IJREAT International Journal of Research in Engineering & Advanced Technology, Volume 2, Issue 6, Dec-Jan, 2015
ISSN: 2320 – 8791 (Impact Factor: 1.479)
www.ijreat.org

Analysis Of Cyclone Separator Using Empirical Models And CFD For Variation Of Dimensions

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Abstract

Cyclone performance is determined by pressure drop and collection efficiency. This work presents analytical and Computational Fluid Dynamics calculation to predict and to evaluate the effects of change in dimensions on static pressure and collection efficiency. Velocities, pressures, collection efficiency and the pressure drops have been studied according to change in inlet parameters .Relative Changes in inlet parameters are calculated from a modification reported in [8]. The further study is performed with reference to this parameter. In the present work the pressures and collection efficiency have been generated using CFD. The pressure drops have been evaluated for the existing design and the modified design. Significant pressure drops have been observed in the optimized model. The study has been carried out using three standard models Lapple Model, Swift Model and Starmand Model varying the values of inlet height and inlet width. This paper also reviews four empirical models for the prediction of cyclone collection efficiency, namely Lapple [8], Iozia and Leith , Leith and Licht and pressure drop empirical model. All the predictions proved to be satisfactory when compared with the presented literature data. CFD is used to verify the obtained results with actual and Literature.

Keywords : Empirical Models, CFD, inlet dimensions

1 Introduction

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. It has become an integral part of various processes in agrochemical, pharmaceutical, and cosmetic industries [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 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(2) Dielectrophoresis (DEP) - Dielectrophoresis is 'the translational motion of neutral matter caused by polarization effects in a non uniform electric field '[Pohl, 10] .

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) .

1.3 Optical Separation

Optical fractionation is a recent technique developed by Dholakia and coworkers and Grier and coworkers **.** 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.

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. Fig 1 shows a micro separation array. This is a type of passive sorting of particles.

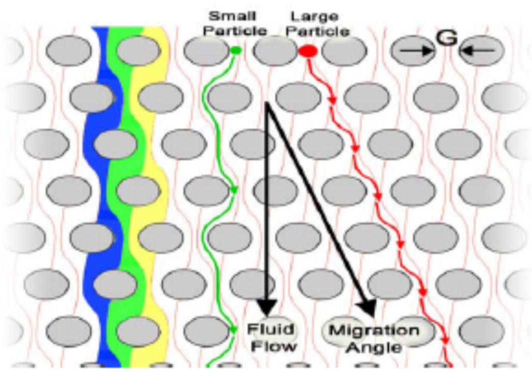

Fig.1 Microparticle separation array [19]

1.5 Cyclone Separator

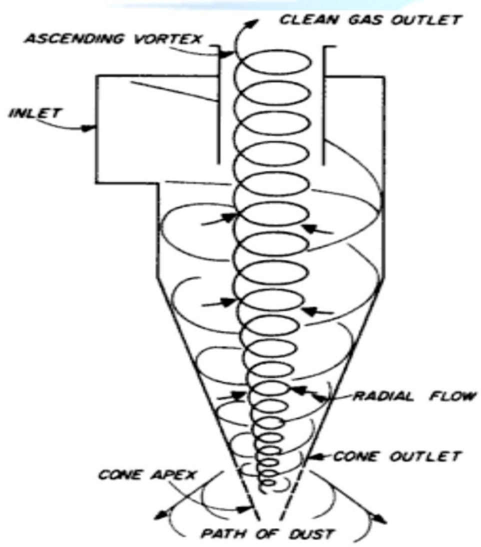

Fig.2 Basic Steps in Cyclone Separator

A cyclone is a conical vessel into which a dust-bearing gas-stream is passed tangentially. Because the rotating motion of the gas in the cyclone separator arises from its tangential entry and no additional energy is imparted within the separator body, a free vortex is established. The flow descends rotating near the wall, until a certain axial location where the axial velocity component reverses itself, thus making the flow to ascend. This is referred to as the vortex end position. The ascension proceeds near the cyclone axis and, since the flow rotation continues, a double vortex structure is formed. [13]. The solids are thrown to the outside edge of the vessel by centrifugal action, and leave through a valve in the vortex of the cone. Cyclones were originally used to clean up the dust-laden gases leaving simple dry process kilns. If, instead, the entire feed of raw mix is encouraged to pass through the cyclone, it is found that a very efficient heat exchange takes place. The gas is efficiently cooled, hence producing less waste of heat to the atmosphere, and the raw mix is efficiently heated. This efficiency is further increased if a number of cyclones are connected in series.

2. Literature

Hesham M. El-Batsh[1] has studied on improving cyclone performance by proper selection of the exit pipe. A numerical technique was used which is based on an Eulerian–Lagrangian approach. The behavior of the cyclone was studied by solving the three-dimensional, incompressible turbulent flow governing equations. The turbulent flow was modeled by using Reynolds Stress Model. Particle trajectories were obtained by solving the particle equation of motion. The collection efficiency was obtained by releasing a specified number of particles at the inlet of the cyclone and by counting the collected particles. The model was verified by comparing the numerical results to published experimental measurements.

Guangcai Gong[2] A two-stage turbulence model based on the RNG j–e model combined with the Reynolds stress model is developed in this paper to analyze the gas flow in an axial flow cyclone separator. Five representative simulation cases are obtained by changing the helix angle and leaf margins of the cyclone. The pressure field and velocity field of the five cases are simulated, and then the effects of helix angle and leaf margins on the internal flow field of the cyclone are analyzed.

Khairy Elsayed and Chris Lacor [3] have reported CFD modeling and multi-objective optimization of cyclone geometry using desirability function, artificial neural networks and genetic algorithms. The low-mass loading gas cyclone separator has two performance parameters, the pressure drop and the collection efficiency (cut-off diameter). In this paper, a multi-objective optimization study of a gas cyclone separator has been performed using the response surface methodology (RSM) and CFD data. The effects of the inlet height, the inlet width, the vortex finder diameter and the cyclone total height on the cyclone performance have been investigated. The analysis of design of experiment shows a strong interaction between the inlet dimensions and the vortex finder diameter. No interaction between the cyclone height and the other three factors was observed.

Sujeet Kumar Shukla[4] has studied the effect of modeling of velocity fluctuations on prediction of collection efficiency of cyclone separators. The effect of modeling of velocity fluctuations on the prediction of collection efficiency of cyclone separators has been numerically investigated using the Reynolds stress turbulence model (RSTM) and large eddy simulation (LES). The Eulerian–Lagrangian modeling approach of CFD code Fluent 6.3.26 has been employed to simulate the three dimensional, unsteady turbulent gas–solid flows in a Stairmand high efficiency cyclone. The simulated results have been compared with experimental observations available in the literature.

Khairy Elsayed[5] has studied the effect of the dust outlet geometry on the performance and hydrodynamics of gas cyclones. Four cyclone separators with different dust outlet geometries (without dustbin, with dustbin, with dipleg and with dustbin plus dipleg) have been computationally investigated. There are two purposes of this study. First, to study the effect of changing the dust outlet geometry on the flow field pattern and performance of air cyclones. Second, to demonstrate whether simulation of the flow without accounting for the dust outlet geometry (i.e., simulate only the cylinder on cone region) is sufficient for performance estimation. Results show that the maximum tangential velocity is almost the same for the four tested cyclones. No radial acceleration occurs in the cyclone space (the maximum tangential velocity is nearly constant throughout the cyclone).

Xiang Gao [6] et.al has performed the Numerical investigation of the effects of the central channel on the flow field in an oil–gas cyclone separator. The Reynolds stress turbulence model (RSM) was used in this study to numerically investigate the effects of the central channel parameters on the flow field in five cylinder-shaped oil–gas cyclone separators that are commonly used in compressor systems. Based on real working conditions, a wide range of central channel dimensions and pressure-out boundary conditions were employed. The results indicated that the central channel diameter and height has an insignificant effect on the flow field in the separator chamber and the effects of decreasing and increasing the central channel diameter and height were analysed. The tangential velocity near the wall was about 0.8–1.0 times that of the inlet velocity , and the maximum tangential velocity was about 1.8–2.0 times that of the inlet velocity. The maximum tangential velocities of the five separators were all in the radial position 0.3D, which was equal to the diameter of the outlet. This suggested that the position of the maximum tangential velocity is decided by the outlet diameter, not the diameter of the central channel.Both decreasing and increasing the diameter of the central channel from 0.5D caused increasing pressure drop and increasing maximum tangential velocity. Decreasing the diameter of the central channel by 40% resulted in a 5.9% increase in pressure drop and a 20% increase in maximum tangential velocity; whereas, increasing the central channel diameter by 40% resulted in a 2.4% increase in pressure drop and a 5% increase in maximum tangential velocity.

3. Overview of Cyclone Separator

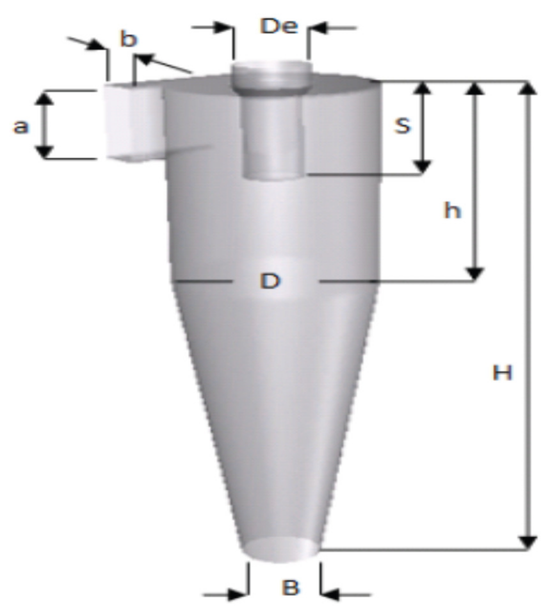

Fig. 3 Schematic Diagram of Cyclone

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.

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. The fluid enters the cyclone tangentially. The cyclone induces a swirl rotation and hence, imposes radial acceleration on particles. 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.

3.1 Analytical Investigation

There are 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. Eq. 1. Eq. 2 and Eq. 3 give drag force , centrifugal and buoyant force respectively .Drag force can be calculated from stoke's law and is given by Eq.1,2,3

$$F_d = 6\pi r_p \mu V_r \quad \ldots\ldots\ldots\ldots\ldots (1)$$

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

$$F_b = -V_p\,\rho_t\,\frac{V_t^2}{r} = -\frac{4}{3}\pi\rho_t r_p^3 \frac{V_t^2}{r} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

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

$$\frac{dr}{dt} = F_d + F_c + F_b = 0 \quad \ldots\ldots\ldots\ldots\ldots (4)$$

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.

$$r_p = \frac{3}{2}\left[\frac{V_r\,r}{V_t\,(\rho_p - \rho_f)}\right]^{1/2} \quad \ldots\ldots\ldots\ldots\ldots (5)$$

The above approach is very rudimentary and there are much more things that need to be considered when designing a cyclone separator.Most famous among these cyclones design are the Stairmand high efficiency cyclone , Lapple cyclone, Kim and Lee cyclone and the German Z cyclone.

3.2 Cyclone 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, 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.

$$M_f = M_c + M_e \quad \ldots\ldots\ldots\ldots\ldots (6)$$

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

$$\eta = \frac{M_c}{M_f} = 1 - \frac{M_e}{M_f} = \frac{M_c}{M_c + M_e} \quad \ldots\ldots\ldots\ldots (7)$$

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.

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 as follows

$$\eta = 1 - (1 - \eta)\frac{f_e(x)}{f_f(x)} \qquad \text{.............(8)}$$

3.3 Cyclone Efficiency Empirical Models

Lapple 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.

$$d_p = \sqrt{\frac{9\mu b}{\pi N_e V_t\ (\rho_p - \rho_g)}} \qquad \text{............ (9)}$$

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

$$d_{pc} = \sqrt{\frac{9\mu b}{2\pi N_e V_t\ (\rho_p - \rho_g)}} \qquad \text{............ (10)}$$

Iozia and Leith 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 Eq. 11 . 33] developed a logistic model based on Barth is given by

$$\eta_t = \frac{1}{1 + (d_{pc}/d_{pa})^{\beta}} \qquad \text{.......... (11)}$$

Leith and Licht 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

$$\eta_t = 1 - exp\left(-\psi d_p^M\right) \qquad \text{.......... (12)}$$

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. The pressure drop in a cyclone is proportional to velocity head as depicted by

$$\Delta P = \alpha \frac{\rho V_t^2}{2} \qquad \text{........(13)}$$

The three changed dimensions has suggested and analysed for cone to diameter ratio. The change in dimension at the outlet should be in concern with the inlet diamensions. The inlet height 'a' and the inlet width 'b' should be change in proportion so as to improve the cyclone performance.

The three models of cyclone separator Starmand (High efficiency), Lapple and Swift (High efficiency) are selected for the dimension variation. The standard dimensions are as shown in table 1.

The same changes are considered for the Stairmand,Lapple and Swift model. The cone tip diameter ratio is used as a reference to change the inlet dimensions.

$$\frac{B}{D} \times \frac{D}{a} = \frac{B}{a} \qquad \text{................ (14)}$$

Similarly

$$\frac{B}{D} \times \frac{D}{b} = \frac{B}{b} \qquad \text{.................. (15)}$$

Table 1 : Standard Geometrical Design of Industrial Cyclone Separator

Source	Starmand (1951)	Lapple (1951)	Swift (1969)
Duty	High Efficiency	General Propose	High Efficiency
D	1	1	1
a/D	0.5	0.5	0.44
b/D	0.2	0.25	0.21
De/D	0.5	0.5	0.4
S/D	0.5	0.625	0.5
h/D	1.5	1	1.4
H/D	4	4	3.9
B/D	0.375	0.25	0.4

Table2: Relation of Inlet Dimension

Model	B/a	B/b
Starmand	0.75	1.87
Lapple	0.5	1
Swift	0.9	1.9

The analytical approach is used on these three models where as the CFD is used to study one of them. The investigation is performed for the air as a flowing fluid.as shown in table 3.

4. Result and Discussion

The variation of dimensions is studied using Empirical Models. The study is performed for effect of inlet velocity on static pressure drop for Lapple , Swift and Starmand Model. The results are compared on a common scale for variation of change of con tip diameter along with inlet width and inlet height.

Inlet velocity Vs static pressure drop for Lapple Model.

The variation of velocity against pressure for the Lapple Model reported in Fig 4. The velocity is on x axis is varied from 2m/s to 16 m/s, whereas the corresponding are observed in range of 0 to 900 Pa.

Table 3: Material Properties of Air

Property	Units	Value(s)
Density	Kg/m^3	1.225
C_p(Specific Heat)	j/kg-k	1006.43
Thermal Conductivity	w/m-k	0.0242
Viscosity	Kg/m-s	1.7894007e-0.5
Molecular Height	kg/kgmol	28.966

.All three variations are plotted on a common reference along with the CFD result and actual result reported in literature.

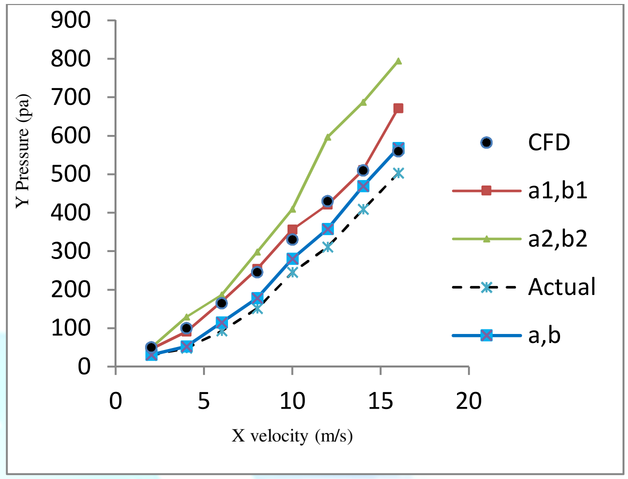

Fig. 4 Comparison with Lapple mode

The model a,b is varied for minimum value of 31Pa at 2m/s and maximum of 568 Pa at 16m/s. Whereas a_1, b_1 in the maximum value change to 671Pa. The highest value reported in Fig.4 is observed for variation of a_2, b_2 is 794 Pa.

The CFD results reported a close degree of agreement to model a_1, b_1. The CFD reports almost 0 deviation for maximum value at a_1, b_1 and trend of variation for a_1, b_1.

The variation of Collection efficiency for the Lapple Model is performed for particle size. The result obtained is shown in Fig. 5.The particle size is on x axis is ranging from 1 m (e^-7) to 8 m (e^-7). Y variation is observed in range of 0 to 120. All three variations are plotted on a common reference along with the CFD result.

The results are obtained for different models such as Lapple, Leith and Licht all are based upon force balance. Lapple model is varied for minimum value of collection efficiency 10 at 1 m (e^-7) and maximum of 86 at 8 m (e^-7). Whereas in Leith model the maximum value changes to 99 and in Licht model is 99. The CFD simulations yielded very good predictions on cyclone collection efficiency.The CFD results reported close agreement to Lapple Model viz. 87. However, the CFD result still yielded an accurate prediction on cut size diameter.

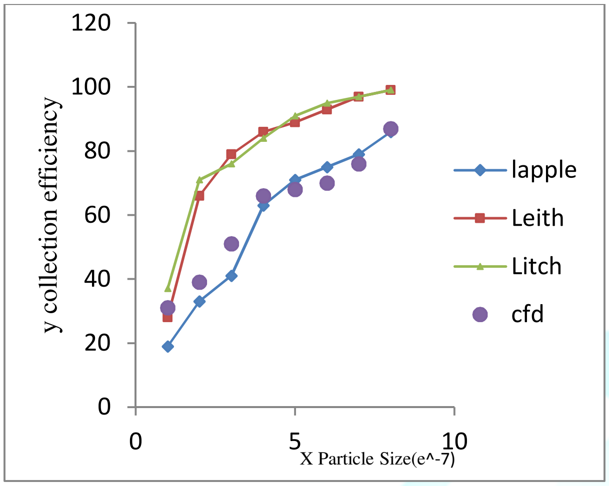

Fig.5 Lapple Model

Among three models Lappel , Swift and Starmand pressure drop given by Lappele model is comparatively less. Also the % deviation is less. This is because the Lapple model simply assumes that particles that enter the cyclone are evenly distributed across the inlet opening and a particle that travels from the inlet half width to the cyclone wall is collected with 50% efficiency. Hence Lapple model is compared with actual and Literature result for more definite conclusion.

The variation of velocity for the Lapple Model is performed for 2m/s to 16m/s. whereas the corresponding are observed in range of 0 to 900 Pa. All three variations are plotted on a common reference along with the CFD result and actual result reported in literature.

The result obtained is shown in Fig.6. The results are obtained for deviation of a, b to a_1, b_1 and a_2, b_2 along with the change of cone tip diameter.

Contours of static pressures are drawn for change in dimensions from a, b to a_2 , b_2 at v = 16 m/s. for Lapple Model as shown in fig. 7

The deviation has been seen for all pressure changes wich is due to the change in diemesion of inlet width(b) and inlet height(a). With the chang in inlet diemnsions the static pressure for Lapple model increases. Static Pressure for changed dimension a_2,b_2 has close agreement with CFD results. From analytical results it has been noticed that at 16 m/s the static pressure is maximum so CFD analysis is done only for 16m/s. It has been also observed that analytical results gives slightly overestimating results than CFD and actual.

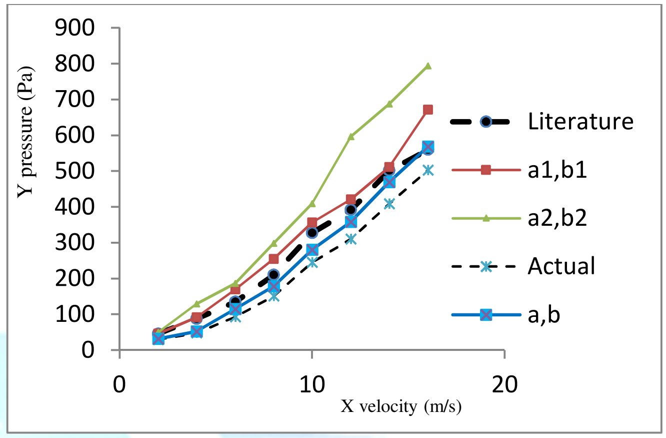

Fig.6 Comparison with literature and actual with Lapple Model

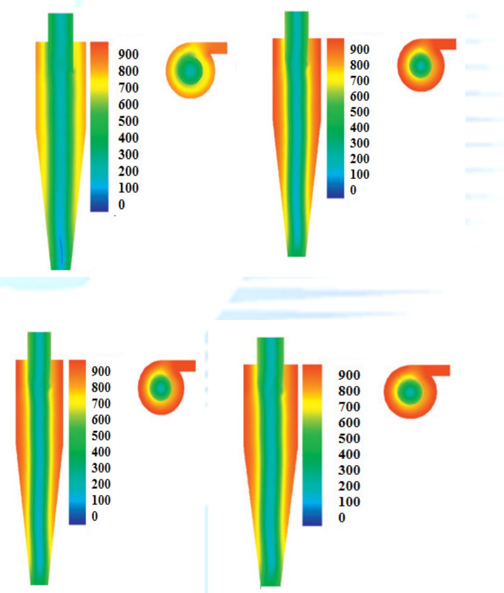

Fig.7 Static Pressure for Lapple Model v= 16 m/s for a,b and a_1, b_1 , :iterature and CFD

Three sections have considered along the cyclone body at the inlet edge ,in the middle of cyclone and at outer edge. The summary of the result is tabuated as under

Velocity	a,b	a_1 , b_1	a_2 , b_2	CFD
16	550	650	790	600

The variation of velocity for the Starmand Model is also performed for 2m/s to 16m/s. The result obtained is shown in Fig.8.The results are obtained for deviation of a, b to a1, b1 and a2, b2 along with the change of cone tip diameter.

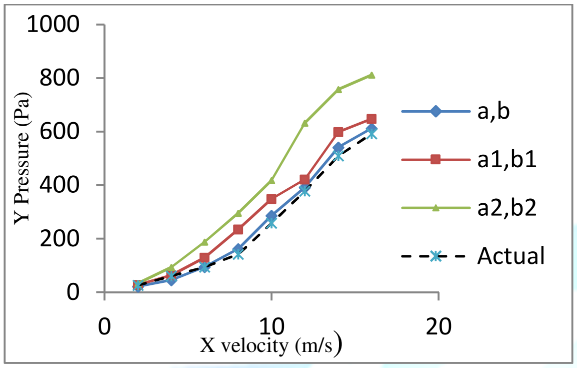

Fig. 8 Comparison with Starmand model

It is observed that the actual Cyclone results without change of a, b are increases gradually with change of a, b. The model M1 is varied for minimum value of 22 Pa at 2m/s and maximum of 612 Pa at 16m/s. Similarly for a1, b1 and a2, b2 the maximum pressure value is 648 Pa and 812 Pa respectively. This pressure drop is higher than the pressure drop given by Lapple Model.

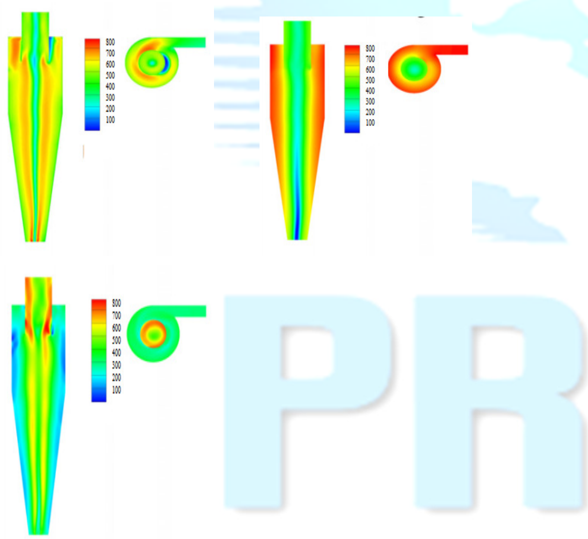

Fig.9 Static Pressure for Starmand Model v = 16m/s fo a1 , b1 , a2 , b2 and actual

Contours of static pressures are drawn for change in dimensions from a, b to a2 , b2 at v = 16 m/s. for Starmand Model as shown in fig.9.

The contour of static pressure is studied using CFD. From Fig 9 highest static pressure has been observed at velocity 16 m/s. This model is compared with actal results for change of dimensions. For starmand model also static pressure increases with change in dimensios. But from analytical results it has been observed that the % deviation is more. The summary of the result is tabuated as under

Static Pressure for changed dimension a1 , b1 has close

Velocity	a1 , b1	a2 , b2	Actual
16	650	800	600

agreement with actual results. Static pressure decrease radially from wall to centre.

5. Conclusion

The cyclone separator has been studied for improvement in performance by changing different dimensions of the separator. Mathematical model has been developed using empirical models. The model is formulated for effect of change of cone dimensions along with proportionate change in inlet dimensions.Using three empirical models such as Lapple Model , Swift Model ansd Starmand Model results are obtained for pressure drop and collection efficiency. By changing the value of inlet width and inlet height various values of pressure and collection efficiency are obtained for Lapple model ,Swift and Starmand Model. Variations are compared with literature and actual results. It has been observed that the value of pressure and collection efficiency are increasing with the change in dimensions of inlet parameters. The velocity variation, change of efficiency and variation of pressure difference is studied for variation of dimension using Lapple , Leith and Licht models.The analysis is verified by using Customized software package of CFD. The results are obtained for three models and are compared for static pressure variation with velocity. Lapple Model has given good agreement with CFD and actual results as it assumes the particles are evenly distributed across the inlet velocity

After comparing all the three empirical models Lapple Model has consistently given good results. Hence the actual and literature result has been compared with Lapple Model.

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