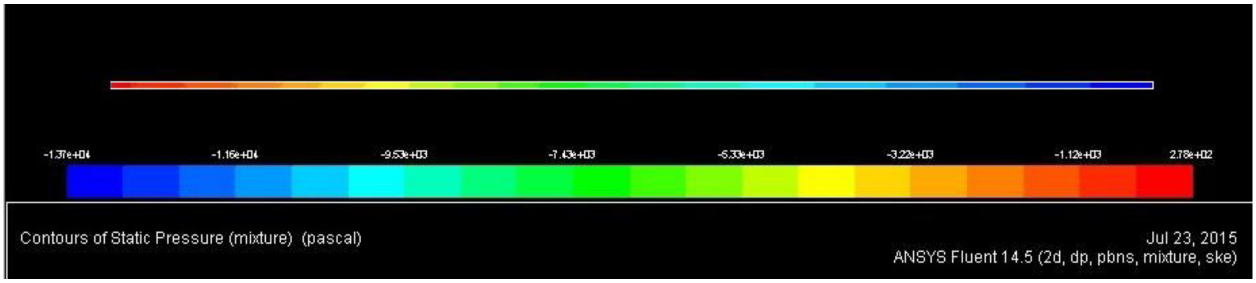


Fig.5.14. Pressure gradient for G=1055 kg/m^2s at vapour quality of 50 %

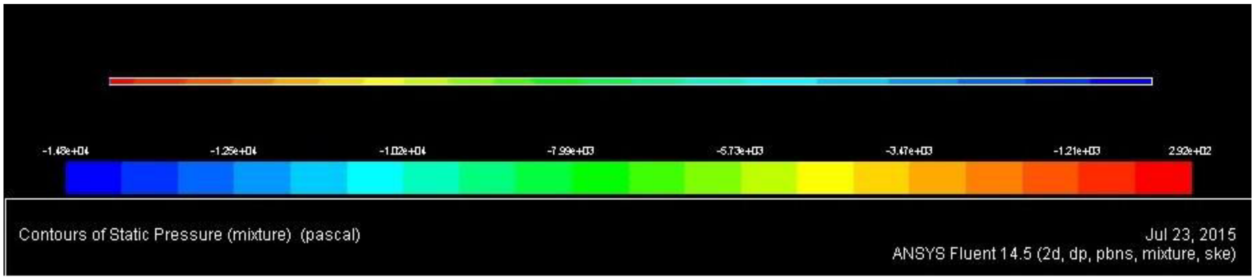


Fig.5.15. Pressure gradient for G=1055 kg/m^2s at vapour quality of 60 %

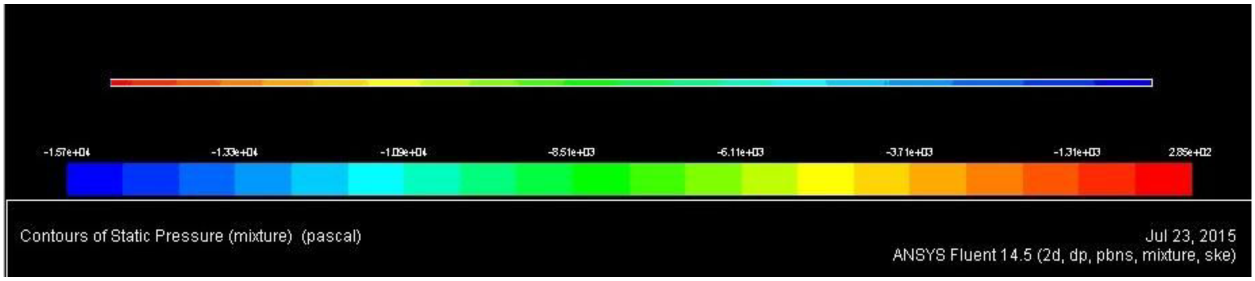


Fig.5.16. Pressure gradient for G=1055 kg/m^2s at vapour quality of 70 %

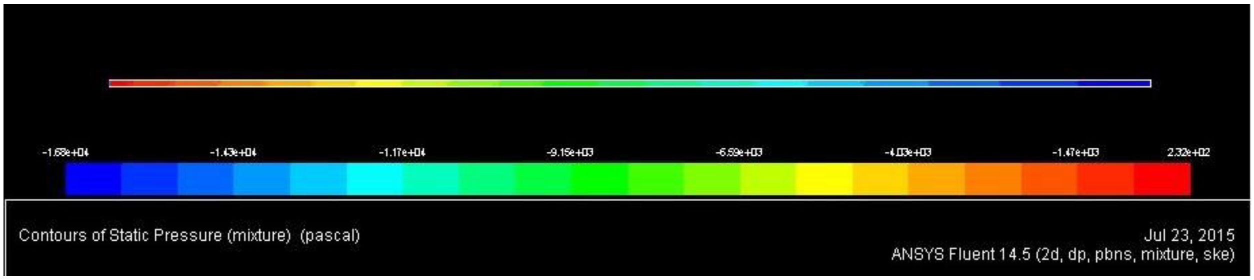


Fig.5.17. Pressure gradient for G=1055 kg/m^{2}s at vapour quality of 80 %

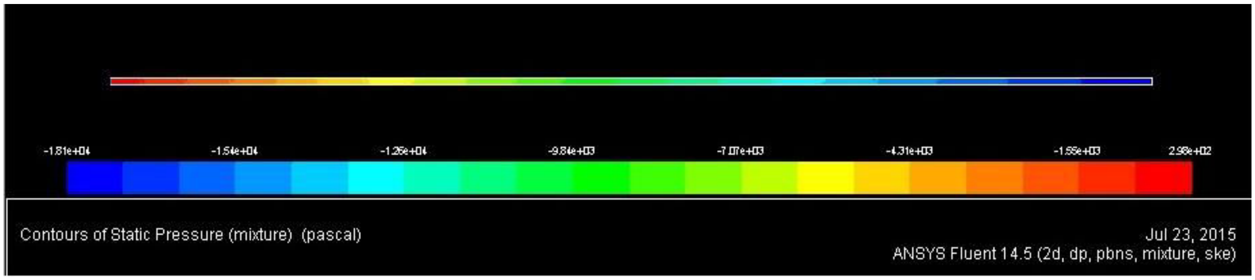


Fig.5.18. Pressure gradient for G=1055 kg/m^{2}s at vapour quality of 90 %

5.2 Comparison of Pressure drop Data:

5.2.1 Comparison of pressure drop for homogeneous models:

For refrigerant R410a, the pressure drop is estimated by employing distinct homogeneous models of dynamic viscosity as described in chapter 3 articles 3.2. Fig 5.19 and 5.20 shows the variation in pressure drop values estimated by three homogeneous models of dynamic viscosity at a saturation temperature of 40 °C and at two different mass fluxes of 350 kg/m^2-s and 1055 kg/m^2-s (i.e. Low and high mass flux).

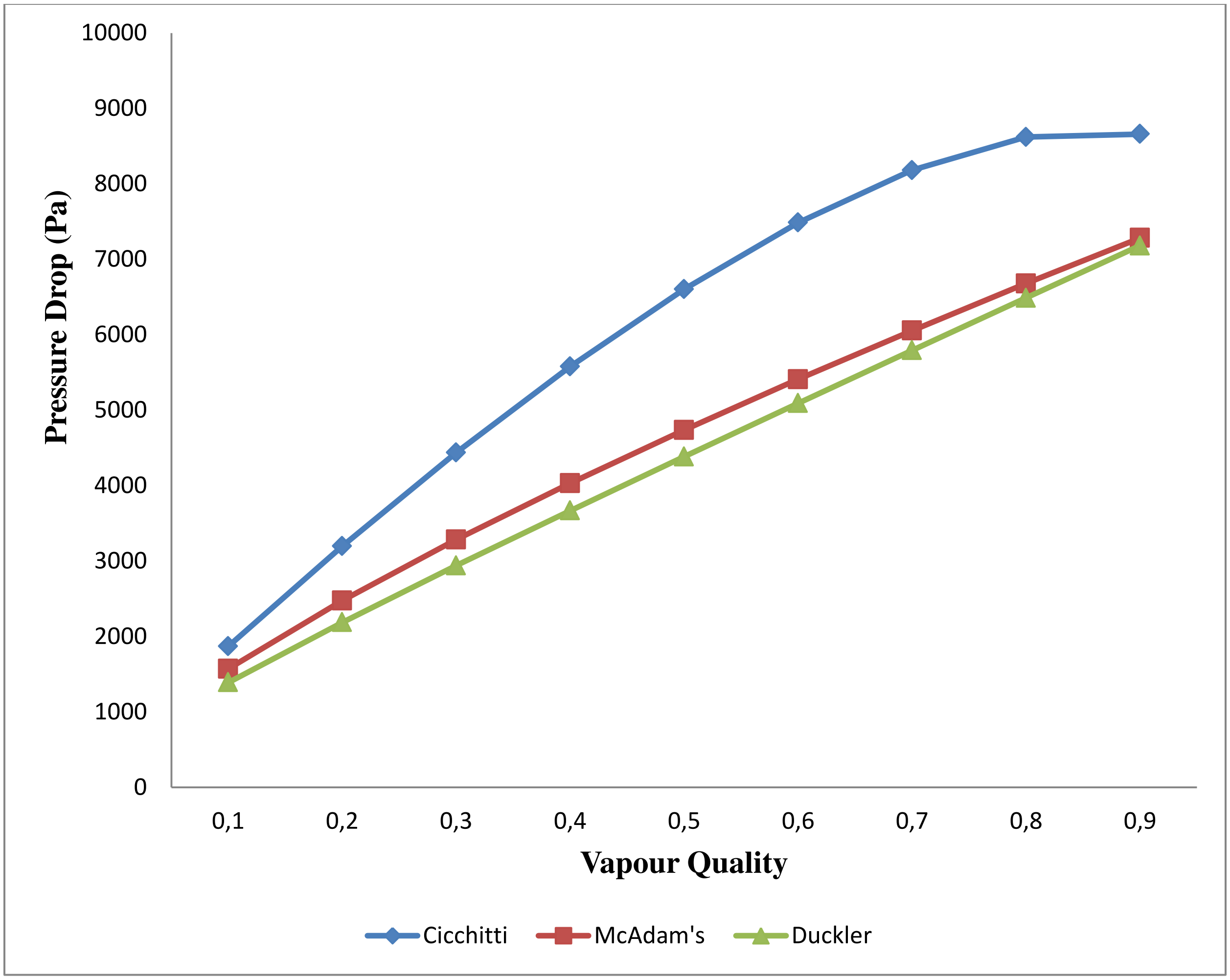


Fig.5.19. Pressure drop for three homogeneous models at T_S=40°C and G=350 kg/m^{2}s

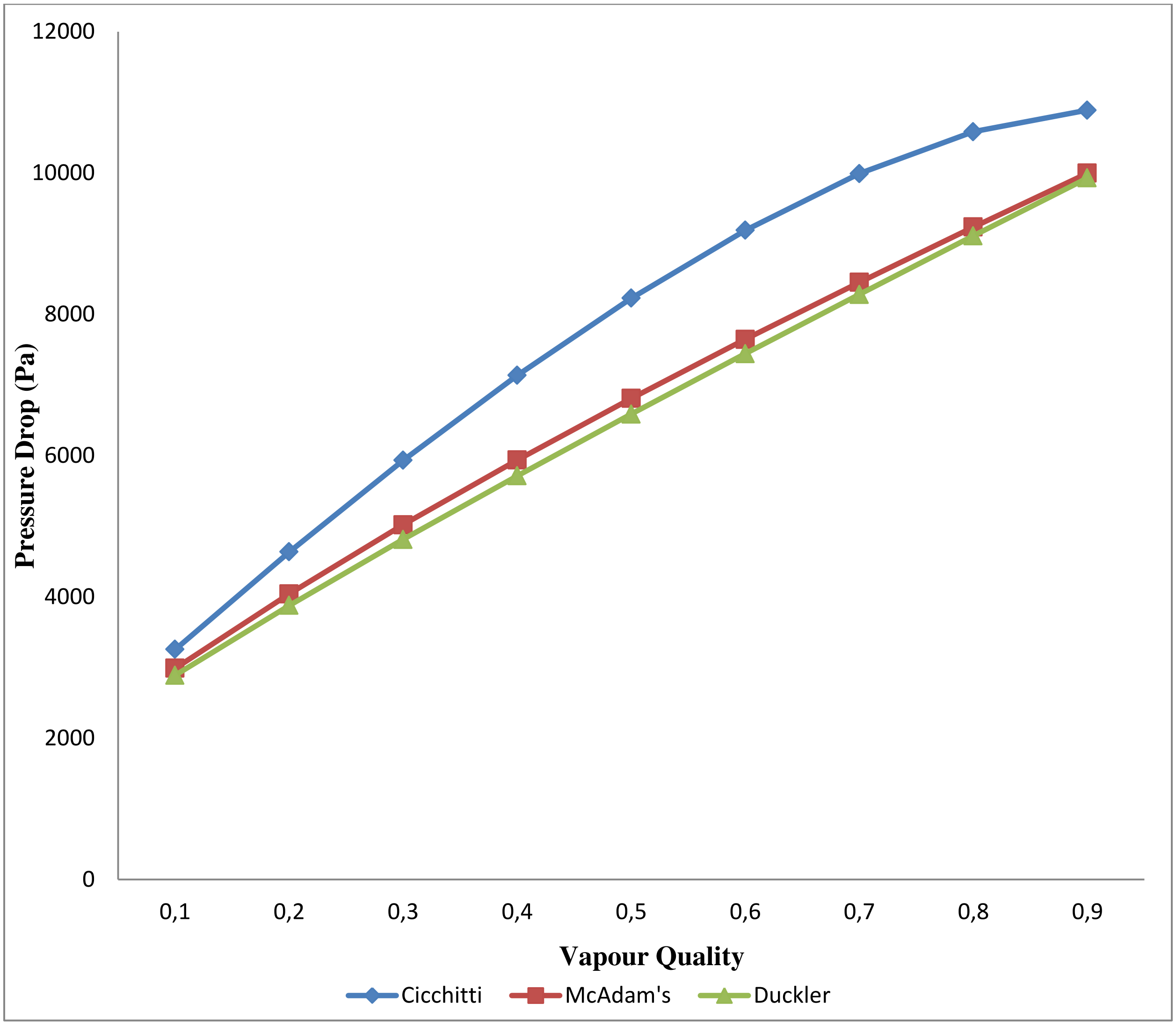


Fig.5.20. Pressure drop for three homogeneous models at T_s=40°C and G=1055 kg/m^2s

It is to observed from the fig.5.19 and 5.20, that at saturation pressure associated to the saturation temperature of Ts = 40°C, the pressure drop values estimated by considering Dukler and McAdam's models for each mass flux are approximately similar, resulting the analogous deviation of the pressure drop. Whereas, the cicchitti model estimated elevated values of pressure drop among them. This can be easily observed by considering the values of mean dynamic viscosities for three models. Hence, Cicchitti homogeneous model of mean dynamic viscosity is considered for further simulation in CFD at each quality of vapour and for both the mass fluxes.

Now another observation from fig. 5.19 and 5.20 is that, the pressure drop curve tend to converge at higher values of mass flux because at higher values of mass flux, the effect of mean dynamic viscosity is trivial in the calculation of Blasius friction factor and hence the pressure drop.

5.2.2 Comparison of pressure drop for separated flow models:

In this section, the results acquired from CFD analysis are plotted on the graph and compared with the pressure drop values obtained numerically from the homogeneous and the separated flow models explained in chapter 3, article.3.2 and article 3.3 respectively.

Fig. 5.21 and 5.22 shows the comparison of pressure drop values obtained from CFD analysis and the pressure drop values calculated by using homogeneous model and the following five separated flow models:

a) Lockhart-Martinelli Correlation.
b) Chisholm Correlation
c) Friedel Correlation
d) Muller Steinhagen – Heck Correlation
e) Gronnerud Correlation.

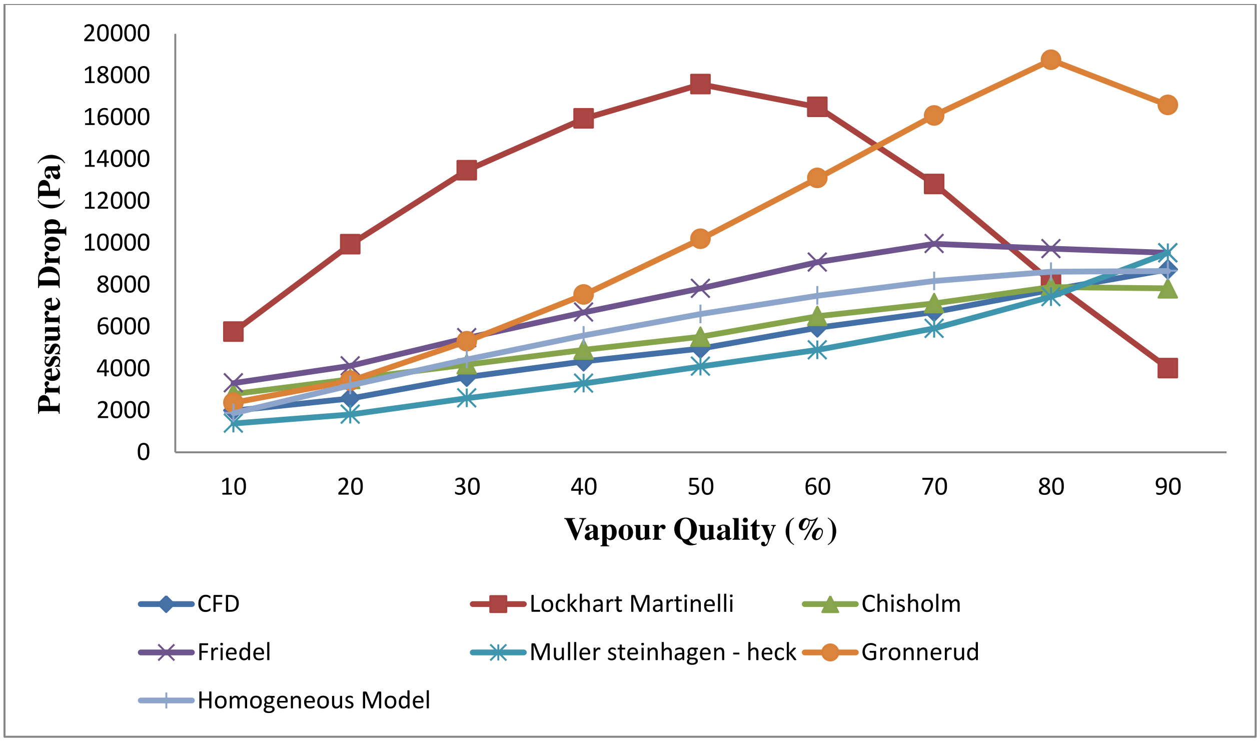


Fig.5.21. Pressure drop of R410a at 40°C with G= 350 kg/m^{2}s

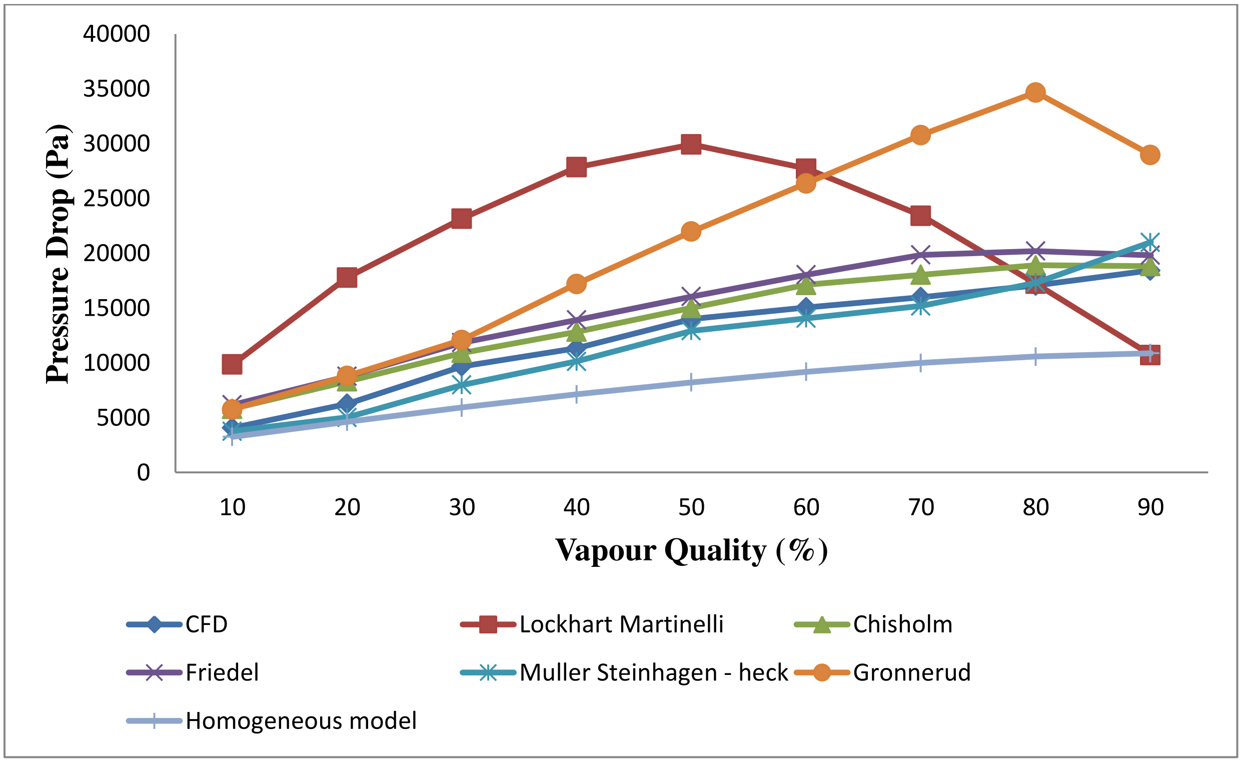


Fig.5.22. Pressure drop of R410a at 40°C with G= 1055 kg/m^{2}s

MASS FLUX	**AVERAGE DEVIATION OF CFD RESULTS**					
(Kg/m^{2}s)	**L-M**	**Chisholm**	**Friedel**	**M-S-H**	**GR**	**H-M**
350	**55.27%**	**07.96%**	**18.35%**	**14.68%**	**50.08%**	**14.73%**
1055	**40.33%**	**09.99%**	**16.88%**	**04.04%**	**40.02%**	**37.62%**

Fig.5.21 and 5.22, shows that, at a given saturation pressure associated to the saturation temperature of 40 °C, R410a signifies almost similar trend of pressure gradient vs. vapour quality plot for various correlations and CFD results at both the mass fluxes. Each plot indicates remarkable deviation of pressure drop data obtained from correlations but the deviation is much higher for Lockhart-Martinelli and Gronnerud Correlations as shown in the given table. Similar to the homogeneous models, separated flow models also tend to converge at high mass flux this is due to the reduction in the fluctuation in the values of Reynolds number and the friction factor.

Now if we talk about the trend of homogeneous model for frictional pressure drops in both the curves, it is to be noticeable that the variation in the frictional pressure drop decreases with the increase in mass flux. The reason for this is that the average viscosity and density at high mass flux tend to attain the value closer to the vapour viscosity and density respectively. This results in the reduction of variation in Reynolds number, friction factor and hence frictional pressure drop.

Chapter-6

CONCLUSIONS AND FUTURE SCOPE

6.1. Conclusions:

Through the analysis of present CFD simulations following conclusions are drawn:

a) It is visible from the results that the pressure drop drastically increases with the increase in mass flux for all separated flow models and CFD model but for homogeneous flow models, variation in pressure drop decreases with the increase in mass flux.

b) The values of pressure drop for all correlation tends to converge at high mass flux except for homogeneous flow models.

c) The pressure drop data obtained from CFD analysis provides satisfactory result which show that the total pressure drop of simulation is pretty much closure to the homogeneous model as well as separated flow models except for Lockhart-Martinelli and Gronnerud Correlations.

d) The CFD results are best predicted by Chisholm Correlation for lower mass flux having 07.96% of average deviation of pressure drop as compared to all other correlations and for higher mass flux, the best results are predicted by Muller Steinhagen – Heck Correlation with 04.04% of average deviation.

6.2. Future Scopes:

The works which are required to be done in future are:

a) To numerically model a smooth horizontal pipe using CFD analysis and to optimize the pressure drop for refrigerant R410a and for other new refrigerants using homogeneous and separation flow models for different pipe dimensions at varying mass flux and at different saturation temperature for evaporative and condensing flow.

b) To numerically model a smooth vertical pipe using CFD analysis and to optimize the pressure drop for refrigerant R410a and for other new refrigerants using homogeneous and separation flow models for different pipe dimensions at varying mass flux and at different saturation temperature for evaporative and condensing flow.

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