A LOW COST MICRO SCALE CYCLONE SEPERATOR- DESIGN AND COMPUTATIONAL FLUID DYNAMICS ANALYSIS

by

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ABSTRACT

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Microparticle separation process has a variety of application varying from application in biological and biomedical industries for analysis and diagnosis, in biogas manufacturing to separate phases as well as in defense sector for detection of biological weapons like anthrax. Available electrical, magnetic, acoustic and various other methods are either very costly or not portable. The proposed design of micro scale cyclone separator is low cost as well as portable and easy to manufacture. Huge cyclone separators are widely used in various industries since decades but due to lack of research in micro scale cyclones no direct and sufficient data is available. This research attempts to develop a microscale cyclone separator and study the effect of parameters like inlet velocity on pressure drop and collection efficiency in a micro scale cyclone separator. It further studies the effect of particle size on collection efficiency through Computational Fluid Dynamics (CFD) approach.CFD analysis has been proved very efficient for

calculations in larger cyclones and hence is used as a tool in this study as well, though experimental verification is recommended. Computational experiments were performed using FLUENT. The results obtained are compared with various empirical relations developed for huge cyclone separators and similarities and dissimilarities in trends are analyzed. Finally a multi-cyclone model is proposed to obtain higher collection efficiency.

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CHAPTER 1

INTRODUCTION

1.1 Microparticle Separation

Microparticle separation is selective sorting of microparticles as per requirements. Microparticle separation has a versatile application. With the advancement in micro and nano technology, separation modules are extensively used in biological, biomedical and microchemical processes. Separation techniques are employed in fundamental cell studies as a diagnostic and analysis tool. Microparticle separation techniques are needed in the field of theranostics. [1]. Prenatal diagnosis is being typically carried out using invasive techniques which are considered risky as they can cause abnormalities or even abortion. Microseparation of foetal cells from mother's blood allows non-invasive prenatal diagnosis. [2,3,4] Microseparation techniques are also needed for detection of cancer cells or the accumulation and counting of various types of cells and bacteria [5]. It has become an integral part of various processes in agrochemical, pharmaceutical, and cosmetic industries [5]. Determination and separation of biologically harmful agents like anthrax [6] and separation of phases in biofuel production also employ microparticle separation techniques. Various micron scale particle separation techniques have evolved in last decade and many state-of-art equipments have been designed to cater to specialized applications. Electrical separation, magnetic separation, optical separation, acoustic separation, and thermal separation techniques are major techniques that have been developed and made available in the market.

1.1.1 *Electrical Separation*

Electrical separation is probably the oldest of the techniques developed for microparticle separation. There are two major techniques which fall within this category. (1) Electrophoresis: In this technique the motion of particles in fluid is governed under the influence of uniform electric field. In 1809, Reuss observed that clay particles dispersed in water migrate under influence of applied electric field and thus discovered electrophoresis [7]. It is majorly employed to separate different type of charged particles. It has been successfully used in different forms for applications in molecular biology, DNA fingerprinting, restriction mapping in nanofluidic devices [8], etc. The following figure taken from website of HOPES (Huntington outreach project for education at Stanford) , presents the idea of gel electrophoresis process applied to DNA isolation [9].

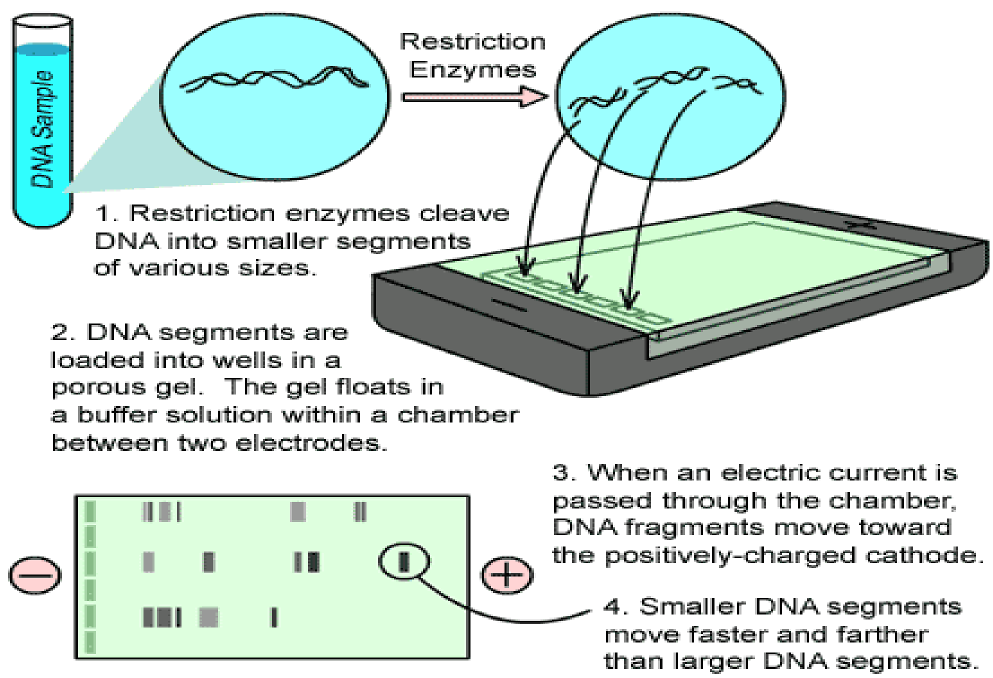

Figure 1 Gel Electrophoresis for DNA isolation taken from HOPES website [9]

(2) *Dielectrophoresis (DEP)* **-** Dielectrophoresis is 'the translational motion of neutral matter caused by polarization effects in a non uniform electric field '[Pohl, 10] Figure 2 shows the working principle of DEP [11].

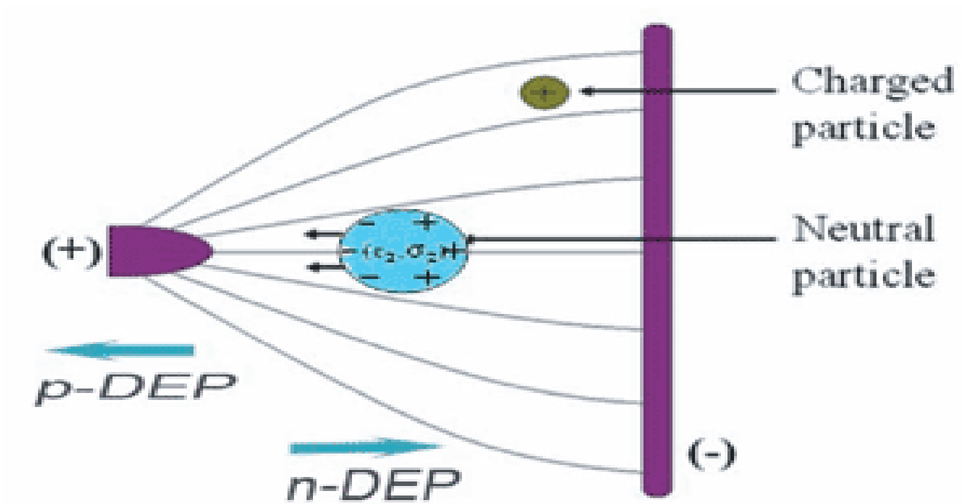

Figure 2 Dielecrophoresis [11]

Dielectrophorosis results in the polarization of a neutral particle (formation of a dipole). As a result, such a particle will move in an electric field either toward a positive or a negative electrode, depending on permittivity and conductivity parameter of the whole system

1.1.2 *Magnetic Separation*

Magnetic separation is widely used in biomedical and biological processes. It has been extensively used in drug delivery application for labeling of drugs, transport and separation [12 13]. The principle for magnetic separation is rather simple. A magnet is placed at an appropriate position. Magnetically charged or labeled particles are retained and non magnetic one pass through the channel. This is called magnetic activated cell sorting (MACS) [14]. The following figure depicts the principle of magnetic separation in micro channel [15]. The sample mixture containing both magnetic and non magnetic particle is passed through the channels.

Magnetic particles are then separated under the influence of magnetic force according to their size and property. Non magnetic particle are not deflected from their path and can be collected at other end.

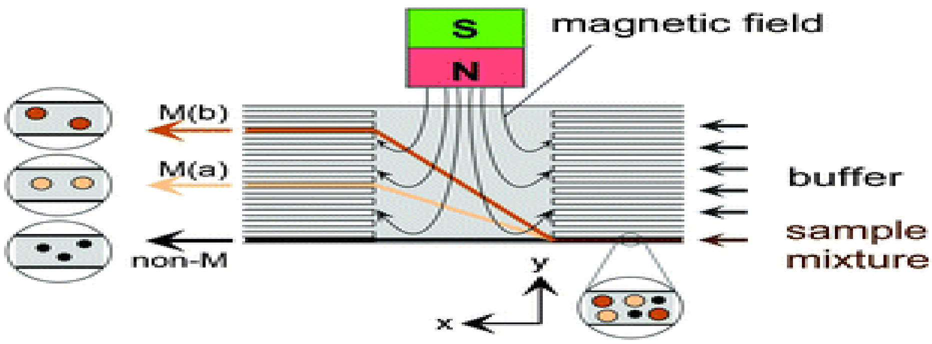

Figure 3 Principle of Magnetic separation in micro channel [15]

1.1.3 *Optical Separation*

Optical fractionation is a recent technique developed by Dholakia and coworkers [16] and Grier and coworkers [17]**.** An optical gradient force called potential energy landscape is developed using optical tweezers. This force deflects particles from their natural path depending upon their size, orientation and properties. As show in figure 4 [18], a 3D optical lattice is placed in part shared by all four chambers. This allows sorting of particles depending upon the selection criteria set in optical lattice.

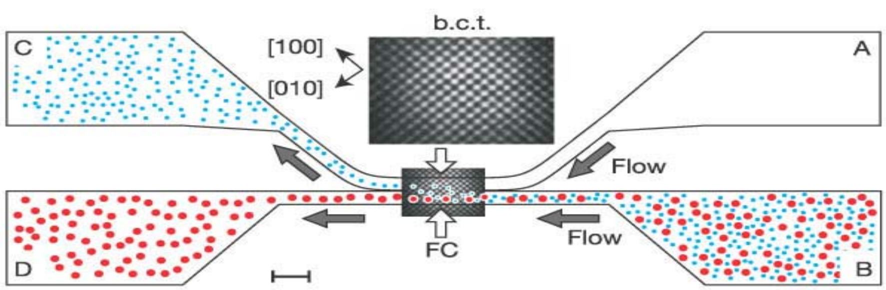

Figure 4 Concept of optical fractionation [18]

1.1.4 *Fluid only type separation -Microparticle separation arrays*

Fluid only type of separation uses only geometry of the instrument and forces acting on the particle to sort them and separate them. Various methods are being developed in this regime as it is cheap and very well suited for mass production. Microparticle separation array is one example of fluid only type of separation. The principle behind its working is controlling the size of particle passing in the channel by micro gap [19]. The particle with size greater than the gap cannot pass through and have deflected motion and hence different size particles are separated. Figure 5 shows a micro separation array. This is a type of passive sorting of particles.

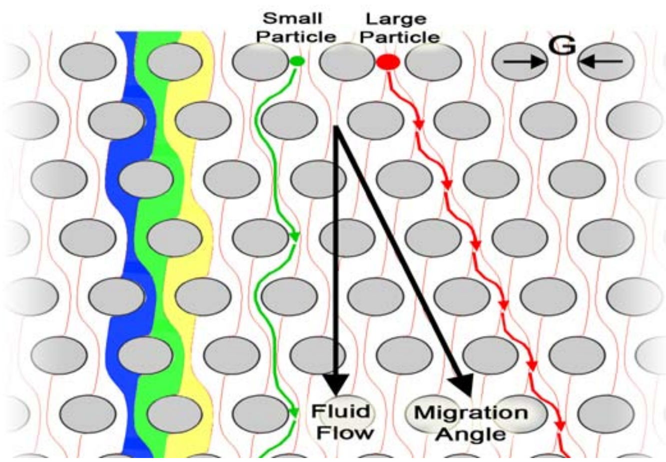

Figure 5 Microparticle separation array [19]

There are various other separation methods like acoustic methods, ultrasonic methods etc. It is beyond the scope of this thesis to discuss each of them in detail. Optical fractionation has very good sensitivity and selectivity but is not portable.[17] Magnetic separation has excellent efficiency along with portability but is very expensive to manufacture.[20] Electrophorosis and dilelectrophorosis are established technique but the fabrication of electrodes increases the cost of microdevice and is not suitable for mass production.[5] All the above mentioned techniques are available in the market starting from few hundred dollars to as high as twenty to thirty thousand dollars depending upon the size of particle to be separated and efficiency required for the particular application. Hence, there arises a need to develop a device that would combine the characteristics of low cost with portability for wide range of particle size [5].

CHAPTER 2

CYCLONE SEPERATOR

This chapter gives introduction to cyclone separators, reasons for its popularity and objective of using cyclone separator at micro level. Overview of various popular cyclone theories is presented and finally, few collection efficiency theories and pressure gradient theories that are used for comparison of computational results are discussed.

2.1 Introduction

Cyclone separator has been used for micro particle separation in various industries. it's simple design and easy constructability make them very popular. Cyclone separator does not have any moving parts and hence it has very low maintenance costs. Also, they consume very less energy as separation occurs due to natural forces action and swirl motion of fluid. Hence, cyclone separator, with its simple design, fluid-only type of separation, and low cost, becomes an obvious choice for experimentation. Although various large and small cyclone separators have been used successfully in cement, agro, oil and various other industries, there are very less data and research available about its application at micro scale. This research explores possibilities for successful application of micro-cyclone separators for microparticle separation and will provide some guidelines for further exploration.

Cyclone separator is a fluid-only type separation device which employs fluid and particle forces to separate particles depending upon their densities. This gives it an upper edge over other techniques as all other techniques require some unique properties like magnetic susceptibility, refractivity, dielectric properties or acoustic and thermal susceptibility.

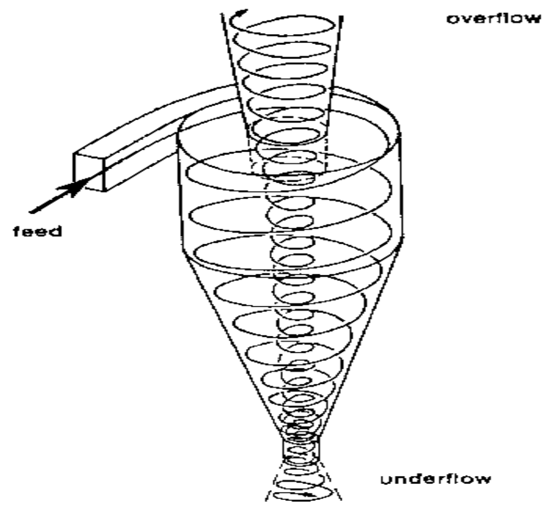

Figure 6 Design of a Typical Cyclone Separator [21]

Figure 6 shows a simple cyclone separator [21]. The fluid enters the cyclone tangentially. The cyclone induces a swirl rotation and hence, imposes radial acceleration on particles. Figure 7 shows the forces acting on the particle in a cyclone separator.

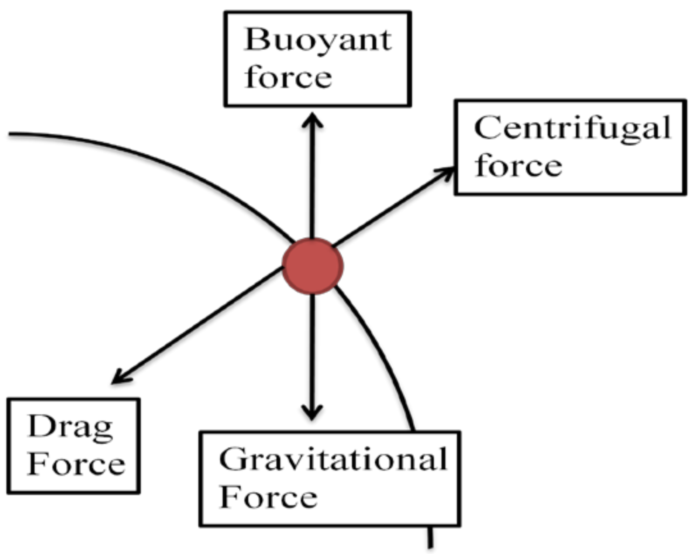

Figure 7 Forces on a particle in a cyclone

Most conventional way of designing a cyclone separator is by determining the cut of diameter of particle that needs to be separated. Various designing approach and empirical models passed on them will be discussed in later chapters. The basic principle of separation is that the particles with higher densities have higher inertia and hence they tend to revolve in larger radius. Thus, the heavier particles are revolving nearer to the wall where they slide down and are removed. Lighter ones rotate near the center and are collected out from the center of the cyclone. Collection efficiency and pressure drop are the two most important parameters for determining design and performance of a cyclone separator. Trade off between higher efficiencies and low pressure drop across the cyclone is essential. Increase in inlet velocity leads to increase in efficiency but it also increases the pressure drop across the cyclone. Pressure developing at the inlet poses limitation on inlet velocities that can be employed and hence, the efficiency of the separator. A higher velocity requires the use of costly materials and increases the manufacturing cost. Also, certain microscale applications might not permit such higher pressure drops. Also at microscale the effect of pressure becomes more significant. Thus, pressure drop across a cyclone is becomes an important parameter for microscale cyclone separator.

Figure 8 various large scale cyclone separators

2.2 Cyclone Separator Theories

Large amount of literature is available describing various theories related to cyclone separator. Various methods are explored by numerous scientists to describe theories of particle collection in a cyclone separator. Cyclone efficiency and pressure drop are the main performance characteristics of a cyclone separator. A simple force balance approach is used below to determine critical diameter of the particle which will be effectively separated for a given geometry and velocity.

Figure 7 shows various forces acting on a particle in a cyclone. Inlet velocity is divided into two components, tangential velocity V_t and radial velocity V_r. Radius of the particle is r_p and the radius at which it is rotating at a given time is r. μ is the molecular viscosity of fluid. ρ_p and ρ_f are particle and fluid densities respectively. Mass of particle is denoted by m. Drag force can be calculated from stoke's law and is given by Eq. 1. Eq. 2 and Eq. 3 give centrifugal an buoyant force respectively.

Eq. 1

$$\mathrm{F}_d = 6\pi r_p \mu V_r$$

Eq. 2

$$F_c = m\frac{V_t^2}{r} = \frac{4}{3}\pi\rho_p r_p^3 \frac{V_t^2}{r}$$

Eq. 3

$$\mathrm{F}_b = -V_p \rho_f \frac{V_t^2}{r} = -\frac{4}{3}\pi\rho_f r_p^3 \frac{V_t^2}{r}$$

Now considering a steady state condition, the particle will rotate at a certain radius from the center of cyclone under the effect of equilibrium of forces action on it. Hence, force balance is given by Eq. 4

Eq. 4

$$\frac{dr}{dt} = F_d + F_c + F_b = 0$$

Now, substituting eq. 1 ,2 and 3 in eq. 4 and solving for r_p will give us the critical radius of particle that will be effectively separated for given velocity.

Eq. 5

$$r_p = \frac{3}{2}\left[\frac{V_r r}{V_t\left(\rho_p - \rho_f\right)}\right]^{1/2}$$

The above approach is very rudimentary and there are much more things that need to be considered when designing a cyclone separator. More efficient cyclones were designed based on experimental results. Most famous among these cyclones design are the Stairmand high efficiency cyclone [22], Lapple cyclone[23], Kim and Lee cyclone[24] and the German Z cyclone[25]

2.3 Cyclone Efficiency

2.3.1 *Overall separation efficiency*

The overall efficiency is usually the most important consideration in industrial process. Lets us consider the mass balance of solid particle in cyclone. As explained by Hoffmann and Stein in their book on gas cyclones[26], M_f , M_c and M_e are the mass flow rate of the feed, mass flow rate of particle collected and mass flow rate of escaped particles respectively. Then force balance of solid particle over the cyclone can be denoted by eq. 6.

Eq. 6

$$M_f = M_c + M_e$$

The overall separation efficiency can be calculated directly as the mass fraction of feed that is successfully collected.

Eq. 7

$$\eta = \frac{M_c}{M_f} = 1 - \frac{M_e}{M_f} = \frac{M_c}{M_c + M_e}$$

The overall efficiency, though useful, does not specify anything about the effect of particle on a cyclone. Hence, it does not provide us with any information that can be used in future to design cyclone. The separation characteristics are best defined by grade efficiency.

2.3.2 *Grade Efficiency*

The grade efficiency curve best describes the separation characteristics. Grade efficiency is the efficiency for feed particle size or for a given narrow range of size. Let $f_f(x)$, $f_c(x)$ and $f_e(x)$ denote differential volume or mass density distribution for feed , captured and escaped particles. Grade efficiency denoted by η(x) is given by Hoffmann and Stein[26] as follows:

Eq. 8

$$\eta(x) = 1 - (1 - \eta)\frac{\mathrm{f_e(x)}}{\mathrm{f_f(x)}}$$

A typical Grade efficiency curve is given by Figure 9.

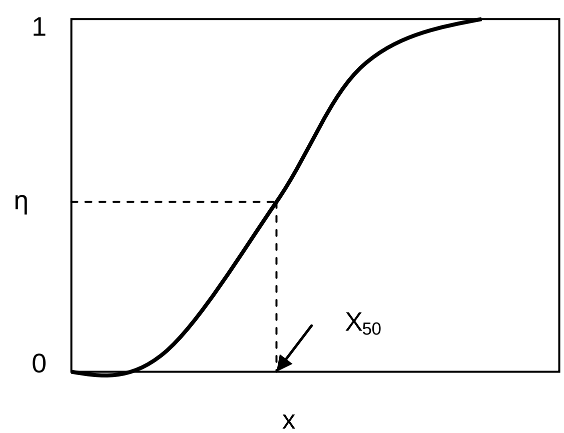

Figure 9 A typical GEC [26]

2.3.3 *Factors affecting the cyclone collection efficiency.*

Various factors are observed to affect the cyclone efficiency. An account of some important factors as presented by Schnell and Brown [27] in Air pollution control technology Handbook is presented here.

Inlet velocity is prime factor effecting the pressure drop and hence the cyclone efficiency. Efficiency increases with increase in velocity as centrifugal force increases but this also increases the pressure drop which is not favorable. Also, decreasing the cyclone diameter increases centrifugal force and hence efficiency. Another factor affecting the cyclone efficiency is gas viscosity. With decrease in viscosity, efficiency increases. This is due to reduction in drag force with reduction in viscosity. Decrease in temperature will increase the gas density. One may be tempted to conclude that this will increase efficiency as viscosity decreases. But increase in temperature also decreases the volumetric flow rate and thereby decreasing efficiency. Another important factor effecting the efficiency is particle loading. With high loading the particles collide with each other more and results into pushing of particle towards wall. This in turn increases efficiency. Figure 10 shows relationship between efficiency and particle size for high efficiency cyclone which slender and long, high throughput cyclone which are broad and create less pressure drop and a conventional standard cyclone.

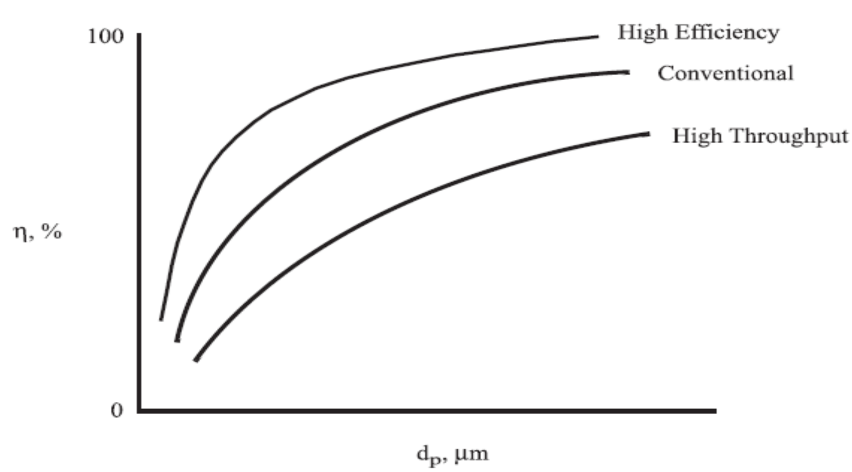

Figure 10 Generalized Efficiency Relationship [26]

2.4 Empirical Models

A prominent problem in calculating the efficiency of cyclone is the effect of flow characters in cyclone. In big cyclones the flow is turbulent and friction factors assumed give good results. This is not true for small cyclones [28]. The flow in small cyclones can be laminar or even transitional. In such case the operational conditions, like velocity, temperature, pressure, viscosity and cyclone diameter, may be of significant importance and their effect changes from cyclone to cyclone [29]. In laminar flow, operating parameters influence cyclone efficiency more than turbulent case. This makes the prediction of efficiency and pressure drop very difficult specially in small cyclone. Most of the models depend on empirical or semi-empirical equations. The models calculate efficiency and predict the cutoff size which corresponds to 50% efficiency. According to Wang et al. [30] cyclone performance is function of geometry and operating parameters of cyclone, as well as particle size distribution of the entrained particulate matter. Several models have been proposed to predict the efficiency of cyclone. It is widely agreed amongst the scientists that cyclone performance is definitely affected by operating parameters and hence they should be included in the modeling. Many theories account for density, gas velocity, viscosity and particle diameter. As far as effect of geometry is considered there is difference in approach for various scientists. Some consider all the geometric parameters where as some consider only few important parameters like inlet and outlet diameter and height in their models. As mentioned, most of the theories consider cut size "d50", which corresponds to diameter of particle where 50% of particles smaller and 50% of particles greater that that size will be collected.[21] Two most common approaches for calculating efficiency are Force Balance Theory [Lapple,23] which assumes that terminal velocity is achieved when drag fore and centrifugal force equal each other and the Static Particle Approach [Barth,31] which considers simple force balance where forces acting on particle are balanced. Various other complicated theories have been proposed but they essentially have their base in one of the two theories.

2.4.1 *Cyclone Efficiency Empirical Models*

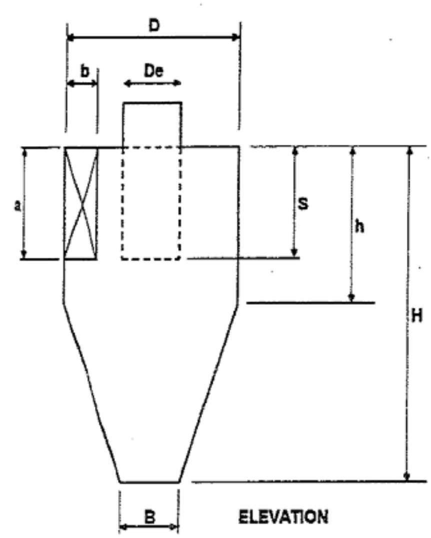

Figure 11 Tangential Cyclone Configuration [32]

Out of many models, three efficiency models have been considered for comparison of computational results. Figure 11 [32] shows a typical cyclone and all the symbols discussed further are the dimensions shown in Figure 11.

2.4.1.1 *Lapple Model*

Lapple [23] model is amongst the earliest of model proposed and is still considered bench mark for design of cyclone separators in many industries. This is comparatively a simple model based on force balance with considering the flow resistance. It assumes that the particles are evenly distributed across the inlet while entering the cyclone. It was based on terminal velocity of particles in cyclone.

From theoretical analysis Eq. 9 is derived which gives the size of smallest particle that will be collected by the cyclone.

Eq. 9

$$d_p = \sqrt{\frac{9\mu b}{\pi N_e V_i \left(\rho_p - \rho_g\right)}}$$

$Where,\ d_p = \ diameter\ of\ smallest\ particle\ that\ will\ be\ collected\ by\ the\ cyclone$

$\mu\ =\ gas\ viscosity\left(kg/m\text{-}s\right)$

$a = \ length\ of\ inlet\ duct\ \left(m\right)$

$b\ =\ width\ of\ inlet\ duct\ \left(m\right)$

$N_e = \ \frac{1}{a}\left[h + \frac{H\text{-}h}{2}\right] = \ number\ of\ turns$

$V_i = \ inlet\ gas\ velocity\ \left(m/s\right)$

$\rho_p = \ particle\ density\ \left(kg/m^3\right)$

$\rho_g = \ gas\ density\ \left(kg/m^3\right)$

$H = \ total\ height\ of\ cyclone$

$h = \ height\ of\ cylindrical\ part\ of\ cyclone$

This is only theoretically possible and cut point diameter d_{pc} was calculated.

Eq. 10

$$d_{pc} = \sqrt{\frac{9\mu b}{2\pi N_e V_i \left(\rho_p - \rho_g\right)}}$$

The efficiency of cyclone is given by :

Eq. 11

$$\eta_i = \frac{1}{1+\left(d_{pc}/d_{pa}\right)^2}$$

d_{pa}= actual diameter of particle in size range a (m)

2.4.1.2 *Iozia and Leith Model.*

Iozia and Leith [33] developed a logistic model based on Barth [31] model. It considers simple force balance on particle in cyclone. It assumes that centrifugal force and drag force act on particle and balance each other. The collection efficiency η_i is given by Eq. 12.

Eq. 12

$$\eta_i = \frac{1}{1+\left(d_{pc}/d_{pa}\right)^\beta}$$

β is the slope parameter and it is derived from experimental results of cyclone with diameter 0.25 m .

Eq. 13

$$\beta = 0.62 - 0.87\ln\left(\frac{d_{pc}}{100}\right) + 5.21lm\left(\frac{ab}{D^2}\right) + 1.05\left[\ln\left(\frac{ab}{D^2}\right)\right]^2$$

d_{pc} is the 50% cut size as defined by Barth[31]

Eq. 14

$$d_{pc} = \left[\frac{9\mu Q}{\pi \rho_p z_c v_{t\,\max}^2} \right]$$

Eq. 15

$$z_c = core\ length\ =\ (H-S) - \left[\frac{H-S}{\left(D/B\right)-1} \right] \left[\left(d_c/B \right) - 1 \right]\ for\ d_c > B$$

$$=\ H\text{ - }S\ for\ d_c < B$$

Eq. 16

$$d_c = core\ diameter\ =\ 0.47D \left(\frac{ab}{D^2} \right)^{-0.25} \left(\frac{D_e}{D} \right)$$

2.4.1.3 *Leith and Licht Model*

In this model proposed together by Leith and Licht [34, 35] takes into account the temperature on top of other factors. It assumes that there is no slip in the tangential direction between the particles and fluid, i.e. both particles and fluid have same tangential velocity. Also, it considers relation VR^n = constant for relation between tangential velocity V and radius R.

The efficiency calculated by this method is given by

Eq. 17.

Eq. 17

$$\eta_i = 1 - \exp\left(-\psi d_p^M \right)$$

Eq. 18

$$M = \frac{1}{1+m}$$

$$m = 1 - \left[\left(1 - 0.67D^{0.14}\right) \left(\frac{T}{283} \right)^{0.3} \right]$$

Eq. 19

$$\psi = 2\left[\frac{KQ\rho_p C'(m-1)}{18\mu D^3} \right]^{\frac{M}{2}}$$

K is the dimension geometric configuration parameter and is estimated based on cyclone configuration. It is typically 402.9 for Standard cyclone, 551.3 for Stairmand cyclone [36] and 699.2 for Swift cyclone [37]. Geometric parameters of each cyclone are presented in Table 1.

Table 1 Geometric Parameter of Various Cyclone [26]

		Standard	Stairmand	Swift
Inlet height	a/D	0.5	0.5	0.44
Inlet width	b/D	0.25	0.2	0.21
Gas exit dia.	D_e/D	0.5	0.5	0.4
Body length	h/D	2.0	1.5	1.4
Cone length	H/D	2.0	2.5	2.5
Vortex finder	S/D	0.625	0.5	0.5
Dust outlet dia.	B/D	0.25	0.375	0.4

In this model a higher geometric configuration parameter means higher predicted efficiency. Also , C' is Cunningham slip correction factor, Q is volumetric flow rate and T is temperature.

2.4.2 *Pressure Drop Empirical Models.*

This section directly mentions the empirical relations represented by formulas derived by various researchers. Details about its derivations are skipped as its out of scope of this research.

Pressure drop across the cyclone is of great importance in a micro scale cyclone separator. The pressure drop significantly affects the performance parameters of a cyclone. The total pressure drop over a cyclone is sum of losses at the inlet, outlet and within the cyclone. Normally most significant pressure drop occurs in the body due to swirl and energy dissipation. We have calculated static pressure drop across the cyclone and compared it with three empirical models, namely Shepherd and Lapple [38], Casal and Martinez [39] and Coker [40]. In all these models the pressure drop is assumed equal to static pressure drop and thus can be compared with our calculations. The pressure drop in a cyclone is proportional to velocity head as depicted by Eq. 20

Eq. 20

$$\Delta P = \alpha \frac{\rho v_i^2}{2}$$

Various empirical models present different values of α. In Shepherd and Lapple [38], α is obtained by static pressure drop given as Eq. 21. In Casal and Martinez [39], α is derived by statistical analysis from experimental data and given by Eq. 22 and for Coker [40] by Eq. 23.

Eq. 21

$$\alpha = 16 \frac{ab}{D_e^2}$$

Eq. 22

$$\alpha = 11.3 \left(\frac{ab}{D_e^2} \right)^2 + 3.33$$

Eq. 23

$$\alpha = 9.47 \frac{ab}{D_e^2}$$

These equations of empirical formulas for efficiency and pressure drop will be used to compare our results obtained from computational fluid dynamics approach

CHAPTER 3

COMPUTATIONAL FLUID DYNAMICS

3.1 Introduction

Computational Fluid Dynamics (CFD) is a branch of fluid mechanics that uses computational techniques like numerical methods and algorithms to simulate various phenomenon associated with fluid flow. It has emerged a third approach in fluid mechanics after experimental and theoretical fluid mechanics. Advancement in computing technology and development of efficient numerical schemes has propelled the field of CFD. It has helped us simulate complex phenomenon, like turbulence, shock waves, phase transformation and heat transfer, occurring within the fluid flow. CFD involves solving various partial differential equations (PDE's) that govern the fluid flow with the ultimate goal of understanding the physical events occurring in and around fluid flow.

It has wide range of applications starting from aerodynamics to biotechnology. Whatever the application might be, carrying out a CFD analysis involves following general steps.

3.1.1 Problem Formulation and Geometric Modeling

The first thing that needs to be done is defining the geometry and evaluating the conditions under which the analysis is to be done. Various geometric modeling tools like

Pro-E, Solidworks, etc. are available to prepare geometry for a given problem. The design is obtained from various studies or based on experience and available results. The problem is then specified in terms of objectives and constrains like flow conditions to be considered like velocity of flow, Reynolds number, etc , We have used Pro-E for solid modeling.

3.1.2 Meshing

Mesh generation or grid generation can be defined as division of a given domain in to number of well defined elements. Numerous grid generators are available in market. Grids are classified as structures, unstructured and mixed grids. Grid generation is a very important step in CFD analysis as the results obtained are directly affected my quality of grid, type of grid and type of grid elements. Pointwise was used for grid generation in this research.

3.1.3 Defining Input Parameters and Solver Controls

Various parameters like boundary conditions, initial conditions, fluid properties, etc. are defined. Solution strategy is defined. The strategy for performing the simulation involves determining such things as the use of space-marching or time-marching, the choice of turbulence or chemistry model, and the choice of algorithms. Level of accuracy required is also set depending on the problem in question.

3.1.4 Flow Simulation

Simulation is then performed by various methods depending upon the available resources. The simulation is performed with various possible options for interactive or batch processing and distributed processing. FLUENT, a finite volume code was used for flow simulations in this research.

3.1.5 Post- Processing

The results are then processed depending upon the requirement of problem. Various properties like lift, drag, forces, pressure, temperature, etc. are extracted in desired form from the results. Post processing of results in this research was done using TecPlot.

This whole process may be repeated to carry sensitivity analysis or to see the change in results based on change in various input parameters or geometric variations.

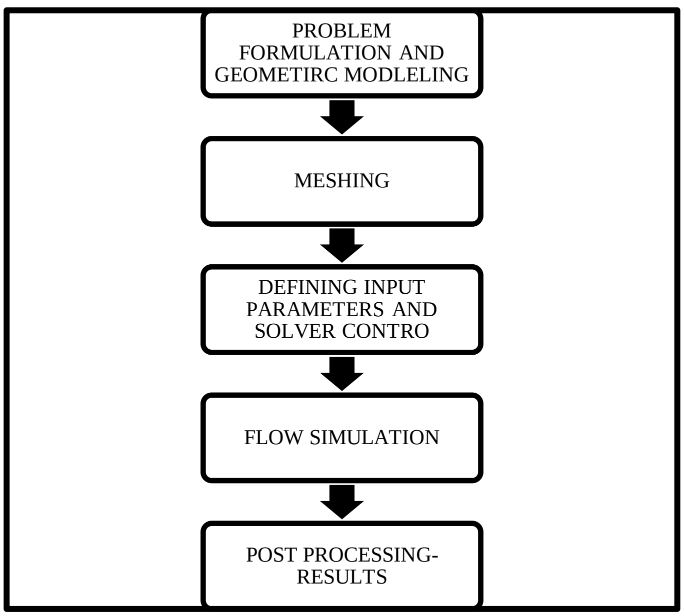

Figure 12 Steps in CFD Analysis

3.2 Governing Equations

The basic fundamental equations behind all CFD problems are Navier-Stokes Equations, which govern almost every single-phase fluid flow. These equations are mainly partial differential equations which define mass, moment and energy flow conservation through a medium like fluid or solid. The CFD governing equations shows the mathematical representations of the conservation laws of physics. It is derived in the numerical form to calculate the nature of fluid flow. For the flow analysis of a model various equations are required depending on the type of flow conditions experienced and requirement of measurement of engineering quantities. The equations that are actually solved numerically are not exactly original equations. They are a bit modified and hence referred to as modified PDE's.

As the flow to be simulated in the cyclone separator is considered laminar, incompressible and steady state flow. The Navier-Stokes equations are presented considering this nature of flow. Also, particle transport equation for spherical particles is considered as all the particles are assumed to be spherical in nature. . The governing equation for the velocity field in incompressible fluid is described by Navier-Stokes equation and mass continuity equation. The particle affected by fluid motion is represented by particle transport equation for spherical particles.

3.2.1 Mass Conservation equation

Mass conservation law states that neither mass can be created or nor mass can be destroyed, it's only transferred. By applying these laws to 3D control volume, we can get the following conservation equation for 3D, steady and incompressible flow.

Eq. 24

$$\frac{\partial \rho}{\partial t} + \nabla . \left(\rho \vec{v} \right) = 0$$

3.2.2 Momentum Equation

Newton's second law of motion states that sum of forces acting on a fluid volume must be same as both input and output. Momentum equations in CFD are also derived using the same principle. Each term is specified in the equation itself.

Eq. 25

$$\rho\left(\underbrace{\frac{\partial\vec{v}}{\partial t}}_{\substack{unsteady\\acceleration}} + \underbrace{\vec{v}.\nabla\vec{v}}_{\substack{convective\\acceleration}}\right) = \underbrace{-\nabla p}_{\substack{pressure\\ \text{gradient}}} + \underbrace{\rho\vec{g}}_{\substack{gravitational\\force}} + \underbrace{\vec{f}}_{\substack{other\\forces}}$$

3.2.3 Particle Transport Equation

FLUENT predicts the trajectory of a discrete phase particle (or droplet or bubble) by integrating the force balance on the particle, which is written in a Lagrangian reference frame. This force balance equates the particle inertia with the forces acting on the particle, and can be written as Particle transport equation as presented below.

Eq. 26

$$\frac{p}{6}d_p^3\rho_p\frac{\partial\vec{v}_p}{\partial t} = \frac{p}{6}d_p^3\rho_p F_D\left(\vec{v}-\vec{v}_p\right) + \frac{p}{6}d_p^3\rho_p\frac{\vec{g}\left(\rho_p-\rho\right)}{\rho_p} + \vec{F}$$

where,

$$F_D = \frac{18\mu}{\rho_p d_p^2} \frac{C_D \mathrm{Re}}{24}$$

$$\mathrm{Re} = \frac{\rho d_p \left| \vec{v}_p - \vec{v} \right|}{\mu}$$

The C_D is drag coefficient and is calculated for Eq. 27 where constants a_1, a_2, and a_3 apply to smooth spherical particles over several ranges of R_e give by Morsi and Alexander [41] Also, $\vec{F}$ is the additional force in the particle force balance that can be important in certain circumstances. For our case the additional forces arise due to pressure gradient in fluid and can be expressed by Eq. 28 and virtual mass force required to accelerate the fluid surrounding the particle can be written as expressed in Eq. 28

Eq. 27

$$C_D = a_1 + \frac{a_2}{R_e} + \frac{a_3}{R_e^2}$$

Eq. 28

$$\vec{F}_x = \left(\frac{\rho}{\rho_p} \right) \vec{v}_{p_i} \frac{\partial \vec{v}}{\partial x_i}$$

Eq. 29

$$\vec{F} = \frac{1}{2}\frac{\rho}{\rho_p}\frac{d}{dt}\left(\vec{v} - \vec{v}_p\right)$$

Eq. 24 to Eq. 27 are the equations build in FLUENT and Eq. 28 and Eq. 29 are user defined.[42]

CHAPTER 4

MICRO CYCLONE SEPARATOR-DESIGN AND CFD ANALYSIS

4.1 Micro-cyclone separator design

The prime consideration during design of micro cyclone was to make it simple, cheap and as easy to manufacture as possible without need of specialized manufacturing techniques. The solid modeling of micro scale cyclone separator was done in Pro-E modeling software. The design is inspired from simple cyclone but differs greatly from it. The conical portion of the cyclone is omitted to make the design as simple as possible. As seen from Figure 14 on page 31 the design is really simple and easy to manufacture. The inlet and outlet vents are equal in dimensions and the swirl collector is in the bottom rather than the top. The design was not obtained from any optimization study but was inspired from previous literature and trial and error method. Pro-Engineering is parametric, feature-based, associative solid modeling software by Parametric Technology Corporation (PTC). Although it provides integrated 3D CAD/CAM/CAE features, only solid modeling capabilities were utilized for the purpose of this thesis. Figure 14 on page 31 gives us the dimensional drawing of the micro cyclone. Data is presented in Table 2

.

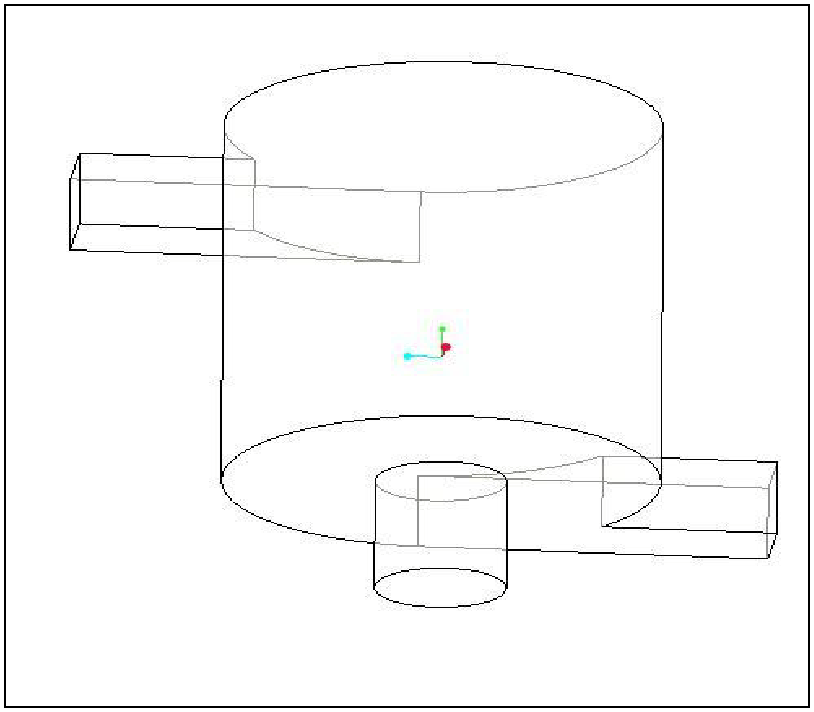

Figure 13 Micro-Cyclone Model

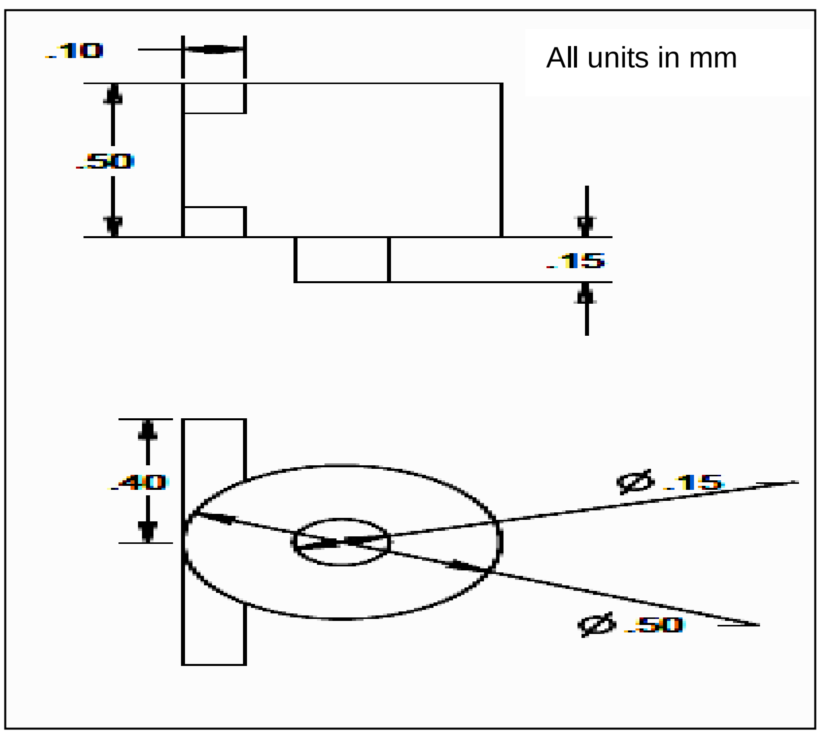

Figure 14 Micro-Cyclone Design

Table 2 Micro Cyclone Geometry Data

Parameter	**Value in mm**
Body diameter	0.5
Length	0.5
Inlet height	0.1
Inlet width	0.1
Flow outlet diameter	0.15
Outlet height	0.1
Outlet width	0.1

4.2 Grid Generation

Pointwise software by company Pointwise Inc. was used to generate an unstructured tetrahedral grid. Tetrahedral unstructured grid is generated in Pointwise by modified Delaunay method. There were 123559 tetrahedral cells in the grid. Figure 15 on page 33 shows the meshed micro cyclone separator. This mesh is then transported to FLUENT for CFD analysis.

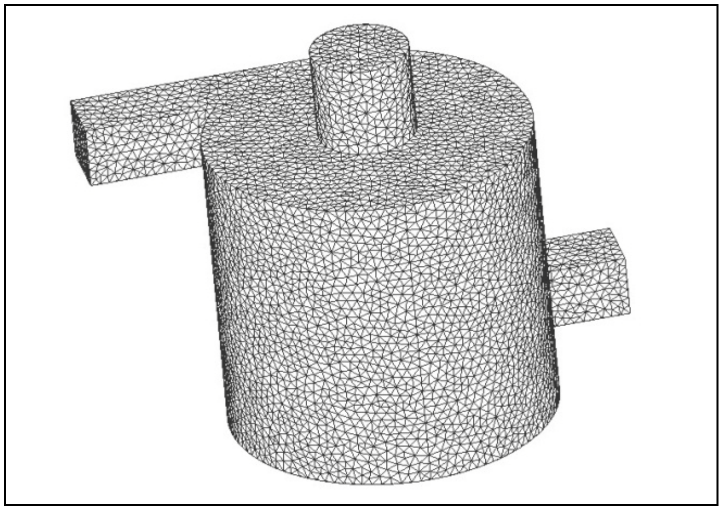

Figure 15 Unstructured Grid

4.3 CFD Analysis

FLUENT, a finite volume code, commercially available by ANYSY, Inc. was used for the purpose of flow analysis. ANSYS FLUENT is pioneer in commercially available finite volume code and has exceptional capabilities for solution to complex physical models on unstructured grids.

The flow in micro cyclone is laminar and the Reynolds number is never greater than 120. Thus for this low velocity and incompressible flow, a pressure based solver is selected. Moreover coupled method for pressure-velocity coupling is used.

4.3.1 Finite Volume Method

Finite Volume Method, popularly known as FVM , is a numerical method for solving partial differential equations that calculates the values of the conserved variables averaged across the volume. One of the major advantages of FVM is that it inherently ensures that the equations (mass, moment and energy) are conserved in discrete fashion. This can be achieved in other methods like Finite Difference but it is obtained naturally in FVM. FVM is also very well suited or unstructured grid as no coordinate transformation is required in FVM. Also, the finite volume method is beneficial to other methods due to the fact that boundary conditions can be applied noninvasively. This is true because the values of the conserved variables are located in the volume element, and not at nodes or surfaces. This makes FVM most popular method for fluid analysis. FLUENT is a finite volume code which is used for analysis in this research.

4.3.2 Pressure Based Solver

Pressure based approach was initially developed for solution of problems involving low-speed and incompressible flows although extensive reformulation has been made to use this approach for all types of flows. As our analysis involves both, low speed and incompressible flows, pressure based solver was the best choice for our analysis. In pressure based approach, the velocity field is obtained from momentum equations and the pressure field is obtained by solving pressure equation or corrected pressure equation obtained from manipulating continuity and momentum equations. Pressure-based solver in uses projection method algorithm [43] in which mass conservation of velocity field is obtained by solving pressure or pressure correction equation. The velocity field is corrected by pressure and is made to satisfy continuity equation which in turn gives us pressure equation from continuity and momentum equations. As the equations are coupled, the solution is essentially a process involving iterative process of solving equations until convergence criteria is satisfied. Pressure based coupled solver was used for solving the flow equations. Coupled method for pressure-velocity coupling is found to give more robust solution for steady state flows [44]. Figure 16 below shows algorithm for pressure based solver utilizing coupled approach for pressure-velocity coupling.[44]

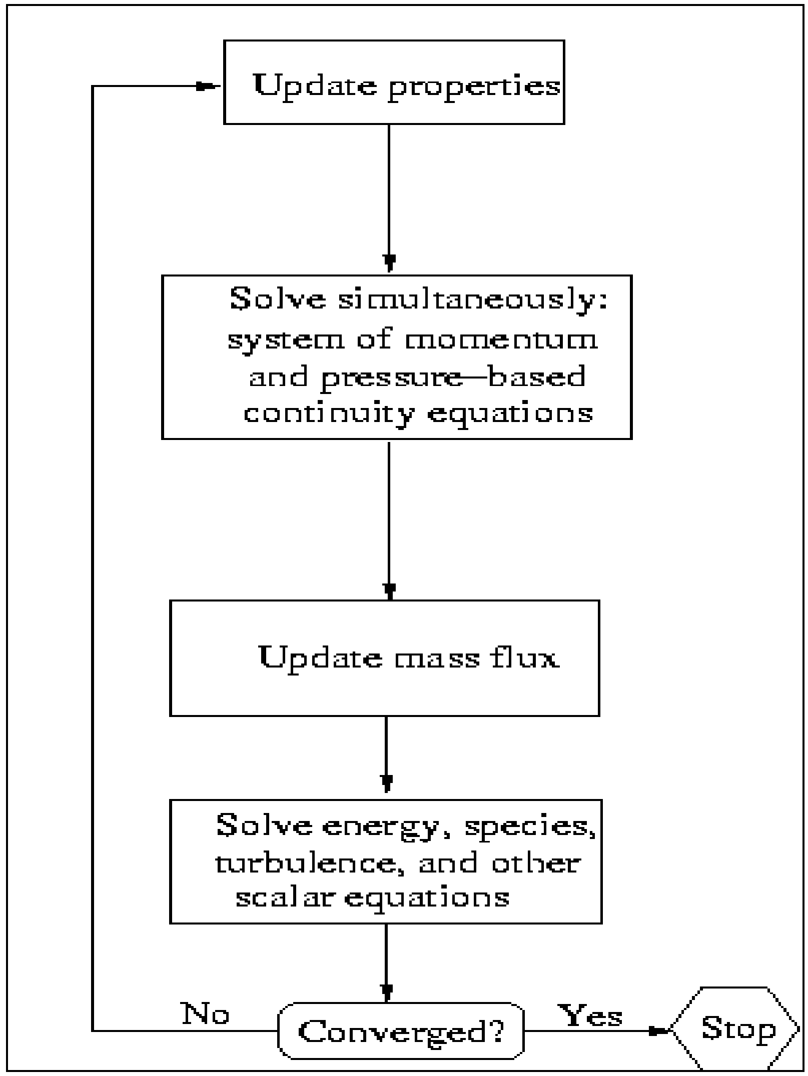

Figure 16 Pressure-based Coupled Algorithm [42]

4.3.3 *Flow Parameters and Fluid Properties*

A laminar, inviscid and incompressible flow of fluid Air is considered in analysis. The properties of Air are tabulated in Table 3

Table 3 Material Properties of Air

Property	**Units**	**Method**	**Value(s)**
Density	Kg/m^3	constant	1.225
Cp(specific heat)	j/kg-k	Constant	1006.43
Thermal conductivity	w/m-k	Constant	0.0242
Viscosity	Kg/m-s	Constant	1.7894007e-05
Molecular weight	Kg/kgmol	Constant	28.966

4.3.4 *Boundary Conditions*

Effect of velocity on pressure difference and swirl produces is to be determined. Hence, velocity inlet condition and pressure outlet condition are utilized in the modeling. Velocity is varied and then static pressure difference is observed. Wall conditions for surfaces of cyclone and fluid condition for interiors of cyclone was set up.

4.3.5 *Velocity Inlet*

Velocity inlet boundary conditions are used to define the flow velocity, along with all relevant scalar properties of the flow, at flow inlets. The total properties of the flow are not fixed, so they will be adjusted whatever value is necessary to provide the prescribed velocity distribution. Both velocity defined at the inlet boundary condition and scalar quantities defied on the boundary are used by FLUENT to compute mass flow rate, momentum fluxes, etc. at the inlet. The mass flow rate is given by *Eq. 30*. [44]. It is worth noting that only normal component of velocity to volume face contributes in mass flow rate.

Eq. 30

$$\dot{m} = \int \rho \vec{v}.d\vec{A}$$

4.3.5.1 Pressure Outlet

FLUENT uses the boundary condition pressure you input as the static pressure of the fluid at the outlet plane and extrapolates all other conditions from the interior of the domain. Default condition for pressure outlet, i.e. 0 gauge pressures was implemented.

4.3.5.2 *Solution Controls*

Solution parameters like Courant Number, Under Relaxation Factors, and discretization schemes are manipulated in FLUENT to obtain stable solution as fast as possible. Each of these parameters is discussed below.

4.3.5.3 Under-Relaxation Factors

FLUENT solver uses the under relaxation factors to control the effect of previous iteration on current iterations. Only non-coupled equations use under relaxation factors in coupled solver flow analysis problem such as this analysis problem. Following equation shows the relationship between the under-relaxation factor (α) and the scalar value (ϕ) and resulted change in scalar value (∆ϕ). Table 4 gives list of default values of under-relaxation factors used in this analysis. As seen no relaxation is done for density and forces where as momentum and pressure have been under relaxed by a factor of 0 .75. These are typically defaults and have been found to give a stable solution at faster convergence rate and also reduce numerical dissipations.

Eq. 31

$$\phi_{new} = \phi_{old} + \alpha\Delta\phi$$

Table 4 Relaxation Factors

Parameter	**Value of Under-Relaxation Factor**
Density	1
Body Forces	1
Momentum	0.75
Pressure	0.75

4.3.5.4 Discretization Schemes

A second order discretization was used for pressure equations and a second order upwind scheme was used to discretize momentum equations. Initial calculations were done using first order schemes but final analysis for accurate results was done using second order of discretization.

4.3.5.5 Courant Number

The set of governing equations are discretized with time for both unsteady and steady analysis for flow analysis. But in only steady state analysis the solution proceeds with time until steady state solution with convergence is reached. So, Courant number represents a relaxation factor in steady state analysis. Here Courant Number defined in

Eq. 32 gives the largest velocity component in a given cell (u), time step (Δt) and cell size (Δx) in the direction of velocity. It also helps to decrease numerical diffusion and improve accuracy of the solution. Courant number of 50 was defined in our analysis.

Eq. 32

$$CourantNumber = u\frac{\Delta t}{\Delta x}$$

4.3.6 *Discrete Phase Modeling (DPM)*

A discrete phase consisting of spherical particles of anthracite dispersed in the fluid –Air are considered for the purpose of analysis of cyclone efficiency. FLUENT allows us to simulate a discrete second phase in a Lagrangian frame of reference. This second phase consists of spherical particles dispersed in the continuous phase. FLUENT computes the trajectories of these discrete phase entities. The coupling between the phases and its impact on both the discrete phase trajectories and the continuous phase flow can be included. The fundamental assumption made in this DPM is that the second phase has very low volume fraction compared to primary phase. Equations for particle motion have been discussed in detail in earlier CHAPTER 3. Spherical particles of anthracite with diameter of 1 x 10^{-7} m were defined to be injected normal to the inlet boundary. Anthracite was considered to be inert as no interaction with air was needed to be modeled. A group injection of particles was considered and fixed diameter was set. A boundary condition of trap was set for flow outlet. This enabled us to calculate the mass of particles passing through that outlet and hence calculate cyclone efficiency.

CHAPTER 5

CFD ANALYSIS RESULTS

Computational Fluid Dynamics approach is used to simulate the flow within the micro cyclone. Pressure drop is a major factor contributing towards the collection efficiency of a cyclone. The effect of inlet velocity on pressure drop is the micro cyclone is observed. As the flow is laminar with Re less than 120 in all the cases, no turbulence model is used in analysis. The prime objective of the study is to observe the effect of velocity on pressure drop and cyclone efficiency. Also, a cyclone cut off particle size is found out. These results are compared to empirical relations available.

5.1 Effect of Inlet Velocity on Swirl and Pressure drop

Inlet velocity is a major factor affecting the swirl in cyclone separator. The amount of swirl affects the pressure gradient created in the particle. Pressure gradient is a very important factor effecting the force balance on the particles and hence the collection efficiency of a cyclone separator. Thus, inlet velocity becomes a major parameter effecting cyclone collection efficiency. In this first study, size of particles is kept constant at 1×10^{-7} m and inlet velocity is varied from 2 m/s to 14 m/s. Effect of increase in velocity is observed on pressure drop, flow field and swirl in the micro cyclone.

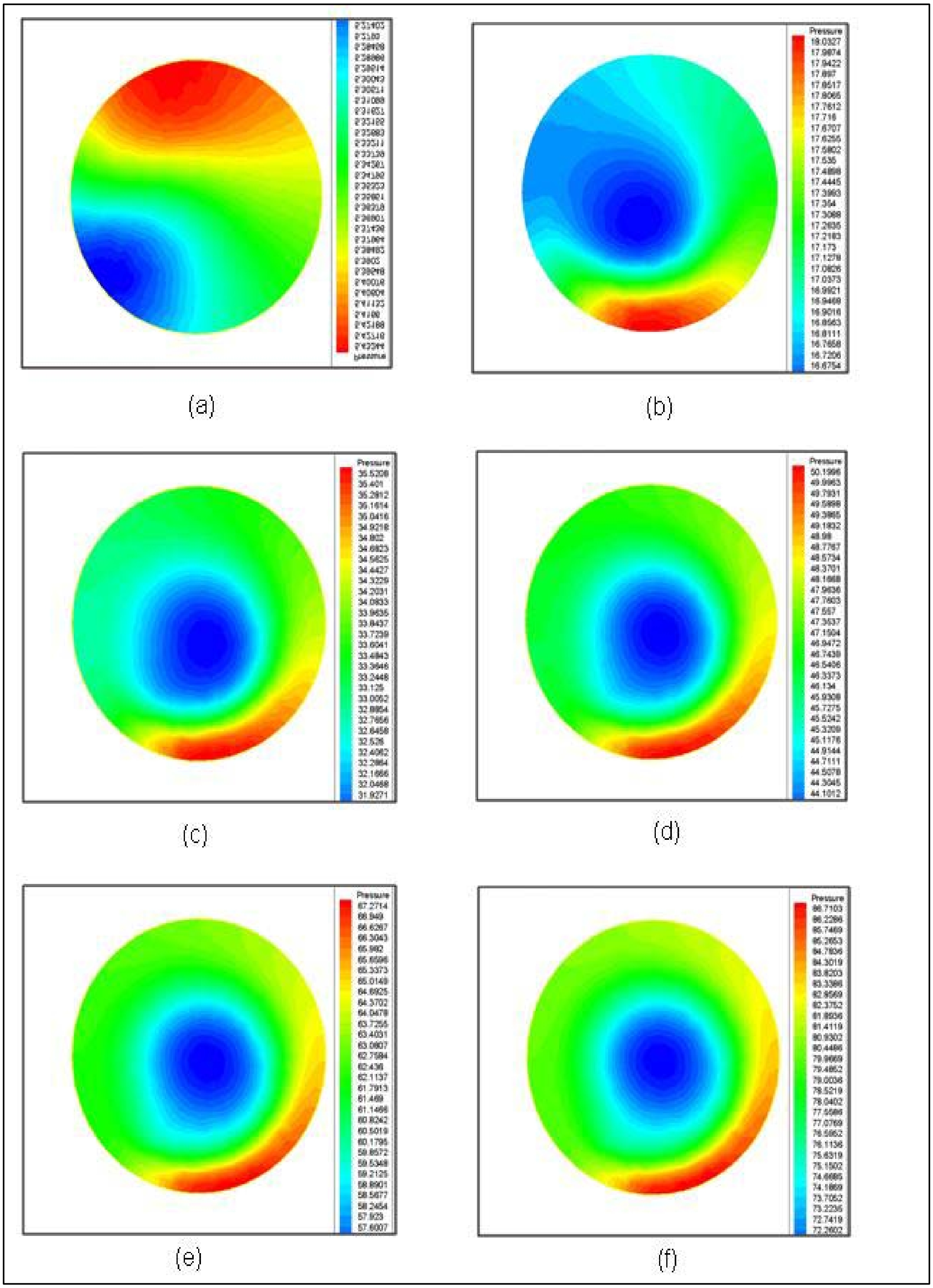

Figure 17 Pressure Contours on a transverse section at mid height for (a) v=2 m/s, (b) v=5 m/s, (c) v=8 m/s, (d) v=10 m/s, (e) v=12 m/s, (f) v=14 m/s

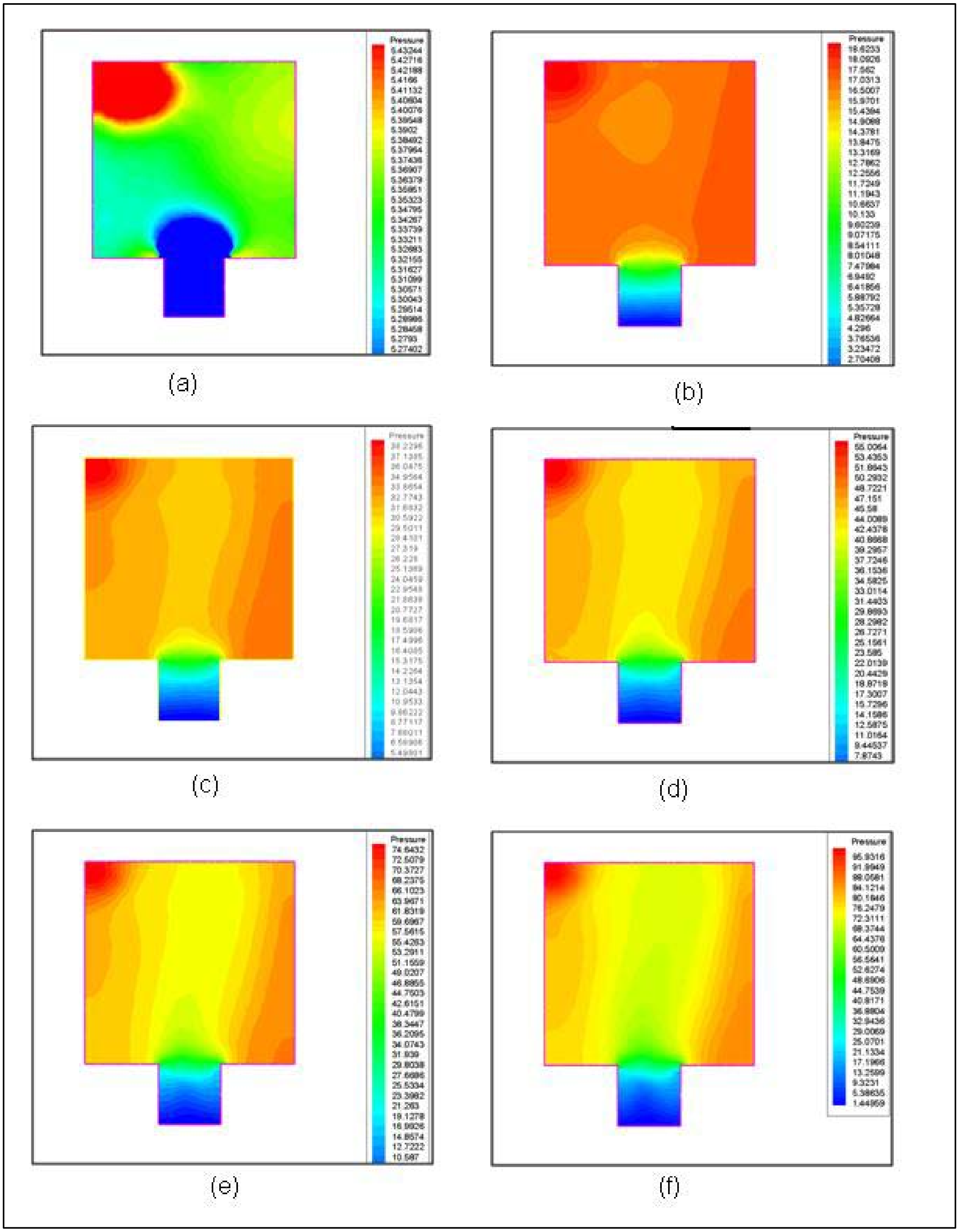

Figure 18 Pressure Contours on a longitudinal section at mid cylinder for (a) v=2 m/s, (b) v=5 m/s, (c) v=8 m/s, (d) v=10 m/s, (e) v=12 m/s, (f) v=14 m/s

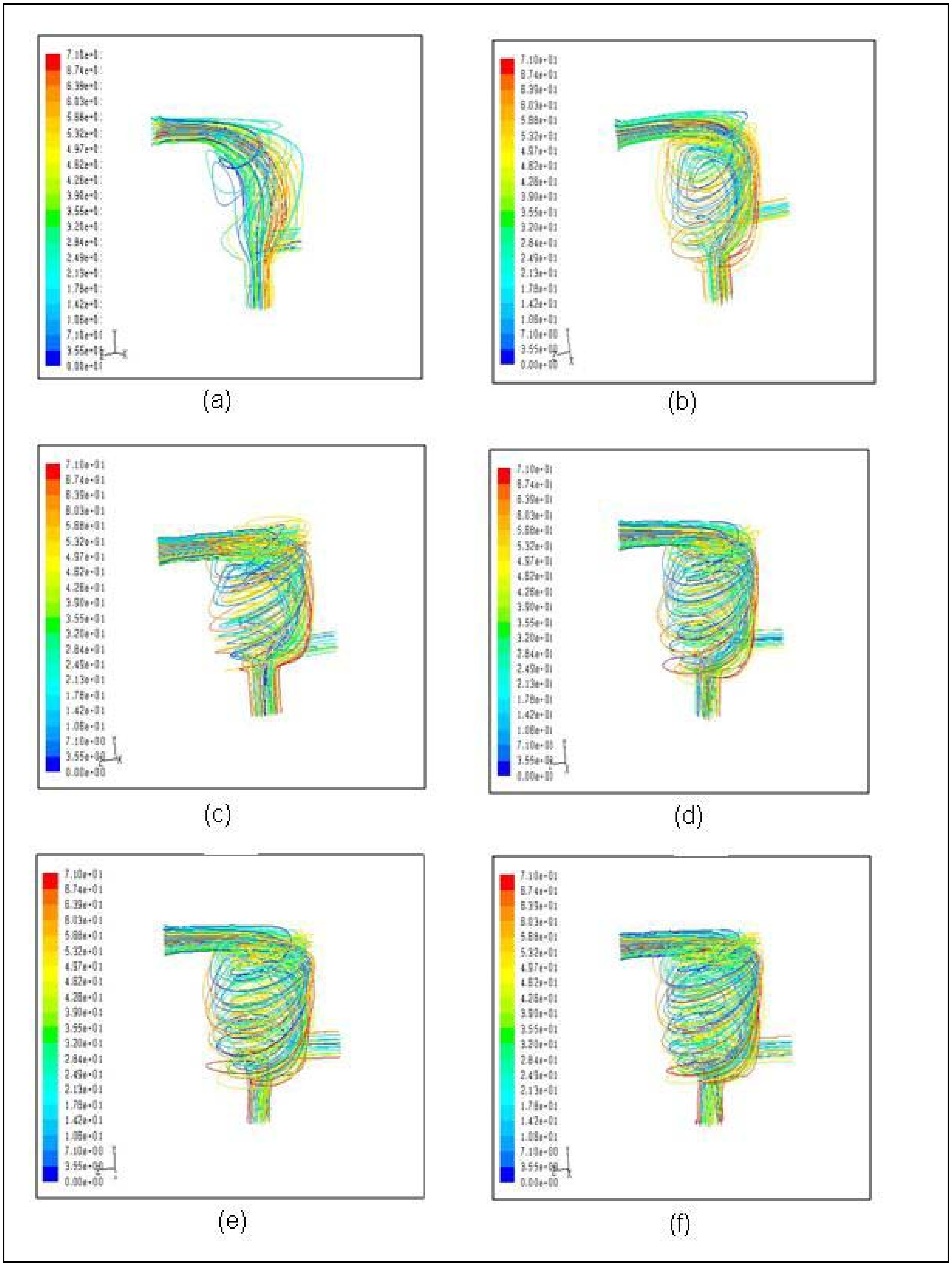

Figure 19 Streamlines of particles released from inlet for (a) v=2 m/s, (b) v=5 m/s, (c) v=8 m/s, (d) v=10 m/s, (e) v=12 m/s, (f) v=14 m/s

Figure 17 and Figure 18 show the pressure contours at transverse and longitudinal mid sections of micro cyclone for velocities increasing from 2 m/s to 14m/s. It can be clearly seen that no significant pressure gradient is developed for low velocities. For inlet velocity of 2 m/s , there is almost uniform pressure gradient. As inlet velocity increases the pressure gradient increases. For velocity of 12 m/s and 14 m/s, a clear zone of low pressure can be observed in the center. This is also verified by development of greater amount of swirl as seen from Figure 19 which depicts increasing swirling motion in the micro cyclone with increase in inlet velocity.

The velocity vectors as seen at mid transverse section are presented in Figure 20 and Figure 21 for inlet velocity 2 m/s and 14 m/s sec respectively.

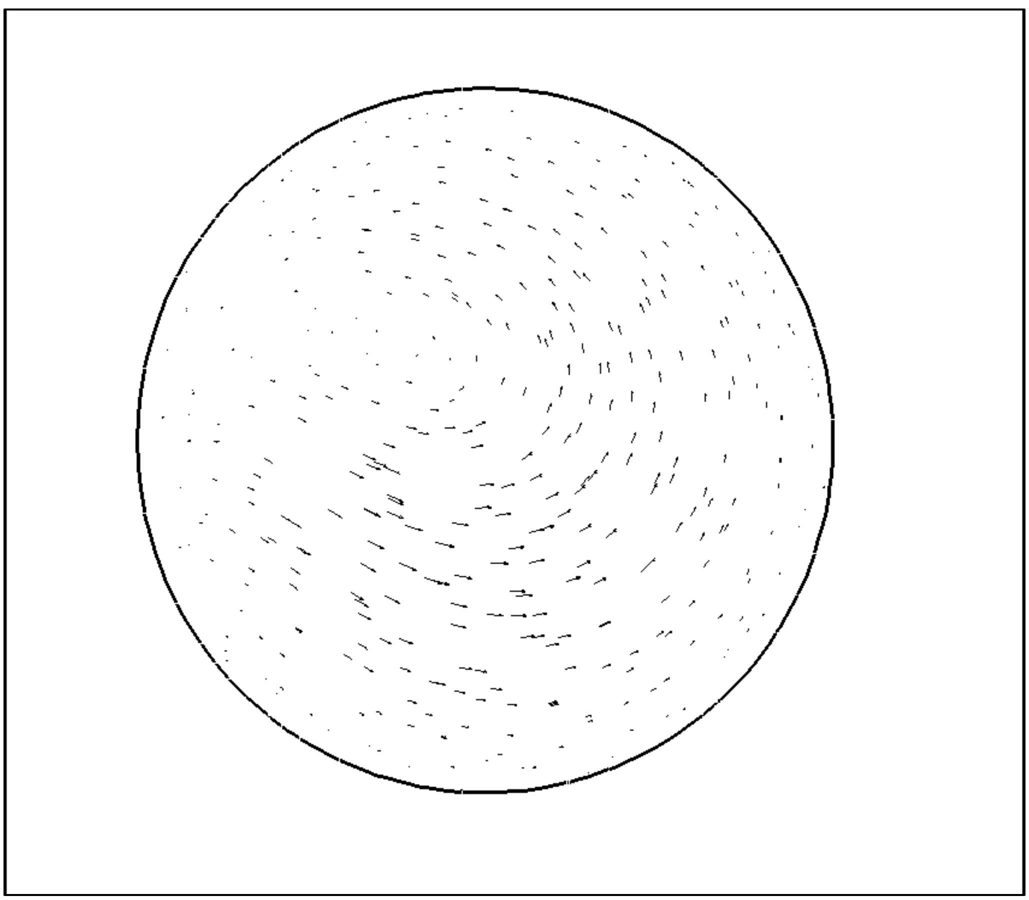

Figure 20 Velocity vectors at mid transverse section for velocity 2 m/s

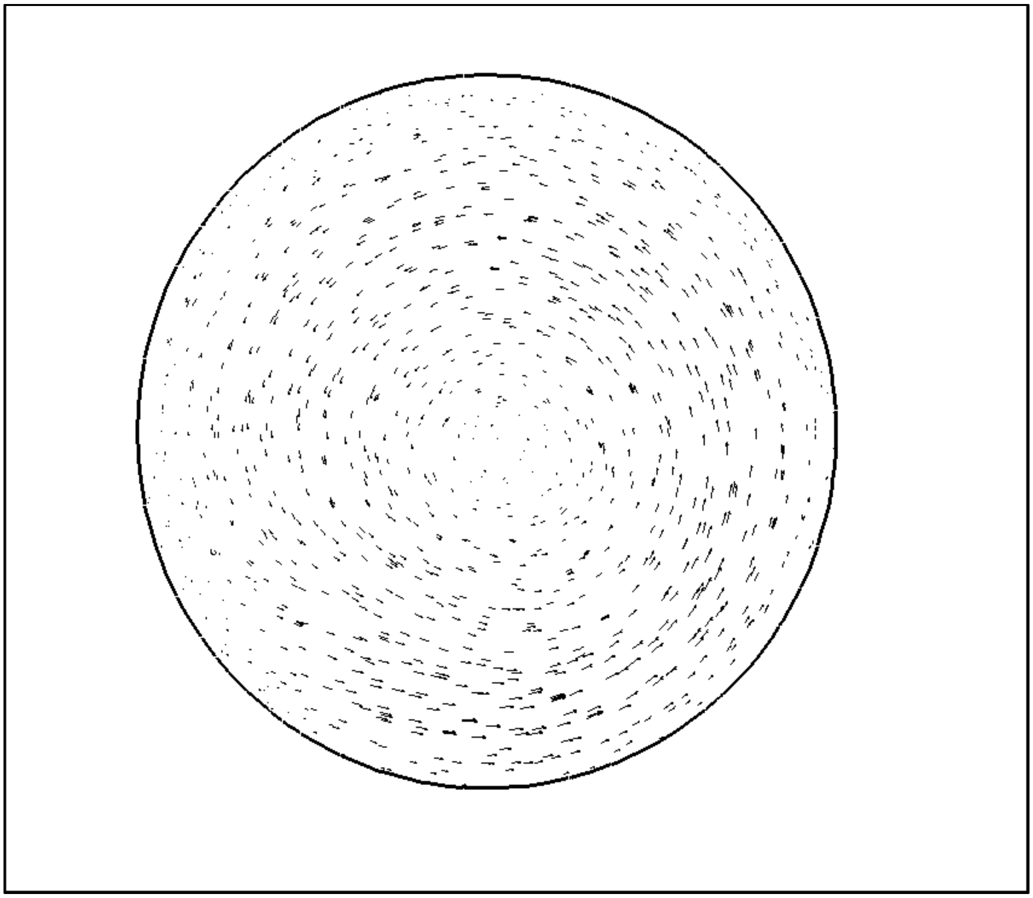

Figure 21 Velocity vectors at mid transverse section for velocity 14 m/s

It is easily observed that vectors are haphazardly distributed for velocity of 2 m/s. This is because of the fact that no significant swirling motion is yet developed. On the contrary for inlet velocity of 14m/s a clear circular orientation of velocity vectors reinforce the fact that a good swirling motion of fluid is developed which, as will be seen later, would give better collection efficiency.

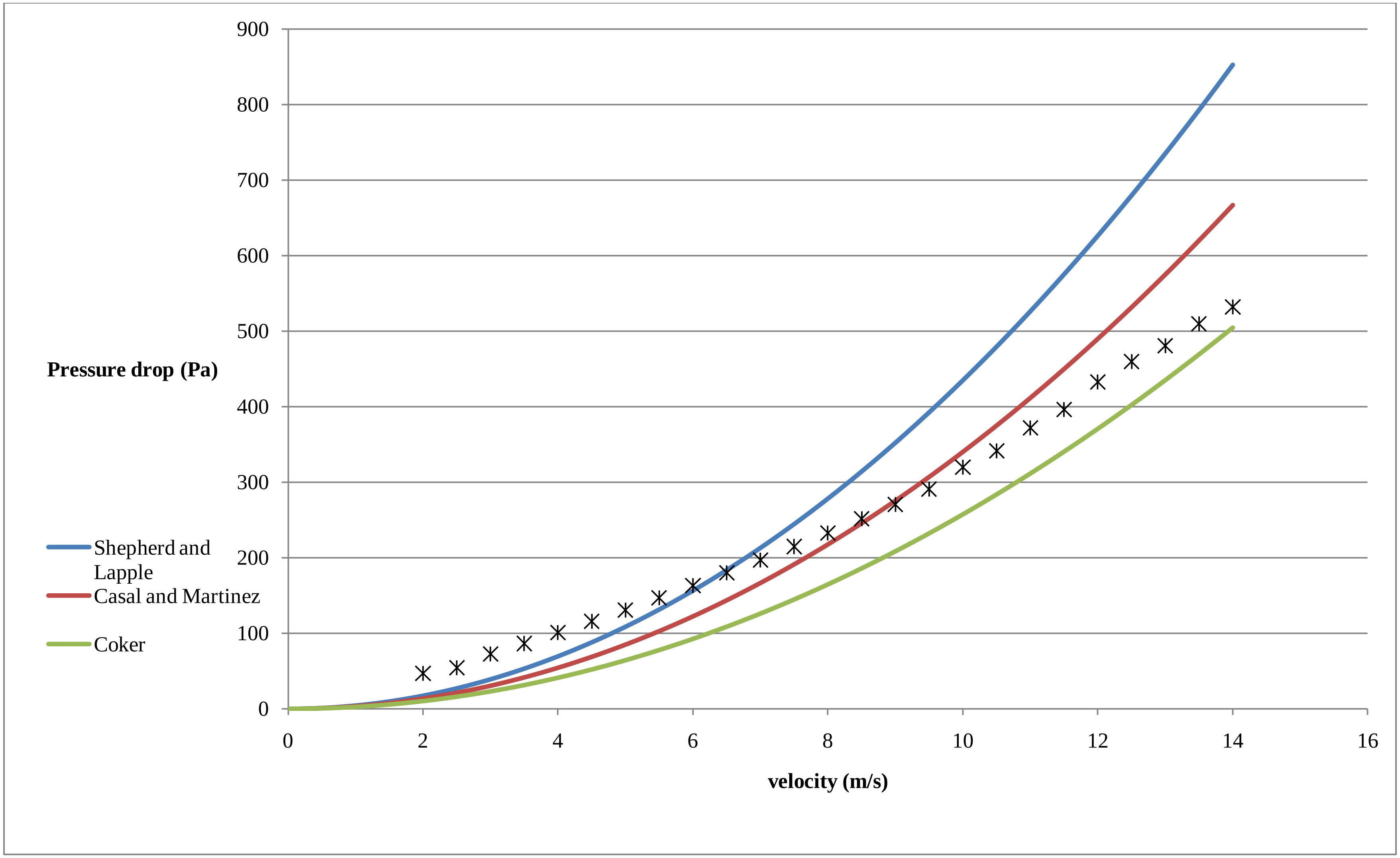

Figure 22 Effect of inlet velocity on cyclone static pressure drop- Comparison with empirical model

Figure 22 shows a comparison of results obtained by CFD analysis with three empirical relations obtained by Shepherd and Lapple [38], Coker and Martinez [39] and Coker [40]. All of these models have been discussed in detail in section on pressure drop empirical models on page 20. Figure 22 compares the results of increase in pressure drop of cyclone with increase in inlet velocity. Although a constant increase is found in the pressure drop for micro cyclone as seen in Figure 23 Absolute inlet pressure vs. Inlet Velocity Graph) , it does not follow any one specific empirical relation (Figure 22). This can be due to the fact that all these empirical relations were developed for larger cyclones. Also, the Reynolds number associated with flow is very small (less that 120) and so the flow is always laminar. Turbulence in the flow is a major contributor towards the pressure drop developed and as there is no turbulence at all in the flow, the increase in pressure drop is more linear in nature that quadratic. Also, it can be inferred that CFD results match Shepherd and Lapple model for velocities lower that 7.5 m/s, they are close to Casal and Martinez model for mid velocities between 7.5 m/s to 12.5 m/s, whereas the pressure drop values match Coker model for velocities higher than 12.5 m/s with a maximum deviation of around 12%. Table 5 shows the percentage difference in pressure drop as measured by CFD analysis and empirical models for practical velocities. Also, for very less velocities the pressure drop is much higher than expected due to micro scale of cyclone model. But such low velocities are not beneficial for operation due to low swirl and consequently low efficiencies. The trends in collection efficiencies are discussed in next section.

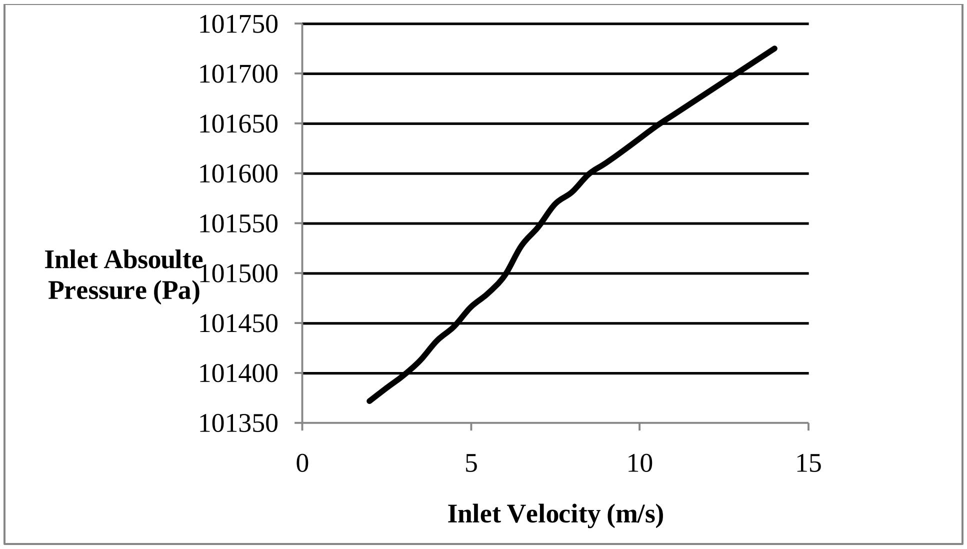

Figure 23 Absolute inlet pressure vs. Inlet Velocity Graph

Table 5 Percent difference between CFD result and Empirical Model of Pressure drop across a cyclone for practical velocities

Velocity (m/s)	Difference in ΔP in %		
	Shepherd and Lapple	Casal and Martinez	Coker
5.5	-11.3946	-42.4173	-88.2062
6	-4.02347	-32.9934	-75.7524
6.5	2.229827	-24.9986	-65.1872
7	7.606275	-18.1248	-56.1034
7.5	12.27825	-12.1517	-48.2099
8	16.37983	-6.9079	-41.2801
8.5	20.01069	-2.26587	-35.1456
9	23.24387	1.867736	-29.683
9.5	25.89315	5.254818	-25.2069
10	26.47237	5.995354	-24.2283
10.5	28.76229	8.923005	-20.3594
11	29.38199	9.715277	-19.3124
11.5	31.09925	11.91079	-16.411
12	30.93546	11.70138	-16.6877
12.5	32.3617	13.52482	-12.278
13	34.59478	16.37981	-10.5051
13.5	35.69007	17.78013	-8.65457
14	37.63353	20.26482	-5.37102

5.2 Cyclone Collection Efficiency Trends

Collection efficiency is the ultimate performance measure of the cyclone. For this micro cyclone, the efficiency is calculated from the results of DPM model in fluent. The mass of particles injected and particle trapped is easily obtained. These mass are used to calculate the efficiency of cyclone and are compared to various empirical relations. The details of these empirical models and efficiency are discussed in Cyclone Efficiency Empirical Models on page 16 of chapter CYCLONE SEPERATOR.

Cyclone collection efficiency is measured for varying the size of particles from 1 x 10^{-7} m. to 7 x 10^{-7} m. and inlet velocity of 12 m/s. This range was chosen considering 50% cut size obtained from literature. It can be seen form Figure 24 that CFD results match closest to the Lapple model. Although, even Lapple model was developed for larger cyclones it had been found to underestimate the efficiency [45]. This better suits micro cyclone model as the efficiency is expected to be less due to size, absence of turbulence and limitations on operational inlet velocities. The cut-off size predicted is 3.5 x 10^{-7} m. This also is in good agreement with that 3.3 x 10^{-7} m. predicted by Lapple model.

Further analysis of effect of inlet velocity on collection efficiency was done considering size of 3.5 x 10^{-7} m and results are presented in Figure 25. It can be seen that there is not much increase in efficiency after operating inlet velocity of 10 m/s. This is due to size limitation on micro cyclone. Due to such a small size even if we increase inlet velocity it does not contribute much on efficiency due to the fact that particles may start colliding and deflected from assumed path. Also the time for which fluid stays in cyclone is so little that there is very less scope of developing higher swirl by increasing velocity after a certain point. as seen from Figure 26 the ratio of mass flow rate at of bottom outlet to side outlet decreases with velocity but even at velocities of 12m/s it is as high as 2.5 and hence it can be concluded that ratio particles to fluid is greater for side outlet and hence it can be used further for multi-cyclone model suggested later.

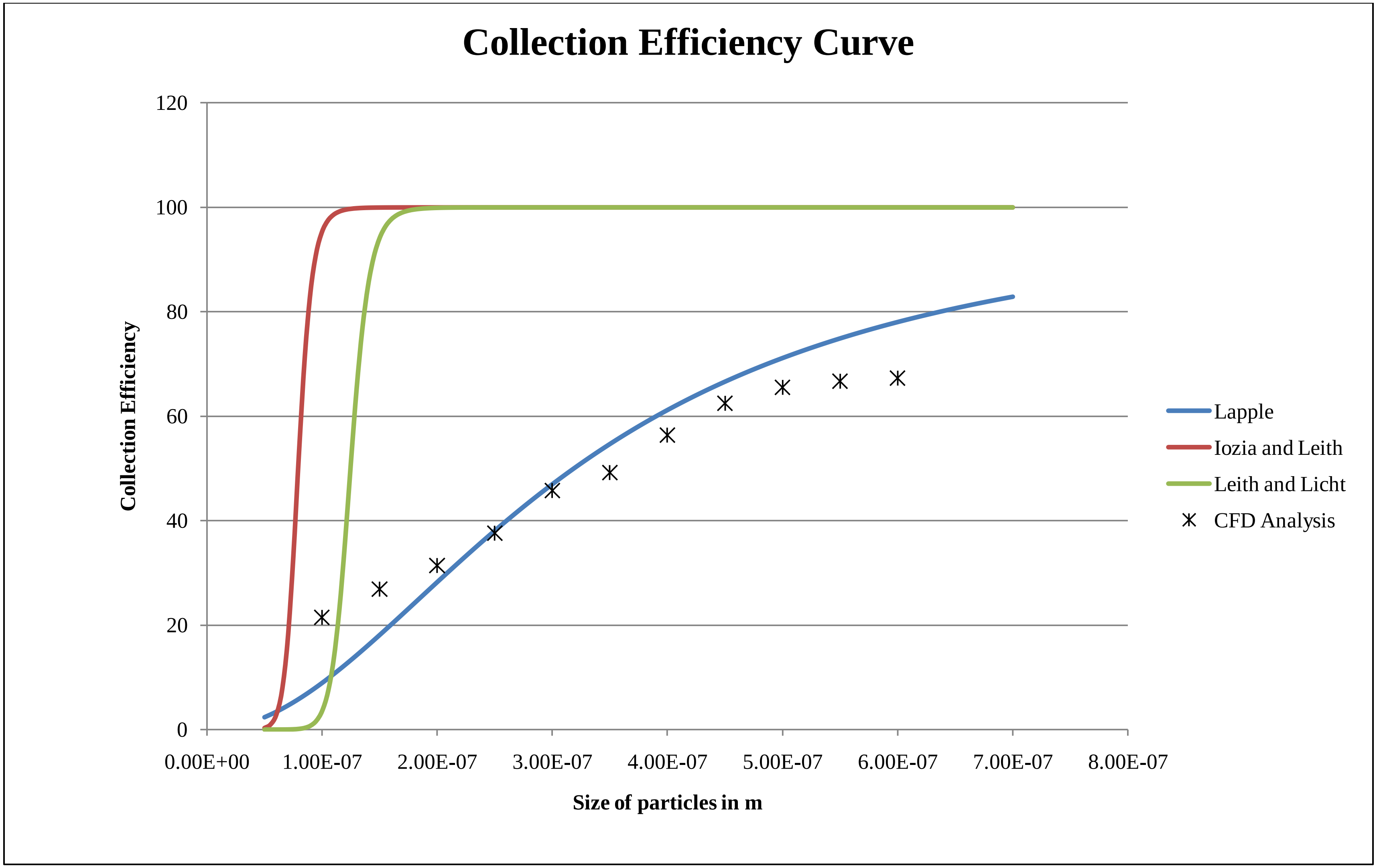

Figure 24 Collection Efficiency Curve- Comparison with Empirical Models

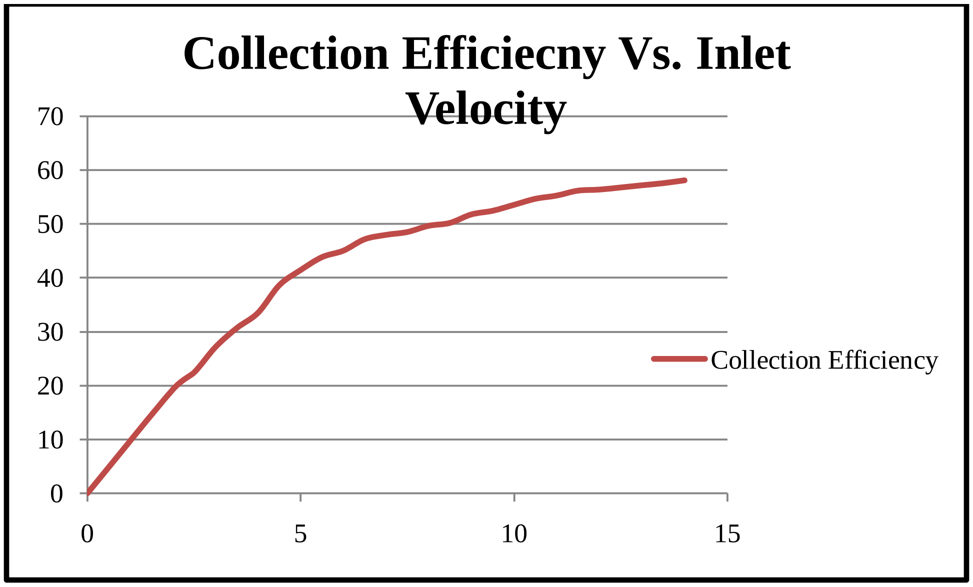

Figure 25 Collection Efficiency vs. Inlet Velocity graph

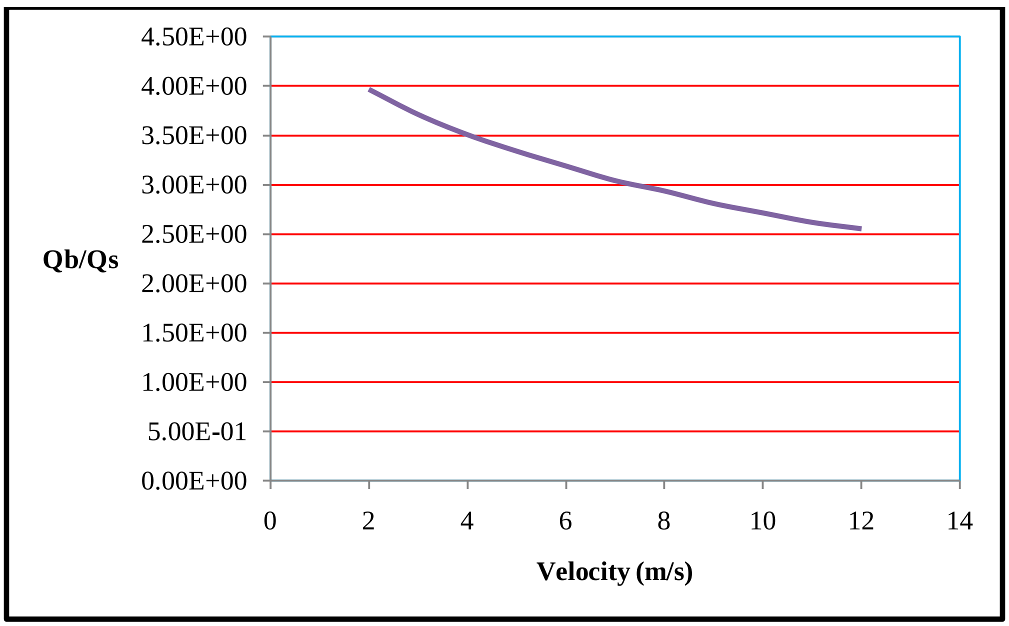

Figure 26 Outflow ration vs. Inlet velocity graph

CHAPTER 6

CONCLUSION

Micro cyclone separator was analyzed using FLUENT CFD code for observing the effect of inlet velocity on pressure drop and collection efficiency. The results were compared to empirical models. Inlet velocity is a major factor affecting the collection efficiency.

Collection efficiency and pressure drop across the cyclone increase with the increase in inlet velocity but the increase in efficiency becomes very negligible after velocity of 10 m/s.

Inlet absolute pressure is of the range of 1 atm. to 1.3 atm. which is manageable and not very high to adversely affect the cyclone performance.

Pressure drop as predicted by CFD does not follow any one empirical relation as all these empirical models were developed by experimentation on larger cyclone separators. However, for higher velocities, which are practical for operation pressure drop is seen to be close to Coker model.

Cut off size is very well predicted by Lapple model which also quite accurately matches the collection efficiency curve obtained from CFD analysis.

Major conclusion here is that the micro cyclone is functional as expected. i.e. it give desired trend in pressure drop and collection efficiency, but does not follow any one model accurately. It can be inferred an empirical model can be developed for micro scale cyclone separator by conducting experiments.

Although having low efficiencies, micro separator with its low cost, simple easy to manufacture design and simple operation has a potential to be developed into a pre-sorting stage for various micro particle separation application.

Table 6 Comparison of Various Microparticle Separation Techniques

	Portability	**Ease of manufacturing**	**Range**	**Efficiency**	**Cost**
Optical Fractionation	poor	moderate	moderate	high	moderate
Electrophoresis	moderate	complex	high	Very high	Moderate- high
Dielectroporesis	moderate	complex	high	Very high	Moderate - high
Magnetophoresis	high	moderate	less	high	High- very high
Micro cyclone separator	high	high	high	Moderate-high	**<$100**

CHAPTER 7

FUTURE RECOMMENDATIONS

This is a primary study and hence lots of work is needed to be done in future for a complete development of this micro cyclone separator. Below are few future recommendations:

- The design was developed from existing literature and trial and error method. The micro cyclone performance is seen not to follow any particular empirical model hence a design optimization study is high recommended. Also, geometry has found to play a great part in cyclone performance and this can be studied only by design optimization studies.
- Efficiency of a single unit of micro cyclone is vey less and micro cyclone can not be employed in practical use with such low efficiencies. .. shows the multi cyclone model developed inspired from Vegini et. al. [46]. This will increase the efficiency of the system. A further studies into characteristics of this system of cyclones needs to be undertaken.
- An empirical model for micro cyclone can be developed from experimental verification of CFD results and further mathematical modeling on the results obtained.

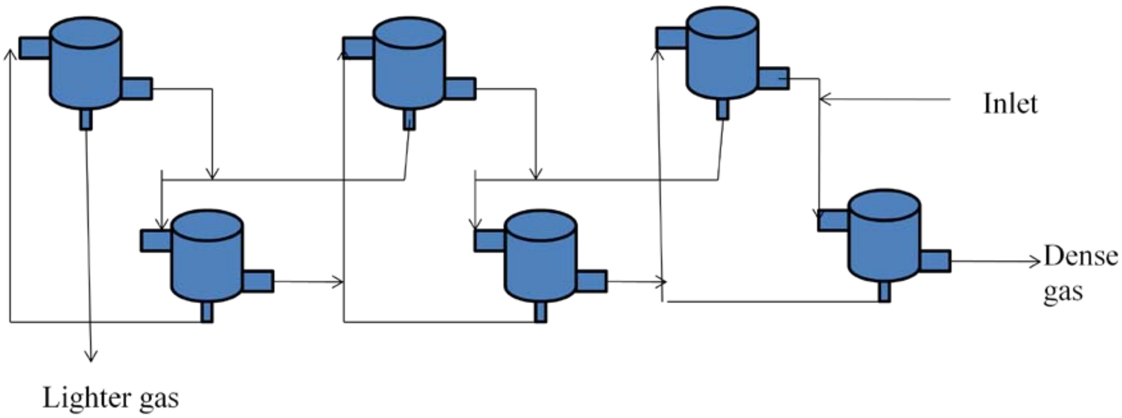

Figure 27 Multi Cyclone Model

APPENDIX A

NOMENCLATURE

A	=	area
a	=	cyclone inlet height
a_i ,i=1,2,3	=	constants for smooth spherical particles given by Morsi and Alexander
b	=	cyclone inlet width
B	=	cyclone outlet diameter
C’	=	Cunningham slip correction factor
C_d	=	drag coefficient
D	=	cyclone body diameter
d_{50},d_{pc}	=	cut off particle diameter collected for 50% efficiency
d_c	=	core diameter
D_e	=	cyclone gas outlet diameter
d_p	=	diameter of particle
d_{pa}	=	diameter of particle in size range a
F	=	additional forces in transport equation
F_b	=	boyant force on particle
F_c	=	centrifugal force on particle
$f_c(x)$	=	mass density distribution for captured particles
F_d	=	drag force
$f_e(x)$	=	mass density distribution for escaped particles
$f_f(x)$	=	mass density distribution for feed particles
g	=	gravitational force
h	=	cyclone cylinder length
H	=	height of cyclone
K	=	dimension geometric configuration parameter
m	=	mass of particle
M_c	=	mass flow rate of particle collected
M_e	=	mass flow rate of particle escaped

M_f	=	mass flow rate of particle feed
N_e	=	number of turns a gas spins in outer vortex
p	=	pressure in fluid
Q	=	volumetric gas flow rate
Q_s	=	mass flow rate of fluid through side outlet
Q_b	=	mass flow rate of fluid through bottom outlet
r	=	radius at which particle is revolving
R_e	=	Reynolds number
r_p	=	radius of particle
S	=	cyclone gas outlet duct length
T	=	temperature
v	=	velocity of fluid
V_r	=	radial velocity of particle
V_t	=	tangential velocity of particle
z_c	=	core length
α	=	velocity head-pressure drop coefficient
β	=	slope parameter
ΔP	=	pressure drop
Δt	=	time step
Δx	=	cell size
η	=	overall efficiency of cyclone
$\eta(x)$	=	grade efficiency of cyclone
η_i	=	cyclone efficiency calculated from empirical models
ρ_f	=	density of fluid
ρ_p	=	density of particle
μ	=	molecular viscosity of fluid

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