DESIGN AND CFD ANALYSIS OF SINGLE AND SYMMETRICAL INLET CYCLONE DUST SEPARATOR

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ABSTRACT

We are using cyclone dust separators for quite a century. Gas-solid cyclone separators are the most frequently used equipment in industries. To enhance the performance of cyclone dust separators, many Computational Fluid Dynamics studies conducted for its wide variety of applications in industries. Computational Fluid Dynamics is a conventional method to forecast the flow and collection efficiency of a cyclone. Primarily three models were used in cyclone simulation K-Epsilon Model, Reynolds Stress Turbulence Model, and Algebraic Stress Model. The K-epsilon turbulence model is the foremost crucial model utilized in computational fluid dynamics analysis to simulate turbulent kinetic and dissipation conditions. Pressure drop in the cyclone separator is one of the most significant functions to be kept in mind while designing the cyclone system. For further improvement in cyclone dust separator, a comparison of the pressure drop in a single and symmetrical tangential input cyclone separator perform theoretically and computational fluid dynamics analysis using the Reynolds stress turbulence model. The result showed that the pressure drop in the symmetric inlet cyclone separator exceeds the single inlet cyclone separator. I also performed the Computational Fluid Dynamics analysis to calculate the efficiency of a cyclone separator with a dust collector using the K-Epsilon Turbulence Model. So far, we all know that the pressure drop in a cyclone separator is directly associated with the tangential velocity of the cyclone separator, which must increase to extend the efficiency of the cyclone. Cyclone efficiency will generally increase with increment in particle size or density, tangential velocity, cyclone body length, and smoothness of the inner wall of the cyclone.

Keyword: *Computational Fluid Dynamics, Pressure Drop, Efficiency Calculation, Symmetrical Inlet Cyclone, Reynolds Stress Turbulence Model*

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1. INTRODUCTION

Cyclone dust separators are pollution control devices designed to extract fine particles from what is also known as dust in an air stream. It consists of a conical shape that utilizes the role of the air vortex to collect dust particles which have proven to be a piece of better settling equipment than gravity. Cyclones do not have any moving parts and are available in many shapes and sizes. It is categorized into two types of orientation, namely vertical and horizontal, and can be set up together as a step or multi-step cyclone separator. In vertical cyclones, air penetrates the equipment tangentially and then forms a vortex as it moves along the conical section. The vortex generates the force that pushed dust particles to maneuver to the walls of the equipment and slides under the influence of gravity. During the design of cyclones, we consider particle size (particles with larger mass subject to greater force), the force exerted on the dust particles, and the time that force exerted on the particles. Discrete levels of collection efficiency and operation can achieve by varying the standard cyclone dimension. There are some limitations of the various models used in cyclone simulation. The K-Epsilon model embraces the hypothesis of isotropic turbulence, so it is unsuitable for flow in a cyclone of anisotropic turbulence. The Algebraic Stress Model cannot predict the recirculation zone and Rankine vortex in strongly swirling flow. Reynolds Stress Model forgoes the hypothesis of isotropic turbulence and solves a transport equation for every component of the Reynolds Stress. It is considered the foremost applicable turbulent model for cyclone flow. Lagrangian and Eulerian techniques are the most commonly used to predict mean particle diffusion in turbulent streams.

2. MODELING

2.1 The Stairmand's High-Efficiency Cyclone Design

In this paper, the cyclone geometry is constructing by using the reference of Stairmand's high-efficiency method. Several experiments were carried out by Stairmand on cyclone dust separator and eventually developed efficient geometrical ratios. The sketching and modeling of the cyclone perform in the design modeler of Ansys Workbench by using the geometrical ratio of Stairmand. Here, I am taking the diameter of the cyclone separator as 0.20 meters, which is close to the standard size diameter of 0.203 meters.

Table-1: The Geometrical Parameter values for Cyclone Design

Sr. No.	Cyclone Data	Dimensions(m)
1.	Diameter of Cyclone (Dc)	0.20
2.	Height of Rectangular Inlet (A)	0.10
3.	Width of Rectangular Inlet (B)	0.05
4.	Diameter of Circular Outlet (De)	0.10
5.	Height of Circular Outlet (C)	0.125
6.	Diameter of Collection Bin (Db)	0.05
7.	Length of Cyclone main Body (L_1)	0.40
8.	The total length of a cyclone (L)	0.80

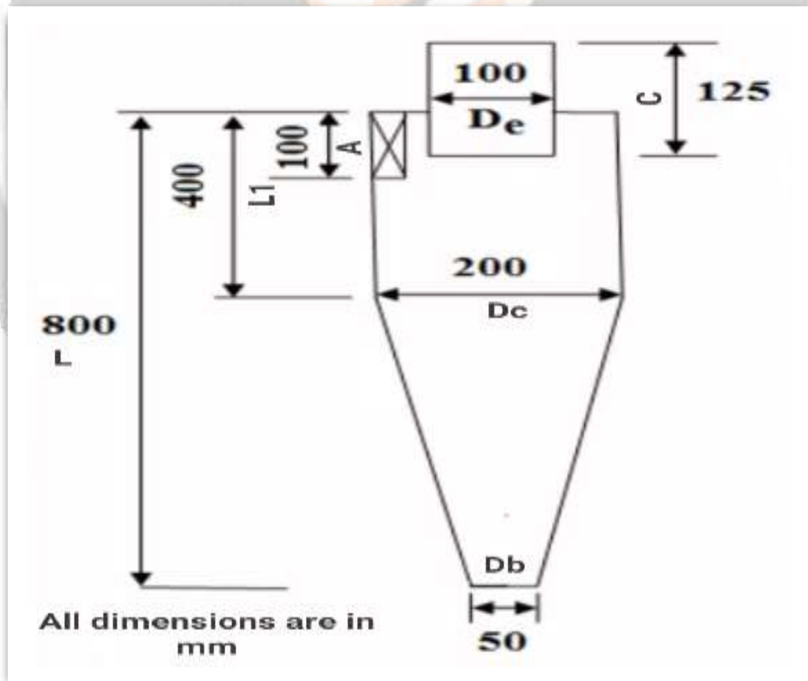


Fig-1: Cyclone Design Dimensions

2.2 Geometry Modification

The performance of the cyclone separator can improve by increasing its tangential velocity. If we do slight modification and add the symmetrical inlet to the geometry of the cyclone then tangential velocity can increase. The dimension of the new inlet is shown below,

- Height of Rectangular Inlet (A_1) = 0.10 m

- Width of Rectangular Inlet (B_1) = 0.05 m

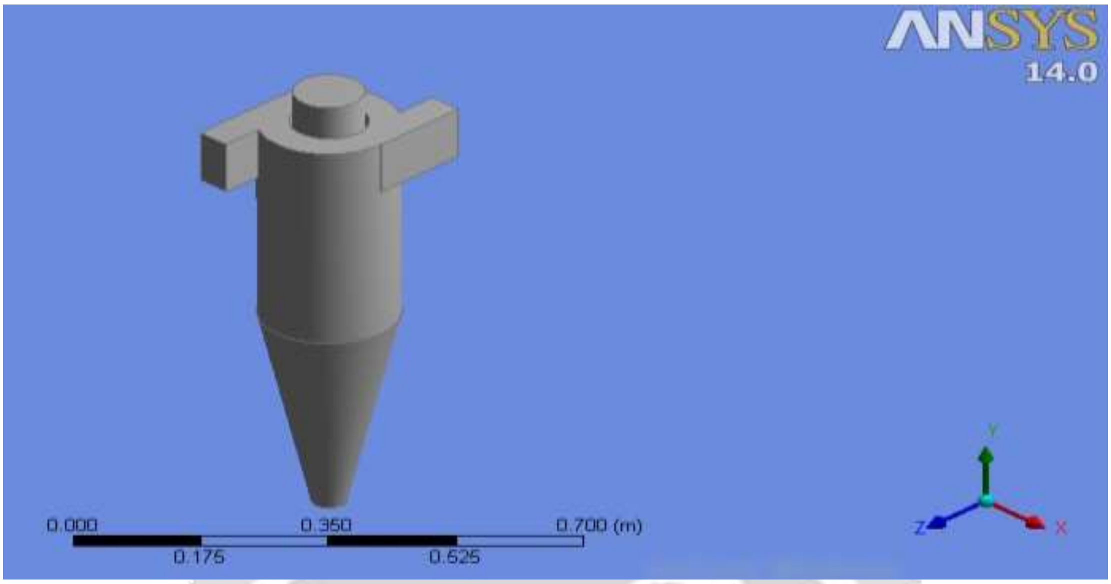


Fig-2: Symmetrical Inlet Cyclone Modelling

3. CFD ANALYSIS

3.1 Single and symmetrical inlet cyclone separator analysis

First, open the Ansys workbench and then drag the Fluid Flow (Fluent) Analysis system from the toolbox to the project schematic window for performing the current analysis.

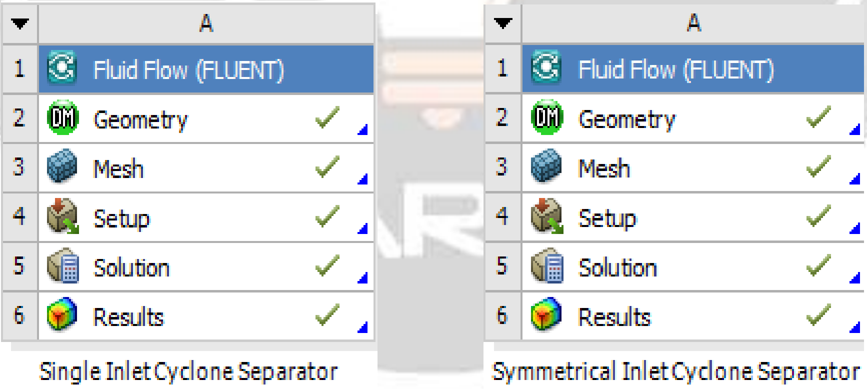


Fig-3: Fluid Flow (Fluent) project schematic

3.2 Single and symmetrical inlet cyclone geometry

For creating cyclone geometry open the Design Modeler tab and select X-Y plane, select the sketch to design cyclone geometry with the given dimensions. After sketching the cyclone go to the modeling section and choose extrude, revolve command to complete the cyclone geometry is. Now, save the geometry and shut the Design Modeler window.

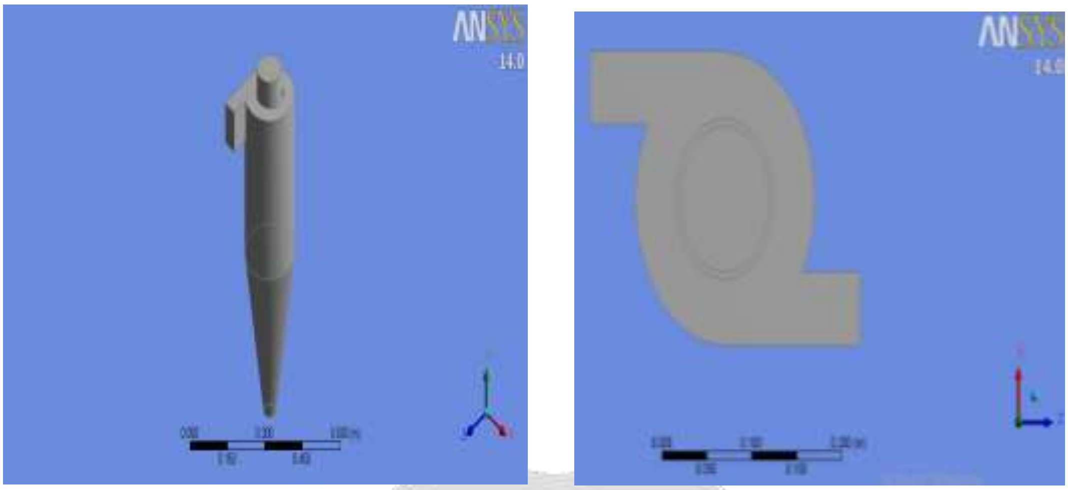


Fig-4: Single and symmetrical inlet cyclone separator geometry for simulation

3.3 Mesh

Double click on Mesh to open the Meshing window, create named selections

1) Select the inlet face and name it as velocity inlet
2) Select the outlet face and name it as a pressure outlet
3) Select the dust outlet face and name it as a collection bin
4) Select the remaining faces and name them like a wall.

Select the mesh in the tree outline after that in the Method option choose Tetrahedron, sizing option choose Relevance Centre: Fine, Smoothing: High and minimum size = 5.e-006 m. Select the mesh and click on generate mesh option to obtain mesh.

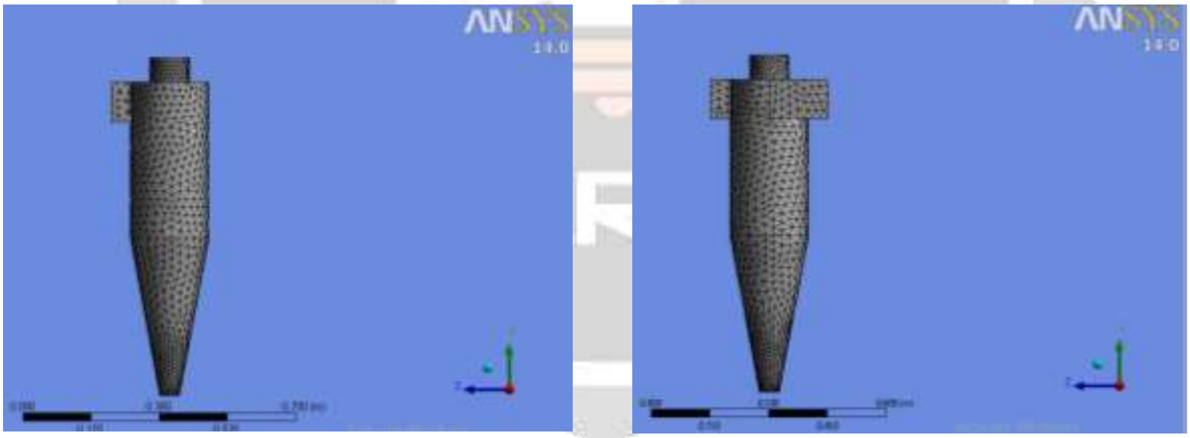


Fig-5: Single and symmetrical inlet cyclone meshed models

Table- 2: Mesh Statistics

Statistics	Single Inlet	Symmetrical Inlet
Nodes	7952	8739
Elements	41127	45425

3.4 Setup

Double click on the setup to open Fluent Launcher, select Double-precision, and in the processing option click on Serial, select ok.

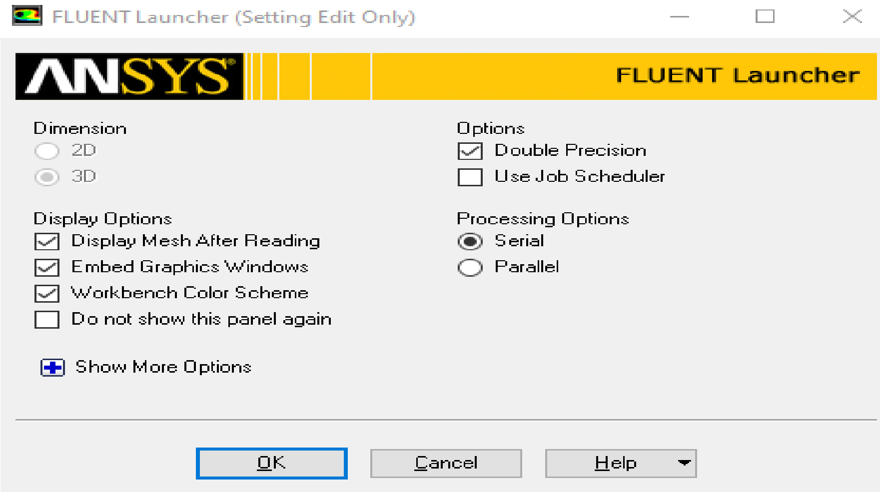


Fig-6: Fluent Launcher

STEP 1: General > check Mesh (To confirm mesh is correct or not) then in Solver select Pressure-Based type, Absolute Velocity Formulation, Transient Time Steps and enable Gravity and put a value of Gravitational Acceleration -9.81 m/s^2 in Y-Axis.

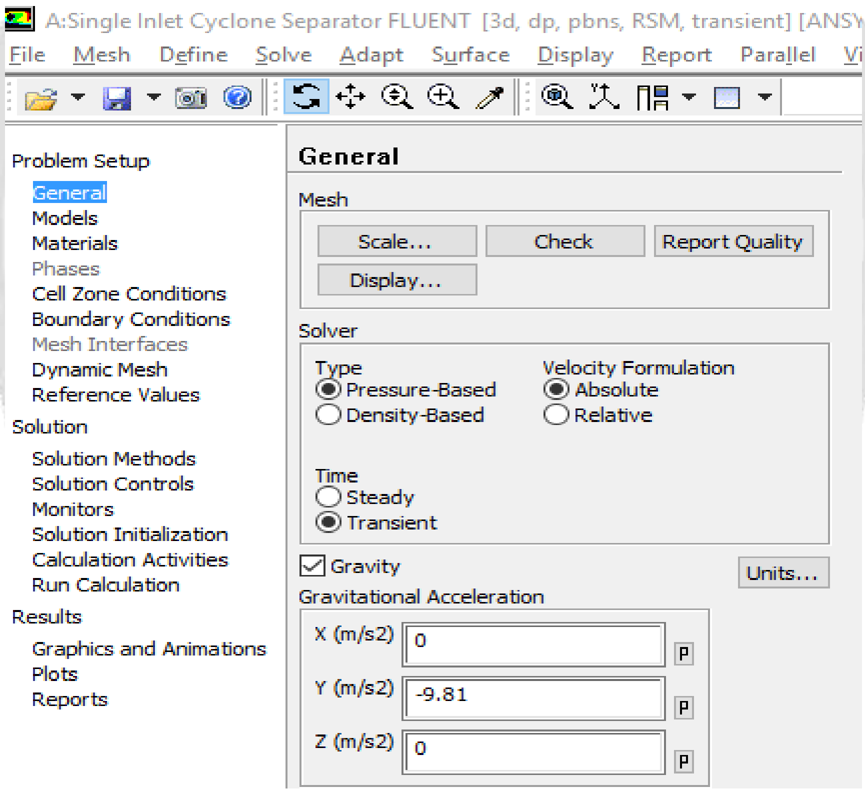


Fig-7: General Conditions

STEP 2: In models select the Reynolds Stress (7 eqn) and in Reynolds-Stress Model select Linear Pressure-Strain, in Reynolds-Stress Options enable Wall BC from k Equation and Wall Reflection Effects, in Near-wall Treatment enable Standard Wall Functions.

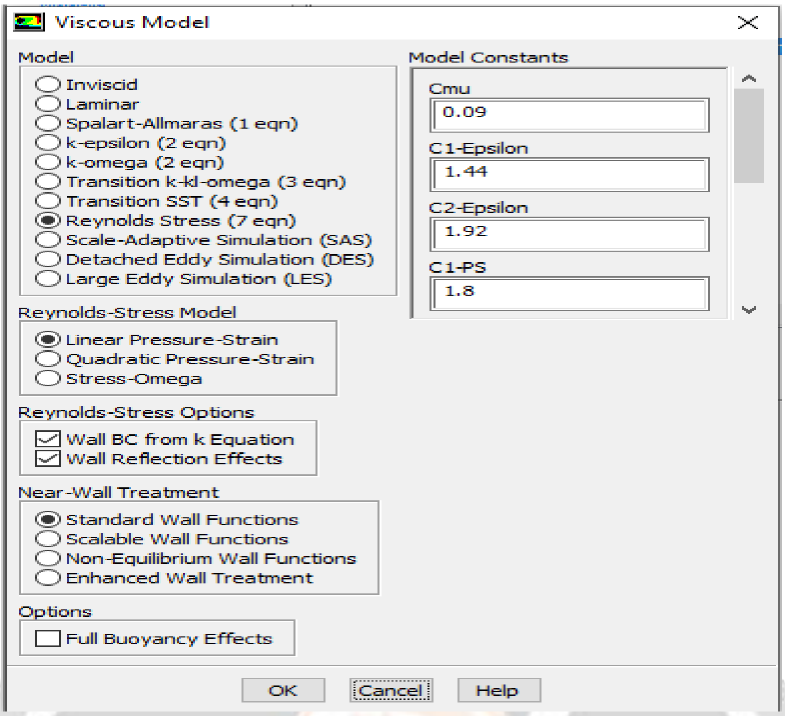


Fig-8: Defining the Model

STEP 3: In Materials choose Air then in properties value of Density = 0.4 kg/m^3, Viscosity = 0.02 kg/m-s and click on change/create option.

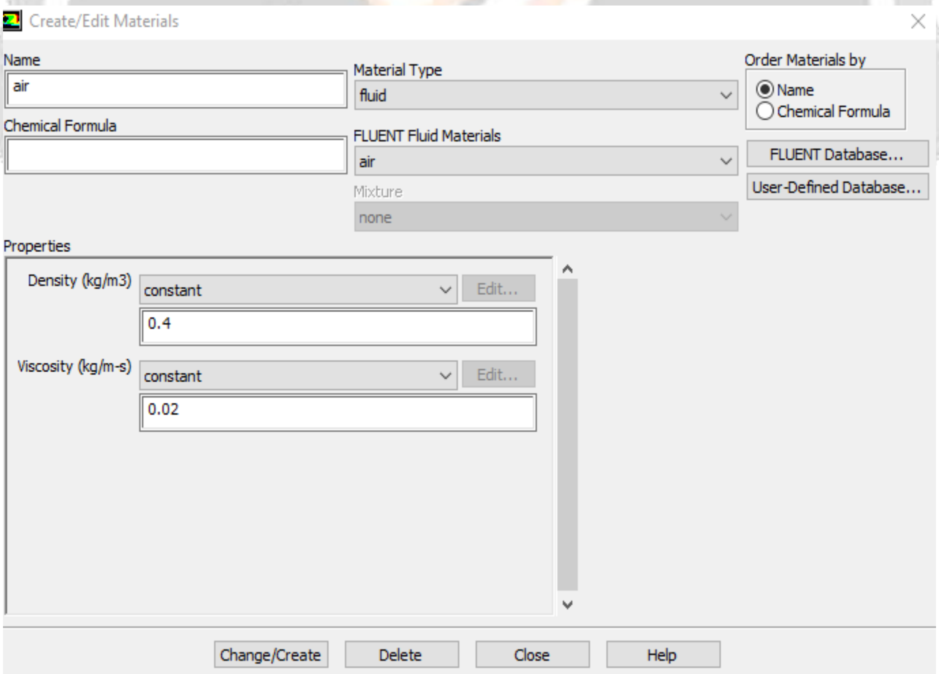


Fig-9: Materials

STEP 4: Boundary Conditions

A) Zone name: Inlet > Velocity magnitude = 15 m/s^2

Turbulence: Specification Method > Intensity and Hydraulic Diameter

Turbulence Intensity (%) = 10, Hydraulic Diameter(m) = 0.067

B) Zone name: Outlet

Turbulence: Specification Method > Intensity and Hydraulic Diameter

Backflow Turbulence Intensity (%) = 10, Backflow Hydraulic Diameter(m) = 0.1

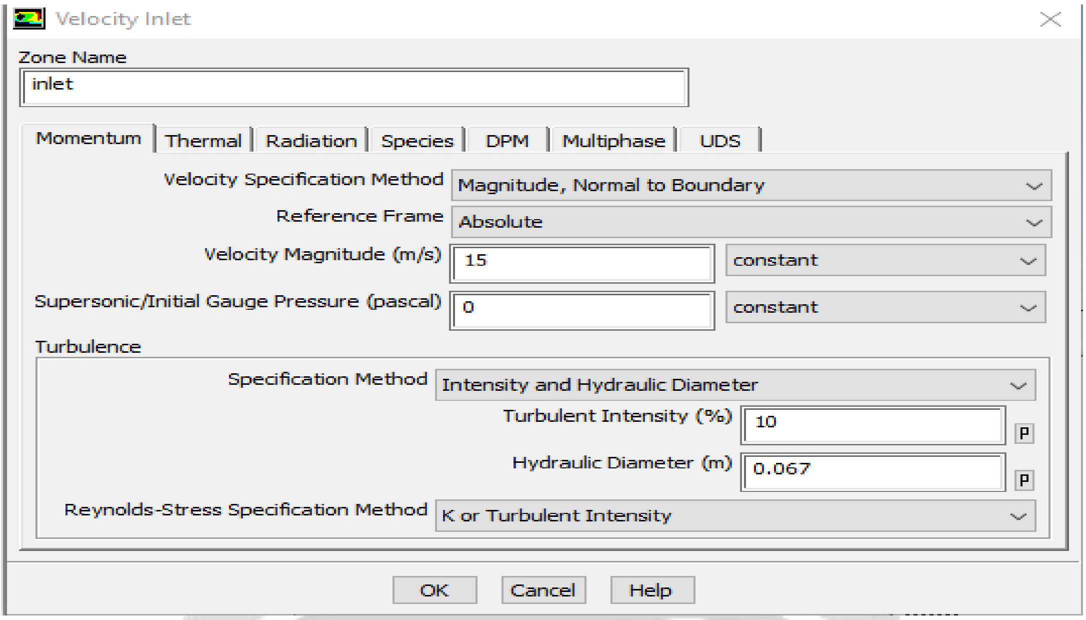


Fig-10: Inlet Boundary Conditions

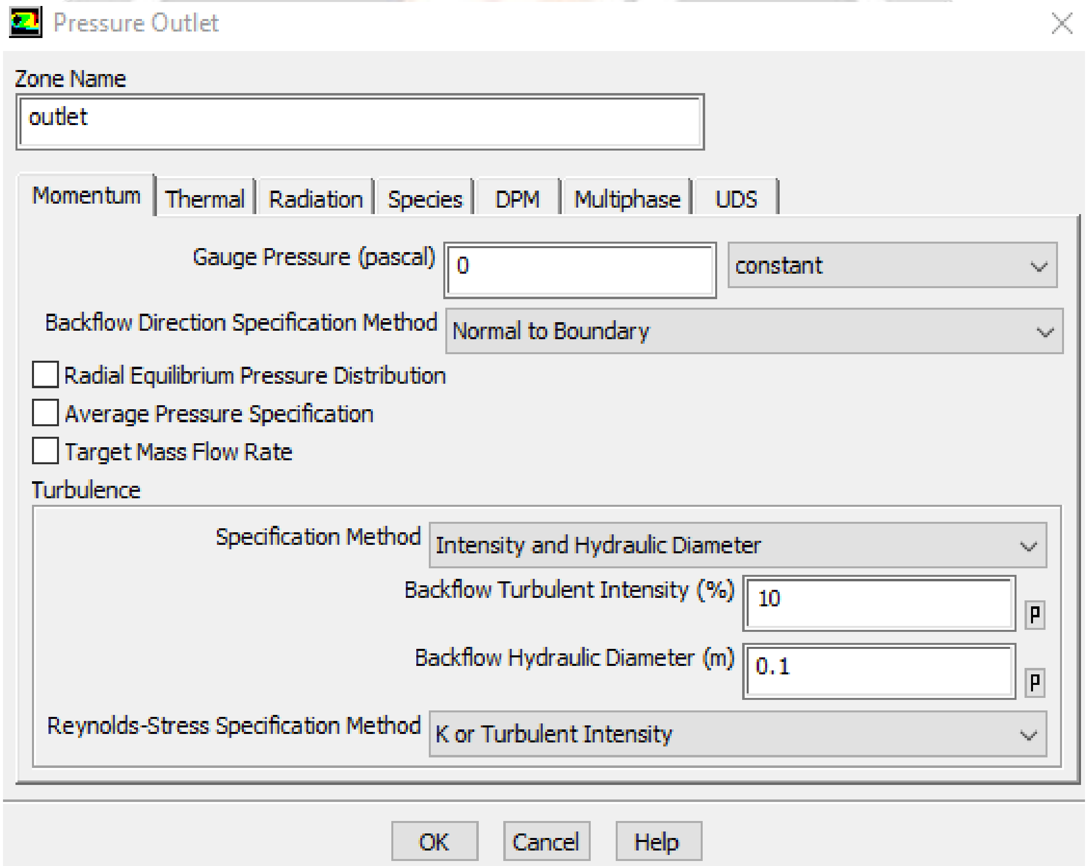


Fig-11: Outlet Boundary Conditions

STEP 5: Solution Methods

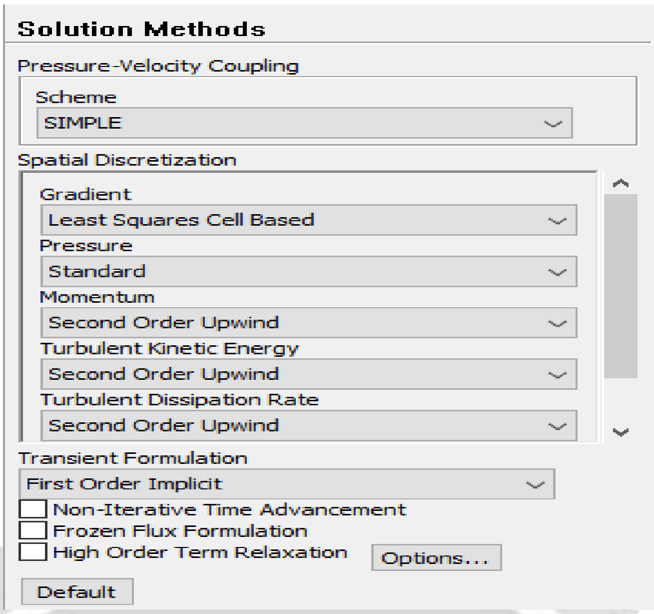


Fig-12: Details of Solution Methods

STEP 6: Solution Initialisation: Standard Initialisation Method and compute from Inlet
Initial values: Y-velocity = 9.5 m/s, Z-velocity = -15 m/s

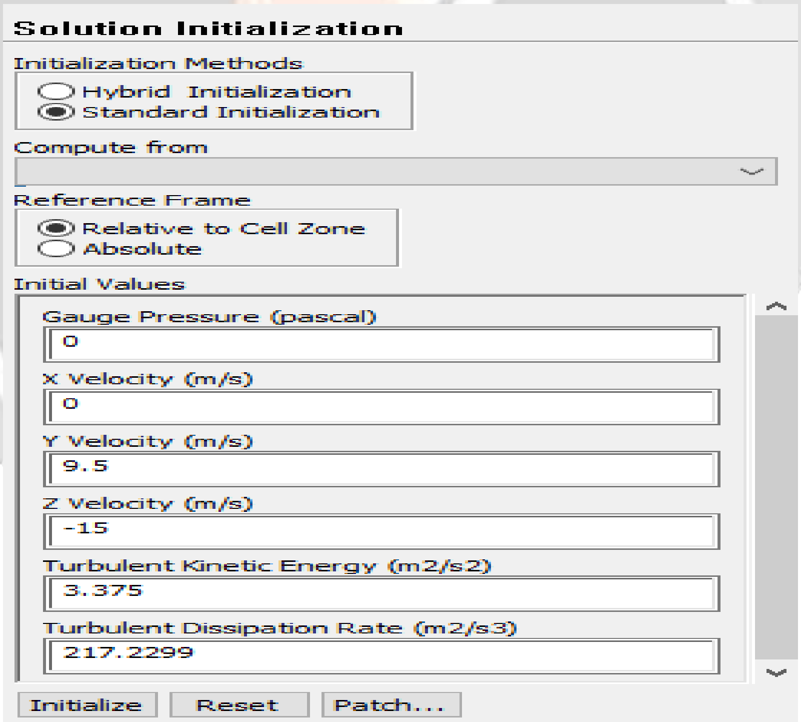


Fig-13: Details of Solution Initialisation

STEP 7: Run Calculation > check case> close
Time step size(s) = 0.0001; Number of Time Steps =3, Max Iterations/Time Step = 20

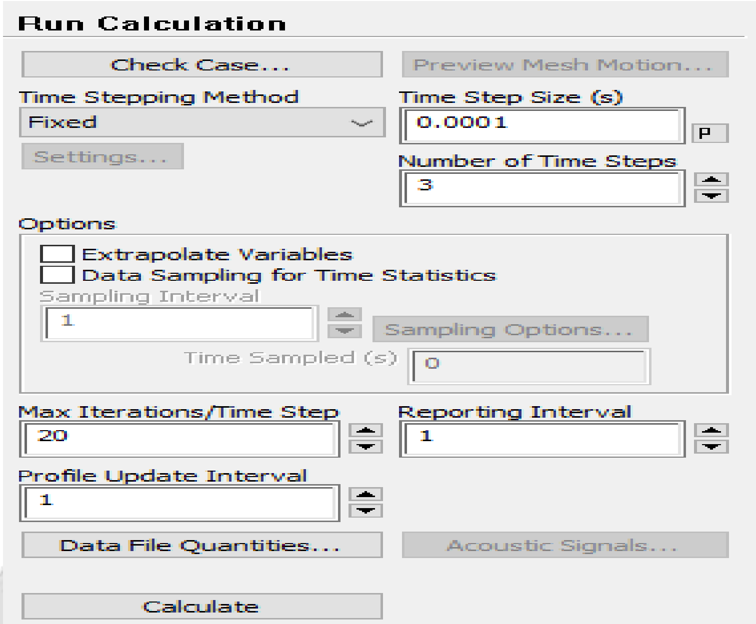


Fig-14:Details of Run Calculation

D. SOLUTION

The solution is converged at the 53rd iteration. Flow time is 0.0003s and time step = 3.

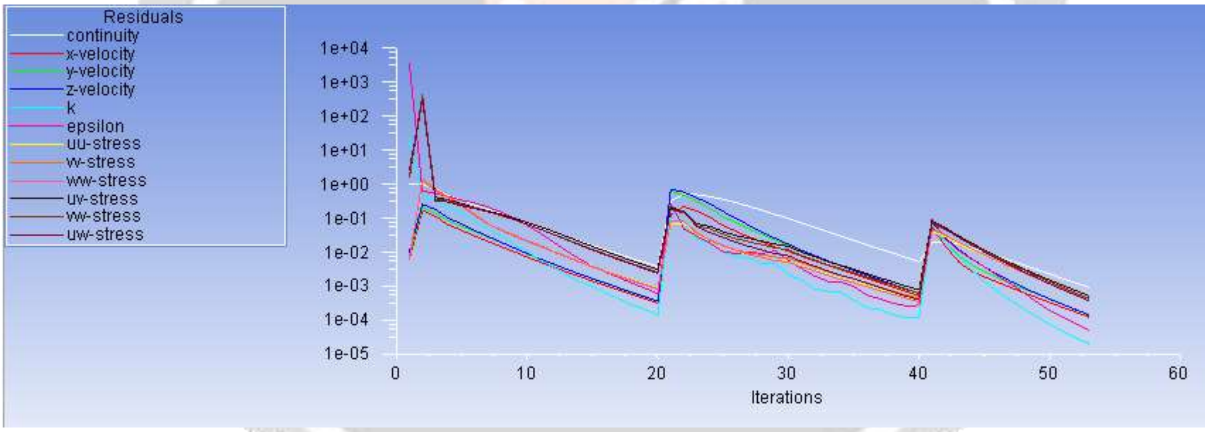


Fig-15: Single inlet cyclone separator residual graph

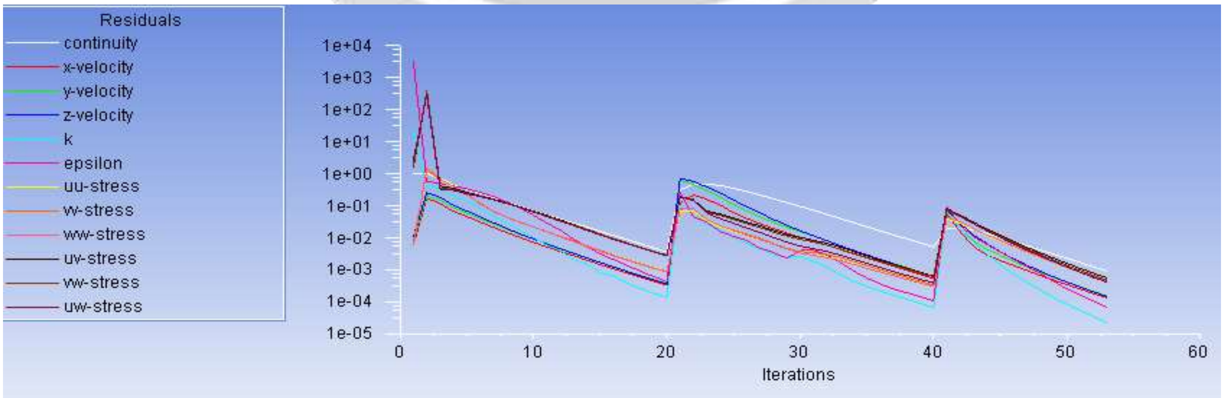


Fig-16: Symmetrical inlet cyclone separator residual graph

4. THEORETICAL CALCULATION

While designing a cyclone dust separator, the pressure drop in cyclone is one of the most important parameters to keep in mind. Theoretical Pressure drop calculation:

- Inlet Velocity (u_1) = 15 m/s
- Gas Density (ρ_f) = 0.4 kg/m^3 and Viscosity of the gas = 0.02 kg/m-s
- Hydraulic diameter of the rectangular inlet = $\frac{4(a\times b)}{2(a+b)} = 0.067\ m$
- Hydraulic diameter of the circular outlet = 0.1 m
- Area of the rectangular inlet (A_1) = 0.1 × 0.05 = 0.0005 m^2
- Cyclone Surface Area (As) = π.200 × (400 +400) = 0.502400 m^2
- ψ = $f_c \frac{A_s}{A_1}$ = 0.5024, here, f_c is taken as 0.005
- $\frac{r_t}{r_e} = \frac{100-\left(\frac{50}{2}\right)}{50} = 1.5$

where $r_{t\,=}$ radius of the circle to which the

centre line of the inlet is tangential and r_e = outlet pipe radius

- $Based\ on\ \psi\ and\ \frac{rt}{re}$ value we can find out φ from figure 17.
-
- $\varphi = 0.9$
- Outlet Pipe Area (Ae) = $\frac{\pi}{4}d^2$ = 0.007850 m^2
- Q = A_1u_1 = 0.075 m^3/s
  Q = $A_eu_{2,}$ → u_2 = 9.5 m/s

$$\rightarrow \Delta P = \frac{\rho_f}{203}\left\{u_1^2\left[1 + 2\varphi^2\left(2\frac{r_t}{r_e} - 1\right)\right] + 2\ldots\right.$$

$$\rightarrow \Delta P = 2.23\ mbar = 223\ Pa$$

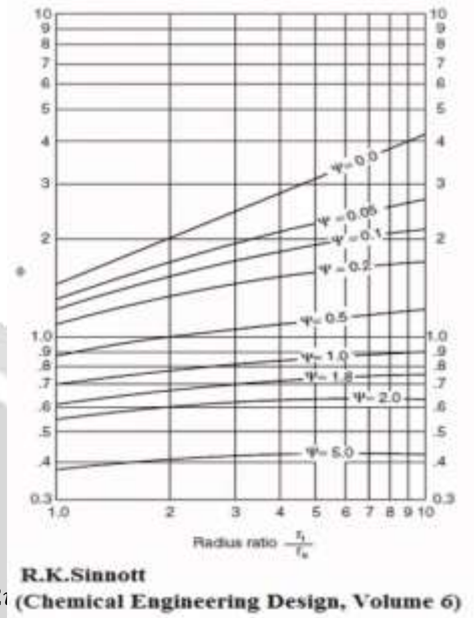


Fig-17: Radius ratio vs ϕ graph

5. RESULTS AND DISCUSSIONS

5.1 Contour Results

- Pressure Contours

Pressure contours obtain from Fluid Flow (fluent) show that non-dimensionalized static pressure is in the range of -36.098 Pa to 833.437 Pa for a single inlet cyclone separator. Static pressure is increasing from center to wall surface but along the vertical section, pressure isn't uniform and decreasing at bottom of the conic section of the cyclone as within the case of a single inlet cyclone separator.

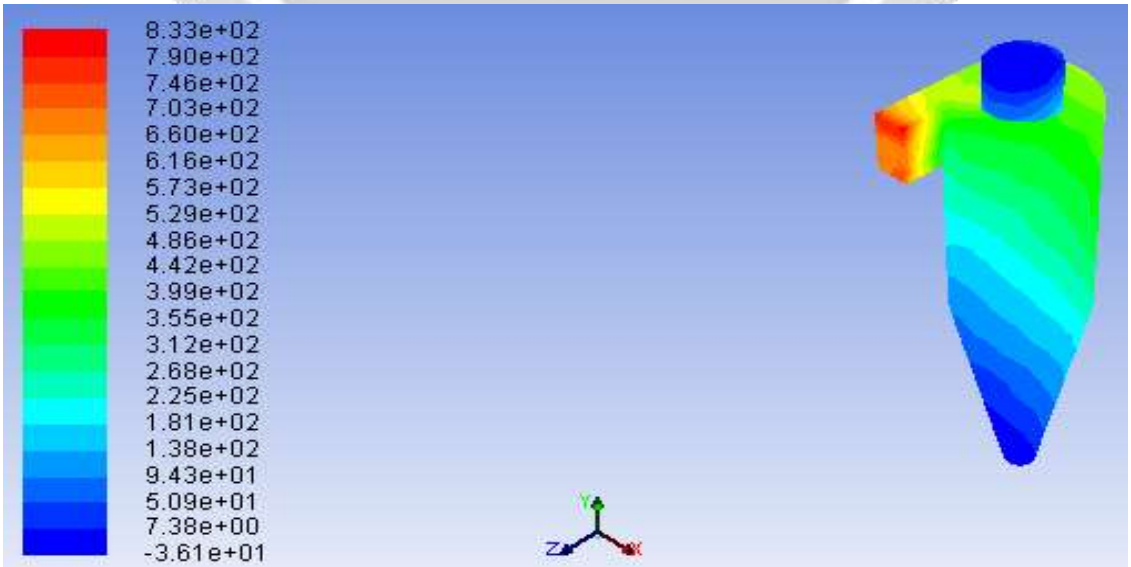


Fig-18: Static pressure contour of single inlet cyclone

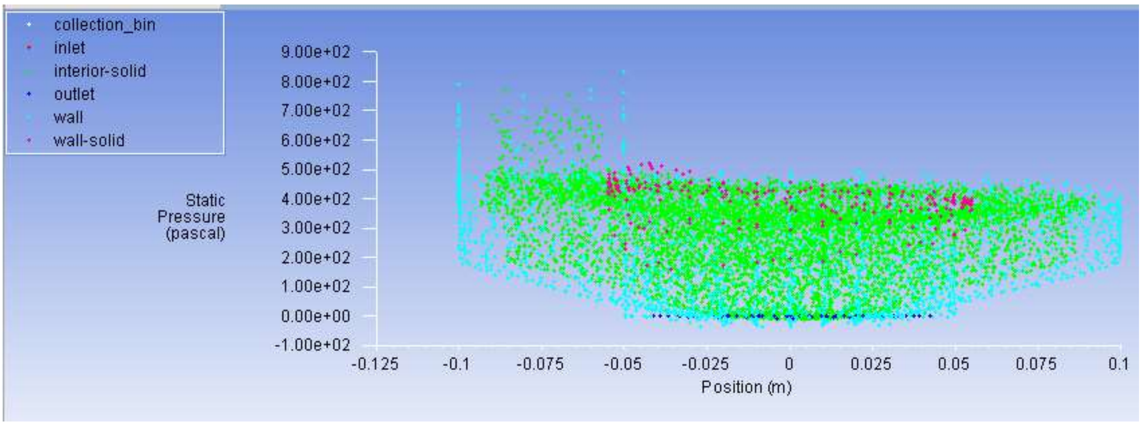


Fig-19: XY plot of static pressure versus position for single inlet cyclone separator

5.2 Comparison of Results for single inlet cyclone separator

- Pressure Drop from CFD Analysis = 252.75 Pa
- Pressure Drop from Theoretical Calculation = 223 Pa
- Error % between two results = 11.77 %

Pressure contours plot and shows that non-dimensionalized static pressure is within the range of -42.703 Pa to 825.722 Pa for symmetric inlet cyclone. The static pressure is increasing from the middle to the wall surface. I observed that maximum pressure is at the inlet and minimum pressure is at the outlet of the cyclone.

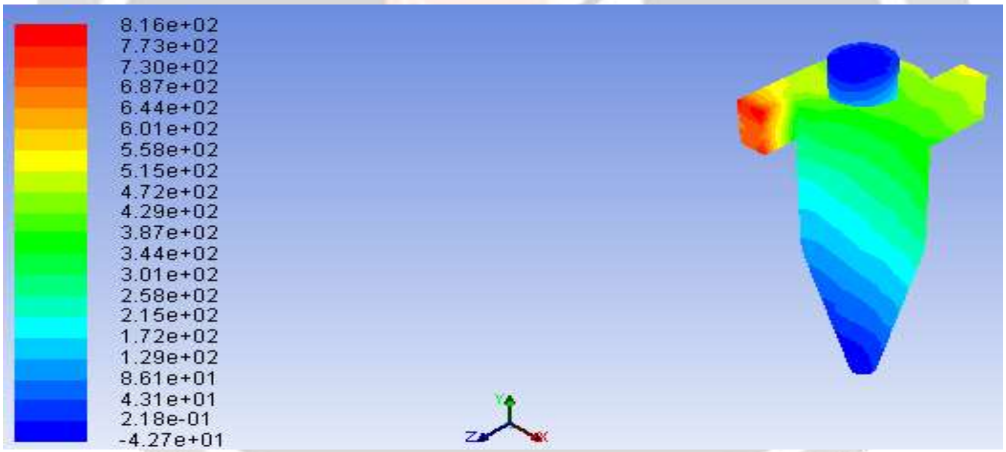


Fig-20: Static pressure contour of symmetrical inlet cyclone separator

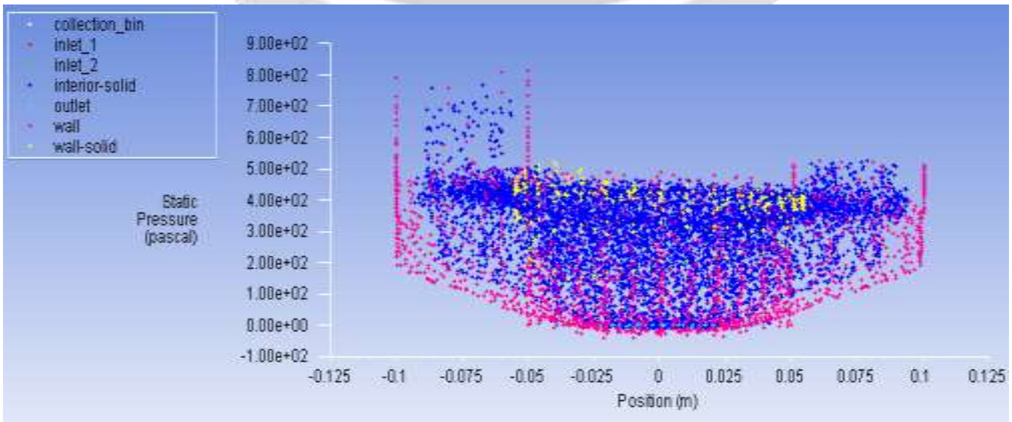


Fig-21: XY plot of static pressure versus position for symmetrical inlet cyclone separator

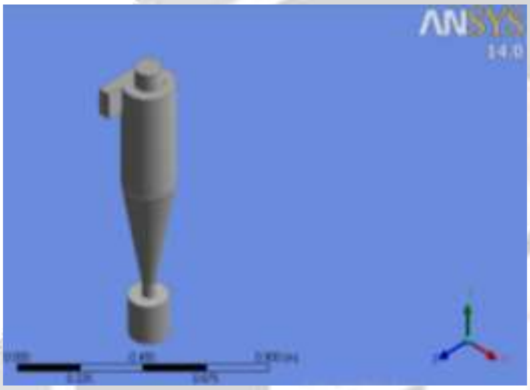
5.3 Comparison of Results for symmetrical inlet cyclone separator

- Pressure Drop from CFD Analysis = 259.27 Pa
- Pressure Drop from Theoretical Calculation = 223 Pa
- Error % between two results = 13.98 %

6. THE ANALYSIS OF SINGLE AND SYMMETRICAL INLET CYCLONE WITH DUST COLLECTOR

The application of dust collectors is to collect dust particles located at the endpoint of the cyclone. A collector can be of any shape (example: cubical, cylindrical). It is fixed at the endpoint of the conic tip and prevents the re-entertainment of particles. During this analysis, two cylindrical-shaped collectors attach at the endpoint of the cone tip (with dimensions 50 mm diameter, 50 mm height for the first cylindrical shape collector, and 150 mm diameter, 150 mm height for the second cylindrical shape collector). The same setup uses to simulate the cyclone with a collector.

Single and symmetrical inlet cyclone geometry with dust collector



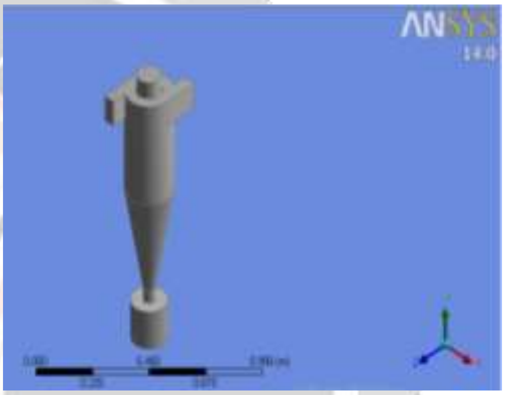
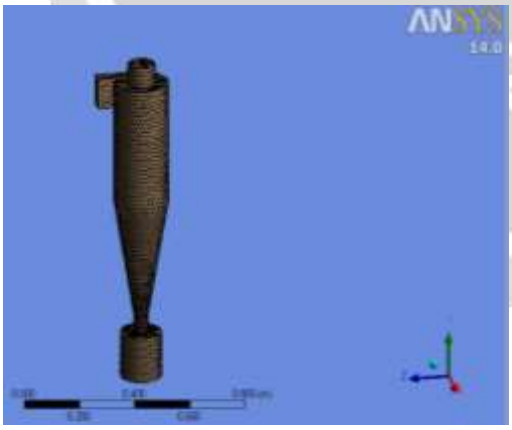


Fig-22: Single and symmetrical inlet cyclone separator geometry for simulation

Mesh



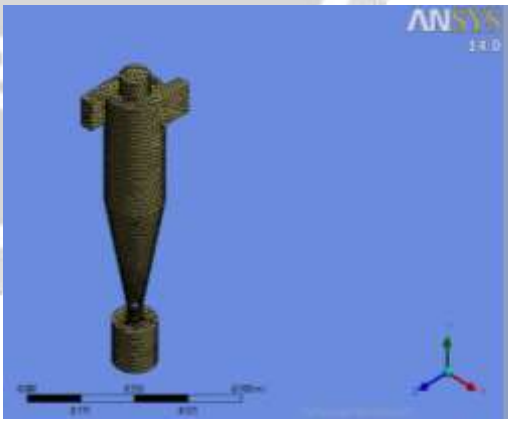


Fig-23: Single and symmetrical inlet cyclone meshed models

Table-3: Mesh Statistics

Statistics	Single Inlet	Symmetrical Inlet
Nodes	8848	8843
Elements	42188	42204

Setup

STEP 1: General > check mesh (To verify the mesh is correct or not) Enable Pressure based type, absolute velocity formulation, and steady time steps.
2) STEP 2: In models select the realizable k-epsilon (2eqn) Model and Standard model and standard wall functions.
3) STEP 3 – Discrete Phase Model is on and create new injection (Injection-0) for both the cyclones. The particles will enter from the inlet and in injection type choose Surface, Diameter distribution: Uniform.

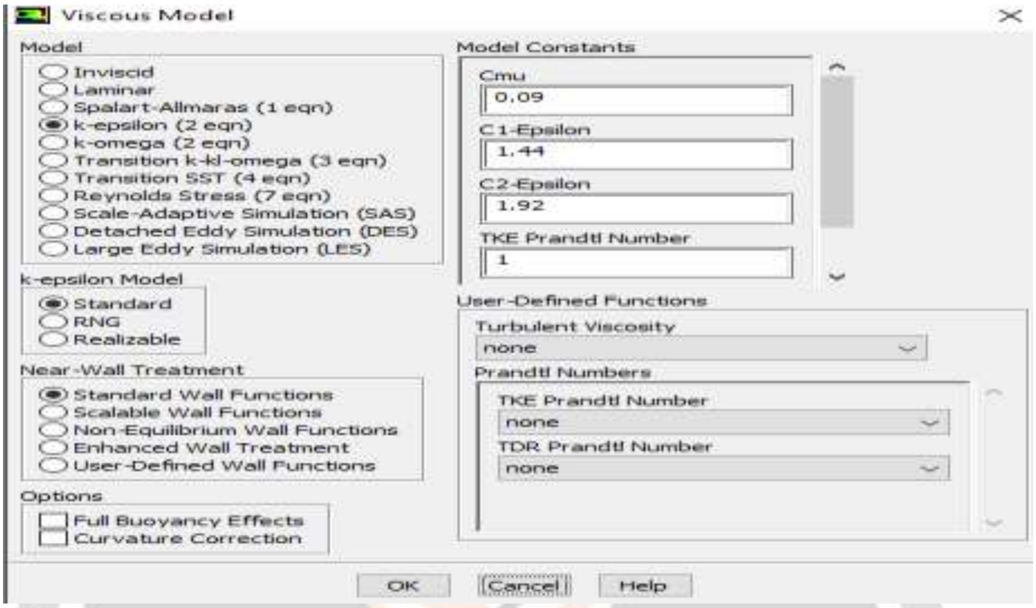


Fig-24: Defining Models

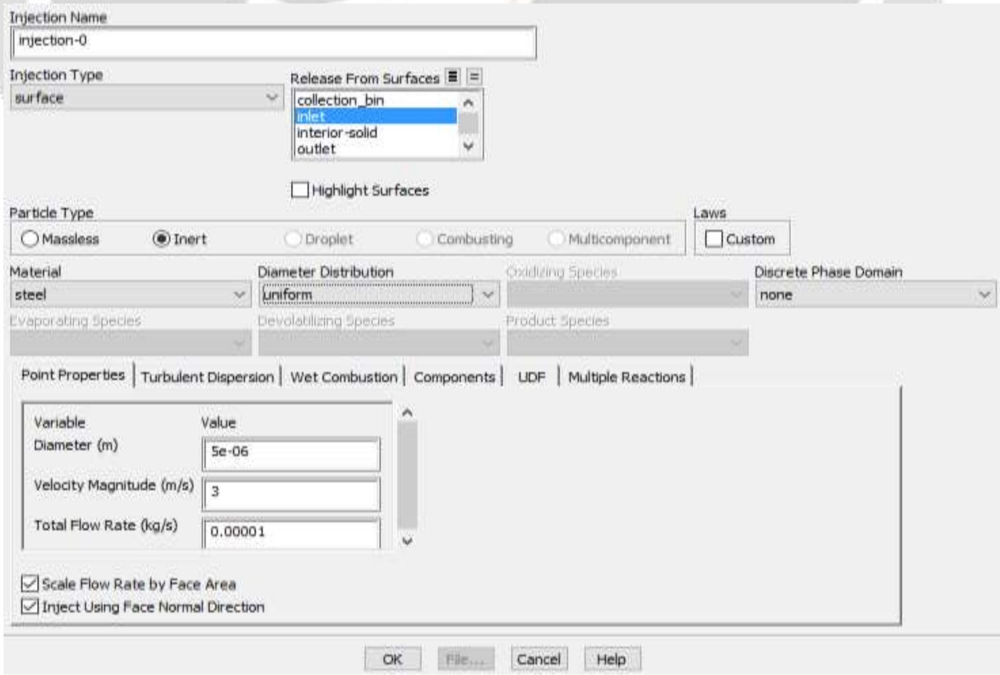


Fig-25: Creating new Injection

Material: Steel, Density of Steel = 8030 kg/m^3, Particle size = 5 μm,Total flow rate = 0.00001 kg/s and Velocity magnitude = 3m/s.

6.2 Solution Methods

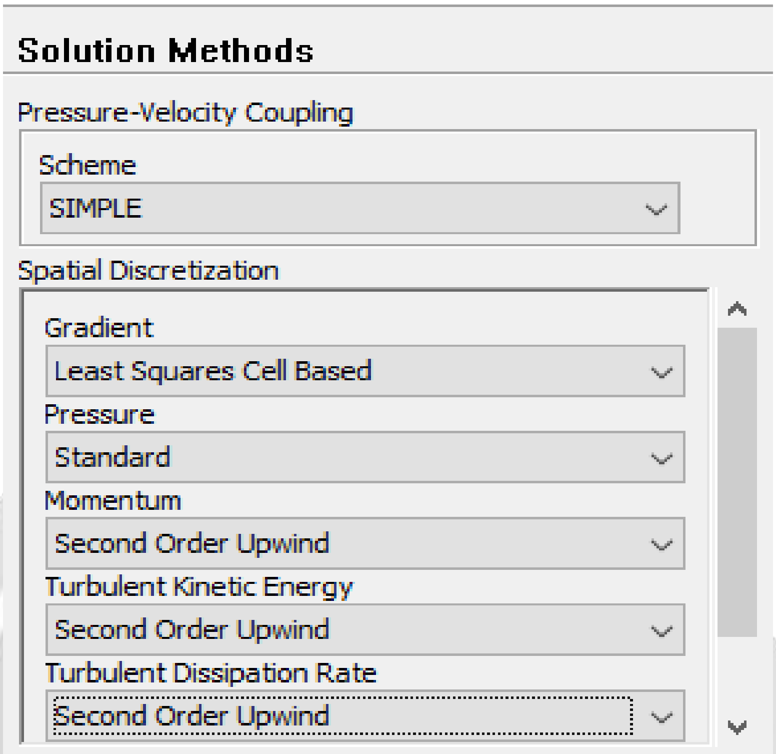


Fig-26: Details of Solution Method

Initialization: Select standard initialization, compute from inlet velocity, and put the value of Z velocity -3 m/s.

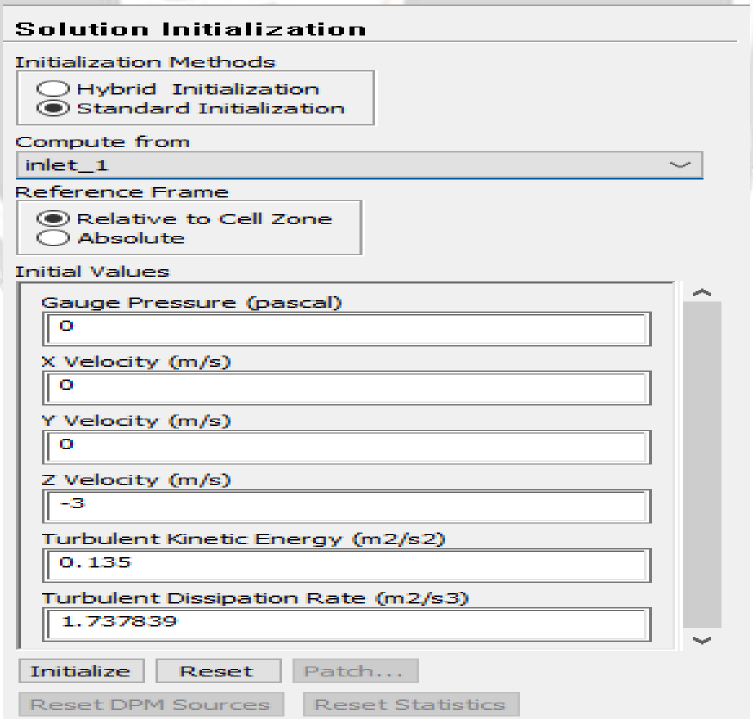


Fig-27: Solution Initialization

6.4 Residual Graphs

The solution is converged at 352nd iteration for single inlet cyclone separator. Total number of iterations = 500, Reporting Interval = 1, Profile Update Interval = 1.

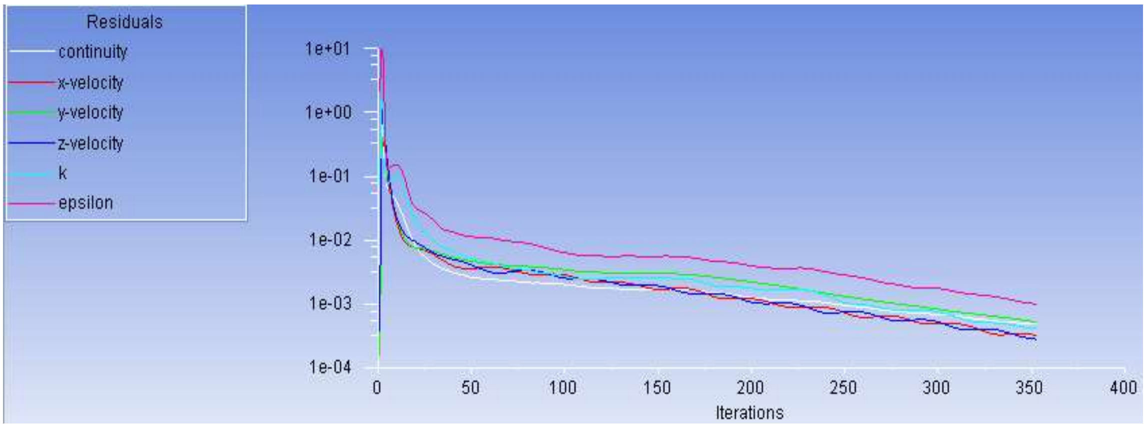


Fig-28: Single inlet cyclone separator residual graph

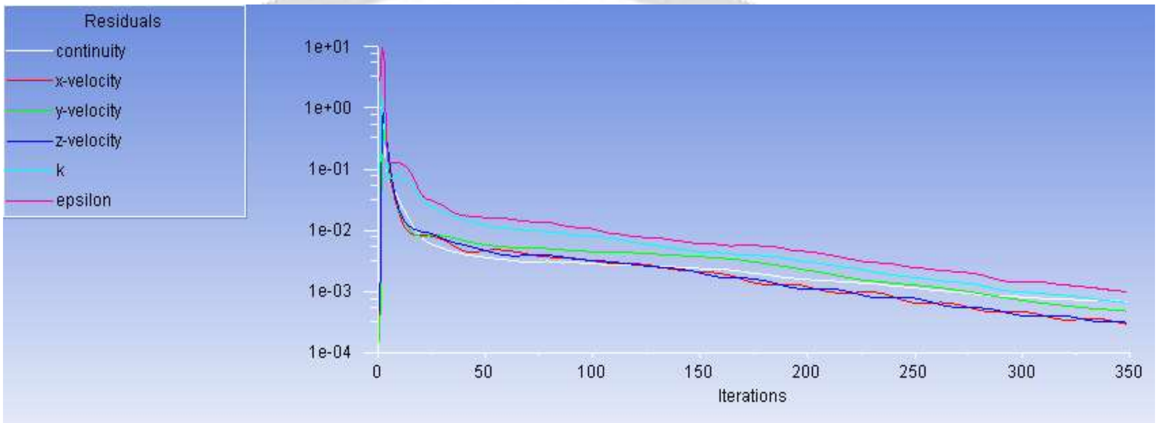


Fig-29: **Symmetrical inlet cyclone separator residual graph**

7 RESULTS AND DISCUSSIONS

7.1 Pressure Contours

Pressure contours obtain from Fluid flow (Fluent) observe that non-dimensionalized static pressures are within the range of – 2.57 Pa to 14.64 Pa for a single inlet cyclone. Static pressure is increasing from the core of the wall surface but decreasing at bottom of the cyclone. I observed that maximum pressure is at the inlet and minimum pressure is at the outlet of the cyclone.

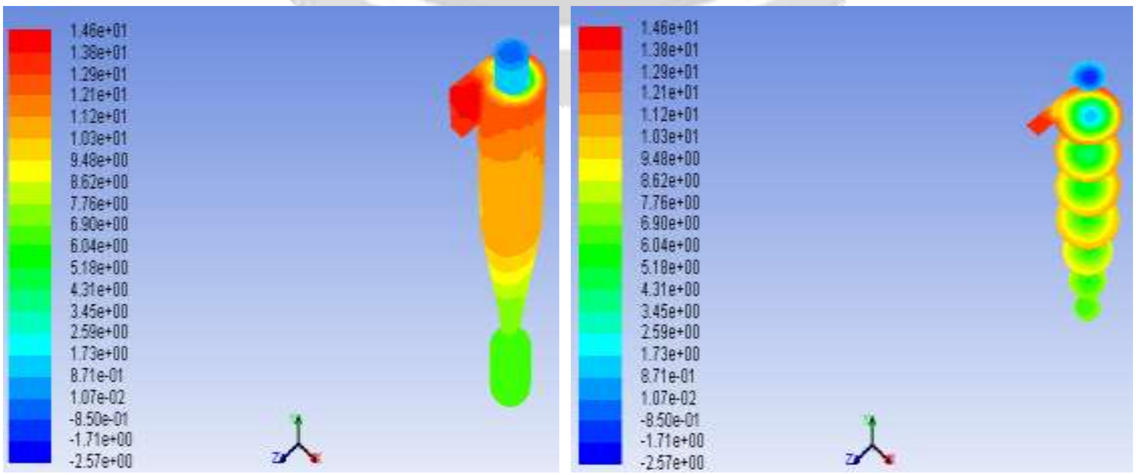


Fig-30: Contours of static pressure (pascal) for single inlet cyclone

Pressure contours obtain from Fluid flow (Fluent) observe non-dimensionalized static pressures are within the range of -2.81 Pa to 14.3 Pa for symmetrical inlet cyclone separator. Static pressure is increasing from the core to the wall surface but decreasing at bottom of the cyclone. I observed that maximum pressure is at the inlet and minimum pressure is at the outlet of the cyclone.

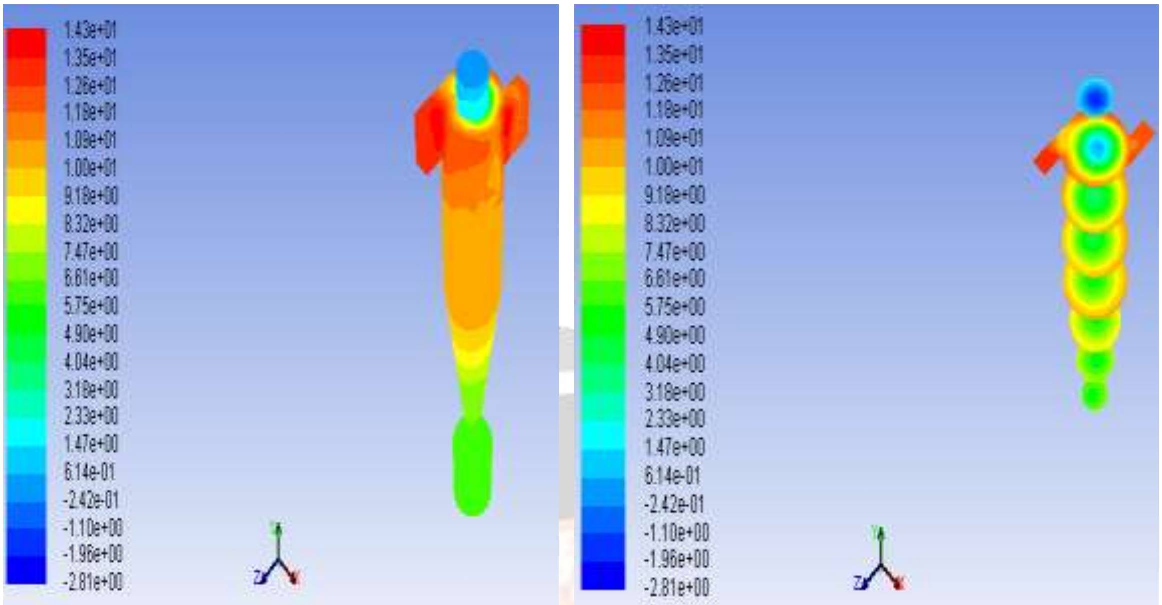


Fig-31: Contours of static pressure (pascal) for symmetrical inlet cyclone

7.2 Velocity Contours

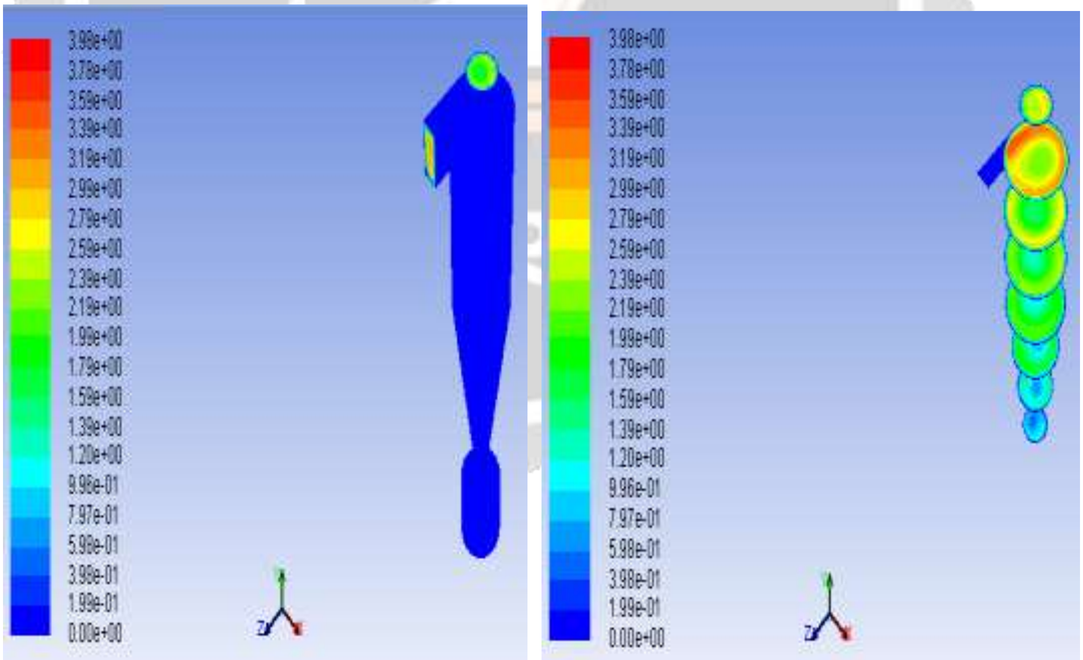


Fig-32: Contours of velocity magnitude (m/s) for single inlet cyclone

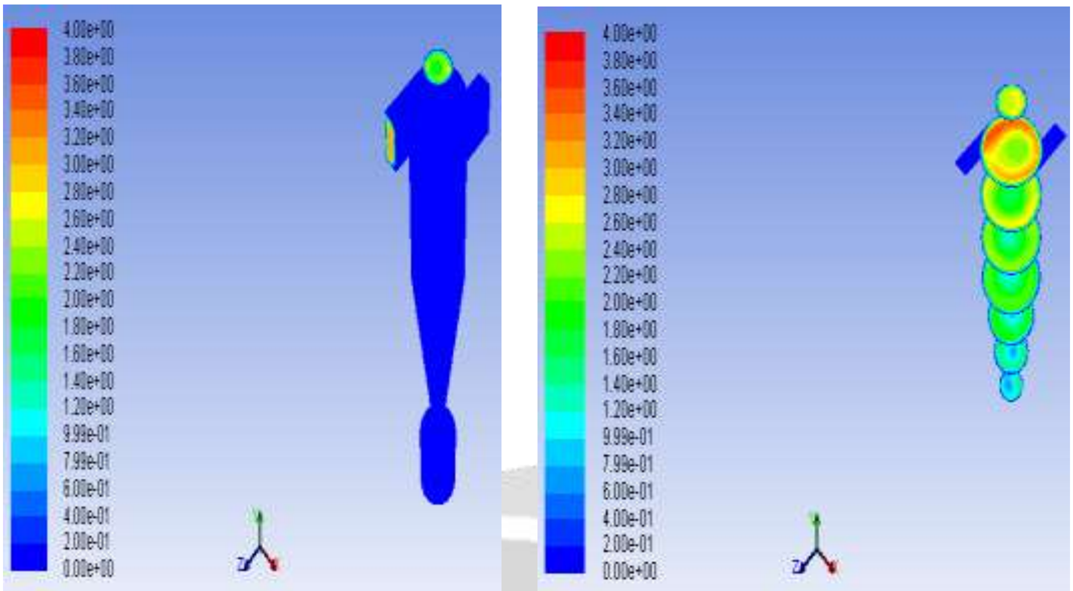


Fig-33: Contours of velocity magnitude for symmetrical inlet cyclone

Table-4: Velocity magnitude for both cyclone models

Cyclone Types	Velocity Magnitude (m/s)		Tangential Velocity (m/s)	
	Minimum	Maximum	Minimum	Maximum
Single Inlet Cyclone	0	3.98	-3.52	2.88
Symmetrical Inlet Cyclone	0	4.00	-3.68	2.92

Here, input velocity is 3 m/s and we can see from the table that the velocity magnitude and tangential velocity in the symmetrical inlet cyclone are more than a single inlet cyclone.

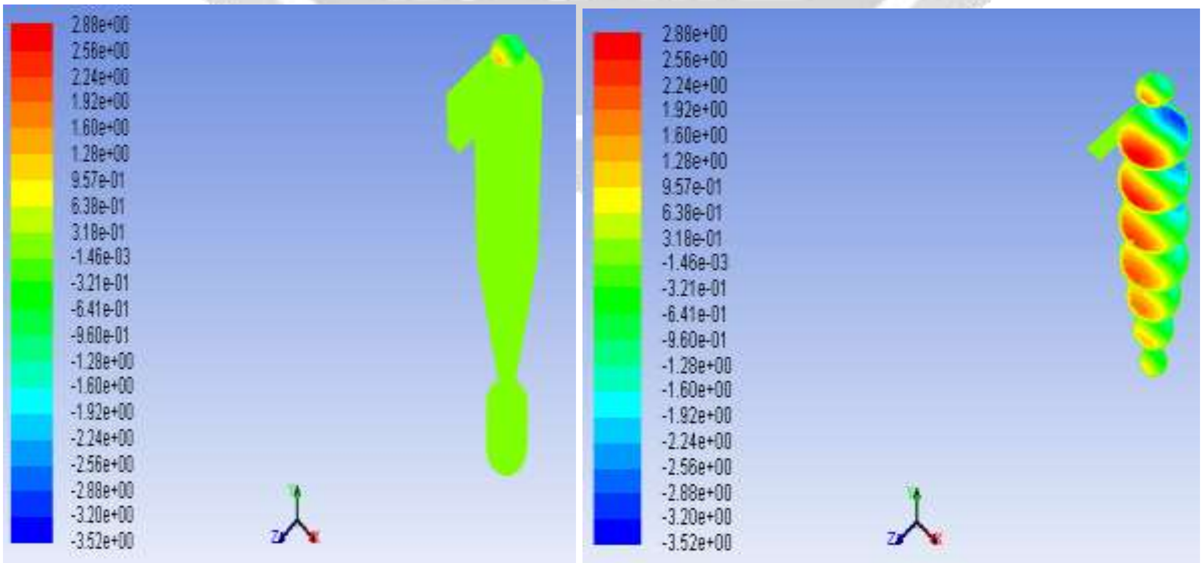


Fig-34: Contours of tangential velocity (m/s) for single inlet cyclone

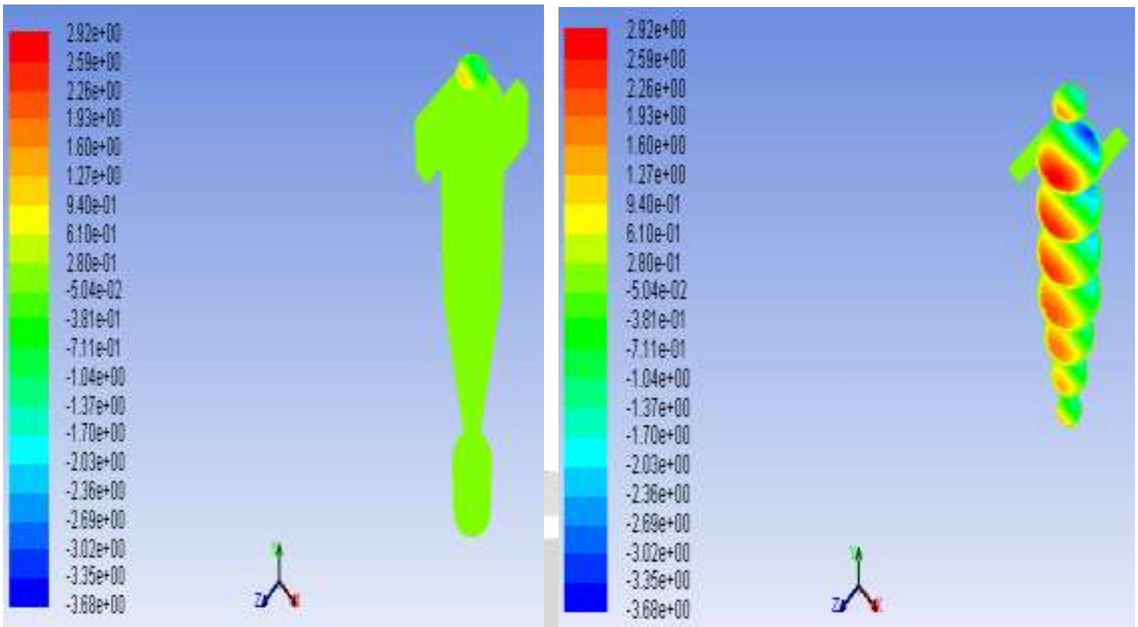


Fig-35: Contours of tangential velocity (m/s) for symmetrical inlet cyclone

7.3 Particle Tracks

Collection efficiency calculation for cyclone dust separator

- Number of particles trapped = 633
- Number of particles escaped = 627
- Number of particles injected = 1260
- Number of particles incomplete = 0

Efficiency = $\frac{(Number\ of\ particles\ trapped)}{(Number\ of\ particles\ injected\ - Number\ of\ particles\ incomplete)}$

Efficiency % = $\frac{633}{(1260-0)} \times 100 = 50.24\%$ for the particle size of 5 μm

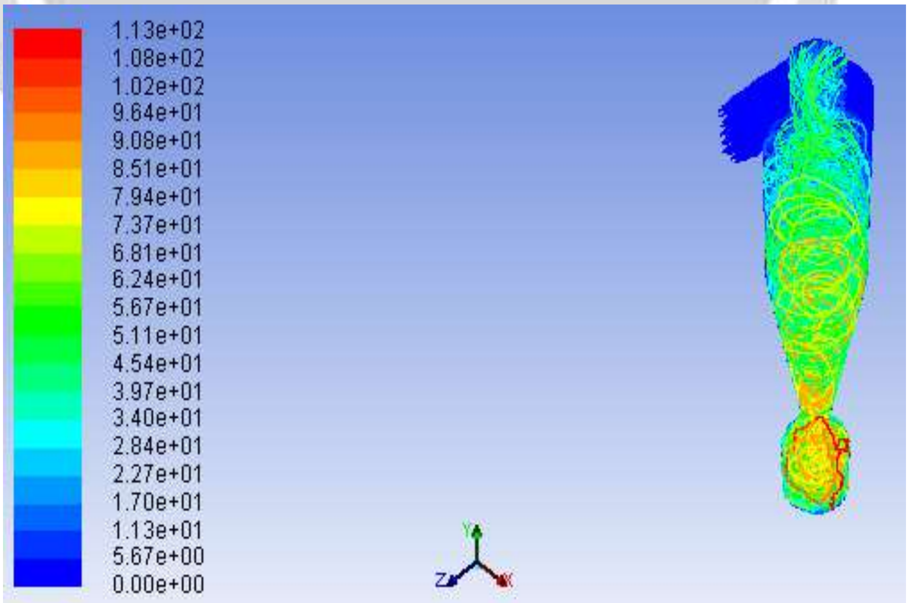


Fig-36: Particle traces contours for single inlet cyclone model

8. CONCLUSION

After studying the prevailing literature and performing CFD[1]analysis on single and symmetrical inlet cyclone separator, the successive conclusion extract: The CFD analysis performed for both the cyclone models under the identical condition of pressure, velocity, material properties, and total flow rate. From the theoretical calculation and CFD analysis result, I found that the pressure drop value varies with the cyclone geometry. There is more pressure drop by symmetrical inlet cyclone separator as compared to single inlet cyclone separator. The error between the theoretical calculation and CFD analysis in a single inlet cyclone is 11.77% and in a symmetrical inlet cyclone separator is 13.98%. The result allowed me to observe that the tangential velocity and the velocity magnitude for the symmetrical inlet are higher than the single inlet cyclone separator. The efficiency calculation for the cyclone with dust collector is 50.24% for the particle size of 5µm.

9. REFERENCES

[1]. Khairy Elsayed 2011, Ph.D. thesis on Analysis and Optimization of Cyclone Separators Geometry using RANS and LES Methodologies. Pages from 20-160.

[2]. Abhijit Gaikwad and Dr.Shivarudraiah “CFD Analysis of Symmetrical Tangential inlet Cyclone Separator” IRJET Vol. 04, No- 08, Aug. 2017

[3]. Ogawa, A. (1984). Estimation of the Collection Efficiencies of the Three Types of the Cyclones Dust Collectors from the Standpoint of the Flow Patterns in the Cylindrical Cyclone Dust Collectors. Bulletin of JSME, vol. 27, n. 223, p. 64.

[4]. Stairmand, C.J. (1951). The Design and Performance of Cyclone Separators. Trans. Inst. Chem. Eng, vol. 29, p.356.

[5]. Zhao, B., Shen, H. and Kang, Y. (2004). Development of a Symmetrical Spiral Inlet to Improve Cyclone Separator Performance. Powder Technology, vol. 145, issue 1, pp. 4750.

[6]. Cyclone Collection Efficiency: Comparison of Experimental Results with Theoretical Predictions By John Dirgo & David Leith.

[7]. Bernardo S, Mori M and W P Martignoni (2006), “Evaluation of Cyclone Geometry and its Influence on its Performance Parameters by CFD”, Powder Technology.

[8]. C B Shepherd and C. E. Lapple. Flow pattern and pressure drop in cyclone dust collectors. Industrial and Engineering Chemistry, 32(9): 1246-248, September 1940

[9]. Optimization of the cyclone separator geometry for minimum pressure drop using mathematical models and CFD simulations By Khairy Elsayed and Chris Lacor, Chemical Engineering Science; 2010

[10]. Numerical study of gas-solid flow in a cyclone separator By B. Wang, D.L. Xu, K.W. Chu, A.B. Yu, Applied Mathematical Modelling 30 (2006) 1326–1342

[1] CFD – Computational Fluid Dynamics