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Analysis of Cyclone Separator for Air Pollution Control

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Abstract: In the present world scenario air pollution is the major concern for all the environmental engineers. Many engineering equipment are available for control of air pollution up to certain level. Cyclone precipitator is one of the most important mechanical device used for air pollution control. In order to reduce the pollution level optimum design of Cyclone precipitator plays important role and influence of their process parameter on the efficiency required critical investigation. In this work, Taguchi methods have been utilized to optimize the pressure drop and particle collection efficiencies. These key parameters play an important role in process parameters of preheater cyclone separators used in the cement industry. The process parameters have been analyzed under varying cone height (300, 340 and 390 mm), inlet height (123, 153 and 173 mm), outlet height (80, 90 and 100 mm) and pipe length (450, 470 and 490) mm. The settings of the test parameters were determined by using Taguchi's experimental design method. Orthogonal arrays of Taguchi and the signal-to-noise ratio have been employed to find the optimal levels and to analyze the effects of the design parameters on pressure drop and efficiency values. Using the signal to noise ratio the optimum value of pressure drop and efficiency is obtained by the MINITAB. The optimum pressure drop is Cone height 340 mm, inlet height 123 mm, outlet height 80 and pipe length 450 mm. The optimum efficiency is Cone height 390 mm, inlet height 173 mm, outlet height 90 and pipe length 490 mm.

Keywords: Cyclone separators; Collection efficiency; Optimization.

I. INTRODUCTION

Many chemical processes which consist of reaction stages and/or separation stages in which the process streams are separated and purified. Such separations involve physical principles based on differences in the properties of the constituents in the stream. Heterogeneous mixtures consist of two or more phases which have different composition. These mixtures consist of components that do not react chemically and have clearly visible boundaries of separation between the different phases. Components of such mixture can be separated using one or more appropriate techniques. These separation processes includes Gas-Liquid (vapor-liquid) separation, Gas-Solid separation (vapour-solid), Liquid-Liquid separation (immiscible), Liquid-Solid, and Solid-Solid separation etc. This separation can be done by exploiting the differences in density between the phases. Gravitational force or centrifugal force can be used to enhance the separation.

The separation units can be either horizontal or vertical. Cyclone separators provide a method of removing particulate matter from air or other gas streams at low cost and low maintenance. Cyclones are somewhat more complicated in design than simple gravity settling systems, and their removal efficiency is much better than that of settling chamber. Cyclones are basically centrifugal separators, consists of an upper cylindrical part referred to as the barrel and a lower conical part referred to as cone (Fig 1.1). They simply transform the inertia force of gas particle flows to a centrifugal force by means of a vortex generated in the cyclone body. The particle laden air stream enters tangentially at the top of the barrel and travels downward into the cone forming an outer vortex. The increasing air velocity in the outer vortex results in a centrifugal force on the particles separating them from the air stream. When the air reaches the bottom of the cone, it begins to flow radially inwards and out the top as clean air/gas while the particulates fall into the dust collection chamber attached to the bottom of the cyclone.

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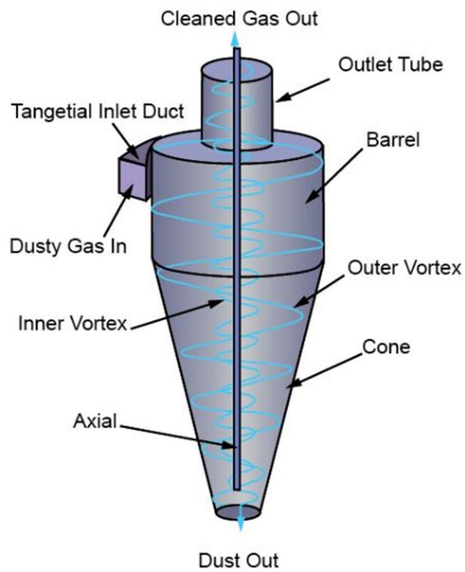

Fig 1. Schematic diagram of cyclone separator (Elsayed, 2011).

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Cyclones are basically centrifugal separators. They simply transform the inertia force of gas particle to a centrifugal force by means of a vortex generated in the cyclone body. The particle laden gas enters tangentially at the upper part and passes through the body describing the vortex. Particles are driven to the walls by centrifugal forces (an expression for this force is given blow eq. 1.1), losing its momentum and falling down to the cyclone leg. In the lower section, the gas begins to flow radially inwards to the axis and spins upwards to the gas outlet duct (Elsayed, 2011).

$$F = \frac{\rho_p d_p^{\,3} v_p^{\,2}}{r} \qquad (1.1)$$

ρ_p = particle density, (kg/m^3)
d_p = particle diameter, inches (µm)
v_p = particle tangential velocity (m/s)
r = radius of the circular path, (m)

The main variables describing the cyclone performance are pressure drop, efficiency and cut diameter. Equations involving each of these parameters are provided in this section.

The collection or separation efficiency is most properly defined for a given particle size. As mentioned, fractional efficiency is defined as the fraction of particles of a given size collected in the cyclone, compared to those of that size going into the cyclone. Experience shows that collection efficiency of cyclone separator increases with increasing particle mean diameter and density; increasing gas tangential velocity; decreasing cyclone diameter; increasing cyclone length; extraction of gas along with solids through the cyclone legs.

Several equations have been developed to predict the collection efficiency in cyclones through correlation equations. The following section describes two methods of calculating cyclone efficiency. First the theory proposed by Leith and Licht (1973) for calculating fractional efficiency will be discussed and then a convenient graphical method developed by Lappel (1951) will be presented.

The fractional efficiency equation of Leith and Licht is given as:

$$E_i = 1 - e^{\left(-2(C\varphi)^{1/(2n+2)}\right)} \qquad (1.3)$$

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Where
C = cyclone dimension factor
ψ = impaction parameter
n = vortex exponent

$$\varphi = \frac{\rho_p d_p^{\,2} v_i}{18\mu D_c}(n+1) \tag{1.4}$$

In this expression, c is a factor that is a function only of the cyclone's dimensions. The symbol ψ expresses characteristics of the particles and gas and is known as inertia or impaction parameter. The value of n is dependent on the cyclone diameter and temperature of the gas stream. And ρp times vi expresses the particle's initial momentum. Although the calculation involved in this method are tedious but are straightforward (Elsayed, 2011).

Many engineering and industrial processes involves different operations like burning of coal, crushing, chemical coatings etc. through which as an end product it rejects small particles to the environment. To reduce environment pollution, many mechanical devices are used in industries. Cyclone separator is one of the most common device employed for the same.

The objective of this study also focused on the same purpose, which is as follows.

1) The detailed study of designs of cyclone separators.
2) The validation of existing literature for computational work.
3) Analysis of flow behavior inside the cyclone separator.
4) Formulation of design of experiments.
5) To obtain number of desired set of output for optimization.
6) Optimization of design parameters for maximum efficiency and minimum pressure drop.
7) Verify the outputs of optimization for desired outputs.

II. LITERATURE REVIEW

It is very economical way using by different particle controlling industries to remove particles larger than 2 μm in size (hinze, 1975) .Two swirling motion of fluid i.e. vertically opposed directions (double vortex phenomenon takes places for particle separation inside cyclone. The larger particles associated with centrifugal force which is caused by swirling motions directs the particles downwards and then separates from smaller particles, whereas small particles depart with the flow. Many studies neglected the conical section and the dust collection section but these two are very important because of the vortex phenomenon. Studies related to the geometry of cyclone separator are very popular in literature, in this regards many studies are focused on performance of cyclone based on particle collection section.

Wang et al. (2020): Wang et al experimentally observed that the collection efficiency for particles around 2 μm is mostly improved, apart from this they observed that because of the agglomeration the particle size get enhanced after some time and hence reduces the collection efficiency. The use of atomization and electrostatic charging get enhanced the collection efficiency.

Qian et al. and Kaya and Karagoz (2009): With the application of down- comer vertical tubes it has been found that there is less pressure drops because of the decrease of wall friction due to reduction of particle re-entrainment from the hopper into the cyclone.

A. Raoufi et. al (2008): The optimization work has been proposed by Raoufi and coworkers for the diameter and inlet type, including single and double inlet to improve the efficiency (Roufi, et al., 2008).

Obermair et al. (2003): Obermair has been reported that the separation of solid at the cyclone bottom is the major factor for collection efficiency which generates due to the natural vortex length of the flow, higher tangential velocities, particle reentrainment and high particle concentrated zones.

A. Avci et. al (2003): The attempts have been conducted to improve the separation performance of cyclone separators by optimizing the structure dimension, such as vortex length vortex finder shape (Avci & Karagoz, 2003).

J.A. Gallego-Juarez et. al (1999): The separation efficiency has been improved by some preconditioning technologies which enlarges the size of fine particles. These technologies mainly consist of heterogeneous condensation, acoustic agglomeration in which the submicron particles can be enlarged, and rearrangement has been done for the solid particle (Gallego-Juárez, et al., 1999).

T. Zhang et. al (1992): They have done some other developments in fine particle collection such as confined vortex scrubber, composite filter separator rotational particle separator and rotating packed bed. Through these all arrangement they observed significant improvement in the efficiency (Zhang, et al., 2017).

Cyclone separator is very well known and commonly used device in almost every industries as well as it is being used time ago, but the accurate behavior based on its design criterion is still not available. The major task during this work is therefore, a detailed study of the flow behavior of different design of cyclones to achieve an optimum cyclone separator (minimum pressure drop and maximum collection efficiency). There are many parameters like operational parameters which governs the cyclone performance, but this study is restricted to and geometrical parameters only. Through this study the effect of geometrical parameters on the cyclone efficiency has been analyzed and based on optimization technique the optimum design of the cyclone separator has been achieved.

Specific objectives of the work are the following:

1) To determine the most substantial factors for the cyclone performance, based on previous studies and statistical analysis of data.
2) Focused study for every important parameter distinctly to obtain more details on their effects on the flow field pattern and hence of cyclone efficiency.
3) To find out optimized design of cyclone for best performance (minimum pressure drop and maximum efficiency) using multi objective optimization techniques.

III. PROBLEM IDENTIFICATION

Every design of mechanical equipment requires maximum performance and minimum cost of production of the equipment. In the same manner the cyclone precipitator is also a complicated design which need very precise design work so that it would give maximum collection efficiency and minimum drop in the pressure. The cyclone performance has been evaluated when the separation efficiency, pressure drop is considered as a major criterion of the design. The analysis has been set on the basis of complex relationship between pressure drop and cyclone characteristics. Since the pressure drop in a cyclone separator is not having linear relationship with cyclone dimensions, hence this condition leads to optimization problem. To make a balance between design and performance optimization tool Taguchi has been adopted which gives optimum design dimensions of the cyclone with maximum collection efficiency and minimum pressure drop.

IV. METHODOLOGY

The simulation work of the entire project has been carried out by the commercial computational fluid dynamics software (ANSYS FLUENT 16.1). At the beginning of this work the simulation work has been carried out with reference geometry to validate the previous literature work (Ganegama Bogodage & Y.T. Leung, 2015). Apart from this the validation of previous work shows the accuracy and system settings of our simulation software. The geometry of the cyclone separator has been created in designing software (Solid Works) and the same has been imported to ANSYS work bench for analysis purpose. Following are the some important steps shown through picture during the setup of the simulation.

In this analysis all the geometry has been taken without any variation and alteration to validate the CFD results with reference work (Ganegama Bogodage & Y.T. Leung, 2015). The ideal geometry has the following dimensions of the cyclone.

Table 1. Dimensions of the cyclone.

Geometric parameter	Dimension (mm)
Body diameter	330.200
Inlet/Outlet pipe diameters	69.120
Cyclone cylindrical body height	254.000
Cyclone conical body height	390.525
Cyclone total height	693.7375
Vortex finder height	303.2125
Vortex finder diameter	152.400
Cone tip diameter	152.400
Hopper height	254.0

For calculation of collection efficiency for different geometries in at the inlet solid loading rate of 1.0 g/m^3 has been provided to the inlet pipe. The collection efficiency has been calculated from the below equation (Santosh , et al., 2011).

Collection efficiency = [(inlet loading — outlet loading)/ (inlet loading)] x 100............4.1

Optimization of the cyclone has been through design of experiments and Taguchi method for which four different design parameters namely cone height, inlet height, outlet height and pipe length of the cyclone precipitator has been optimized (Presented in Table 1). The design of experiments has been performed one the basis of standard value of above mentioned four parameters. The CFD analysis has been done four all standard as well as the range of dimensions (minimum and maximum), through which pressure drop and collection efficiency has been analysed. Geometry and meshing were developed by ANSYS software. Tetra meshing was used due to the geometric complexity, as recommended by ANSYS for Large Eddy Simulation (LES) model has been chosen. The pressure drop has been observed directly from CFD tool ANSYS FLUENT whereas the below equation has been adopted to calculate the dust collection efficiency.

A. Control Factors and Levels

Total of four design parameters with three levels are selected as the control factors such that the levels are sufficiently far apart so that they cover wide range. The four control factors selected are A- Cone height, B- Inlet height, C- Outlet height and D- Pipe length. Control factors and their levels are listed below Table 2.

Table 2. Process parameter and their levels used in the investigations.

Factor	Process parameter	Unit	Level 1	Level 2	Level 3
A	Cone height	mm	300	340	390
B	Inlet height	mm	123	153	173
C	Outlet height	mm	80	90	100
D	Pipe length	mm	450	470	490

B. Design of Experiments (DOE)

The DOE with L_9 orthogonal array (OA) is presented below in Table 3. The selection of OA from the standard OA requires minimum number of experiments to be performed this is based on the number of factors, levels of each factor and the total degrees of freedom (DOF).

Number of control factors = 4.

Number of levels for each control factor = 3.

Total DOF of factors = 4×(3-1) = 8.

Minimum number of experiments to be performed = 8+1 = 9.

Table 3. L_9 orthogonal array for optimization.

Set	Cone height (Level)	Inlet height (Level)	Outlet height (Level)	Pipe length (Level)
Set-1	1	1	1	1
Set-2	1	2	2	2
Set-3	1	3	3	3
Set-4	2	1	2	3
Set-5	2	2	3	1
Set-6	2	3	1	2
Set-7	3	1	3	2
Set-8	3	2	1	3
Set-9	3	3	2	1

V. RESULT AND DISCUSSION

A. CFD Analysis for DOE Combination

As per the DOE combination discussed in the above chapter the CFD analysis has been performed and the collection efficiency has been calculated from Equation 1.3 and pressure drop has been obtained directly from CFD tool. The result of all nine DOE combination has been provided below from Figs 2-10.

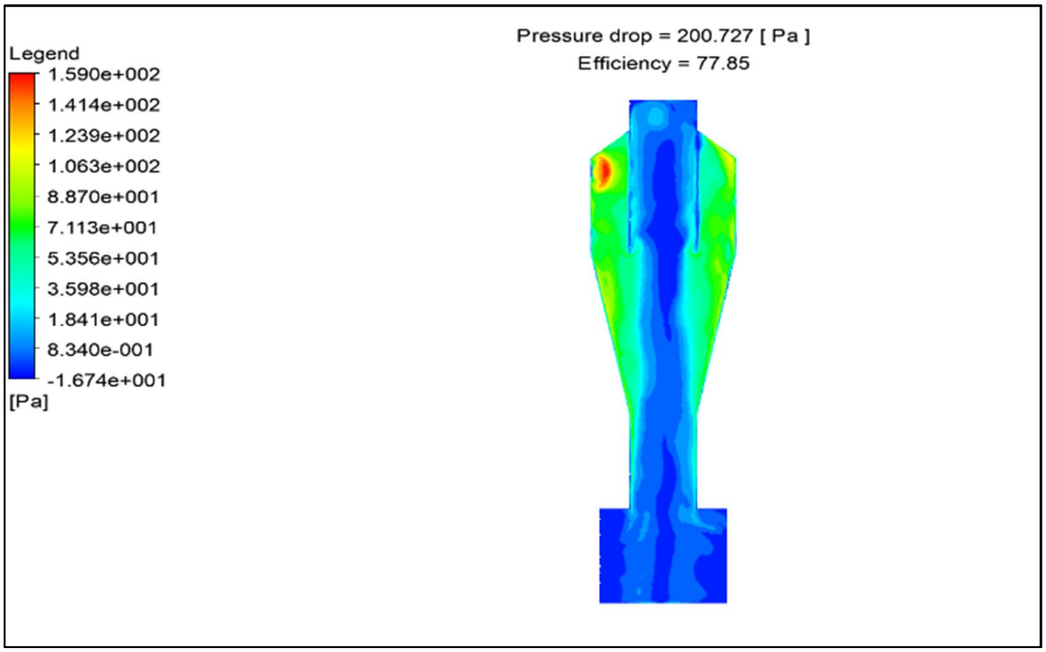


Fig 2. CFD result of set-1.

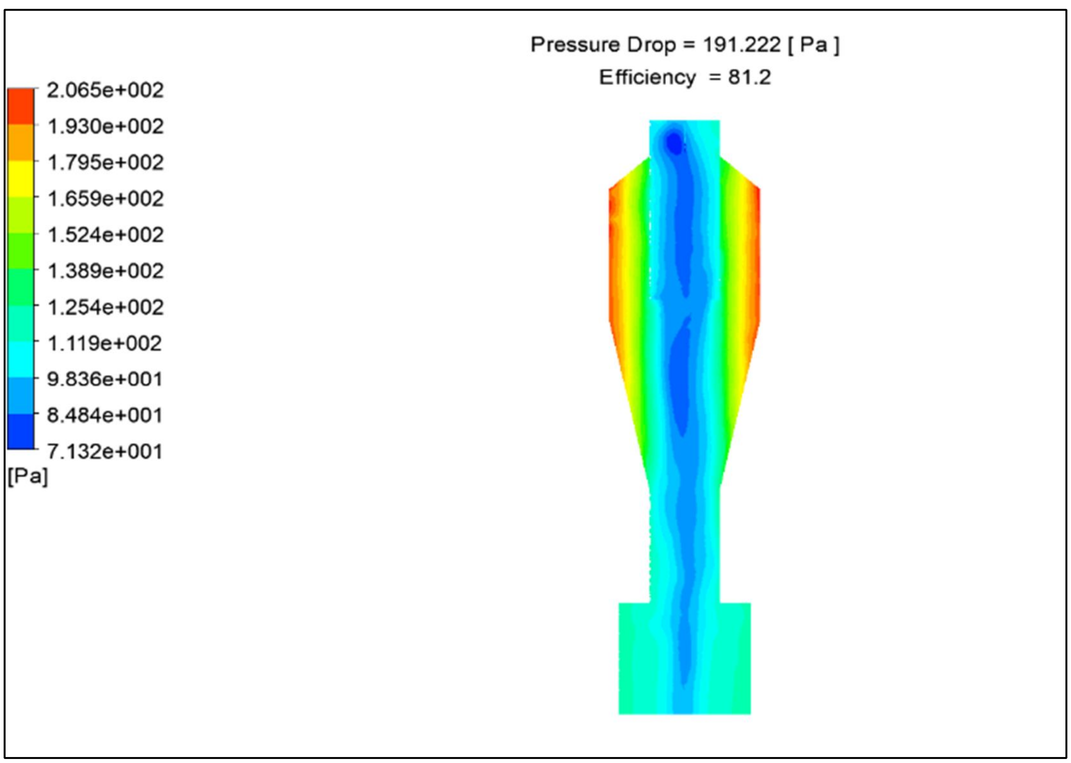


Fig 3. CFD result of set-2.

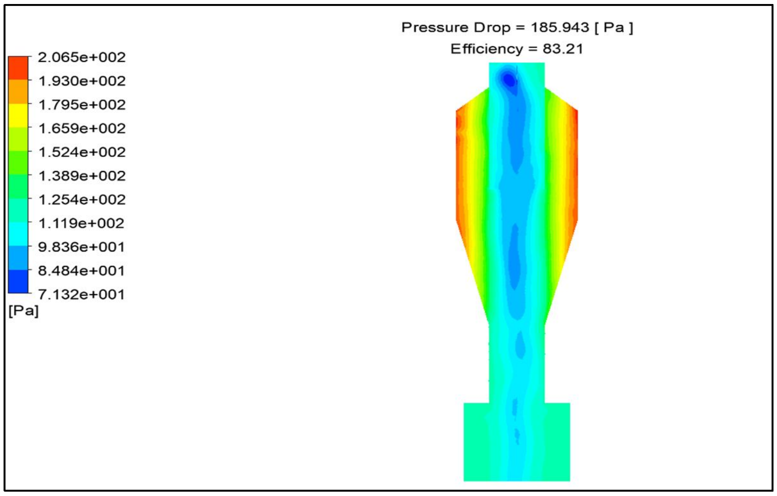


Fig 4. CFD result of set-3.

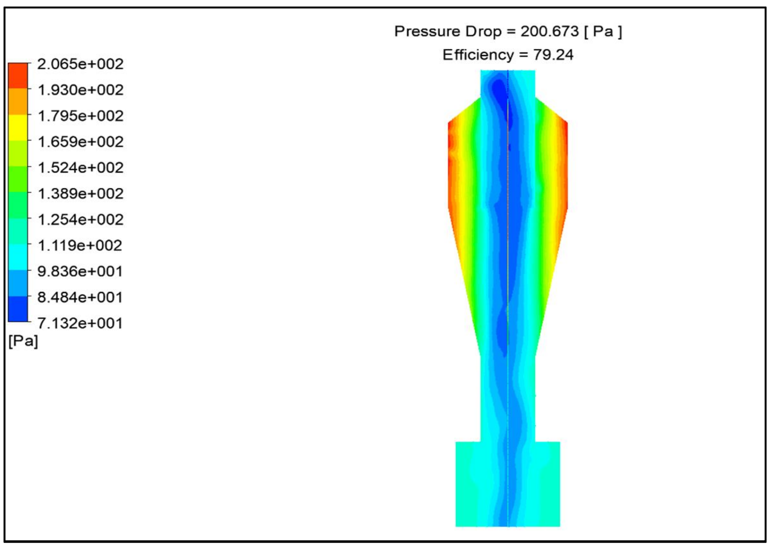


Fig 5. CFD result of set-4

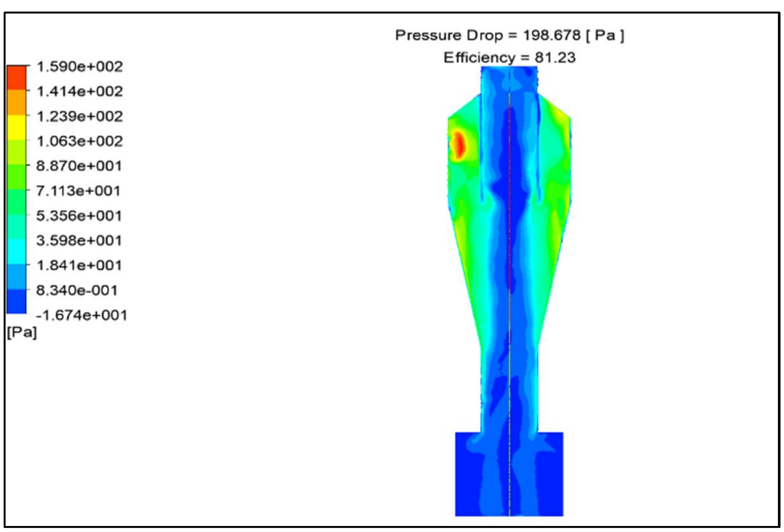


Fig 6. CFD result of set-5.

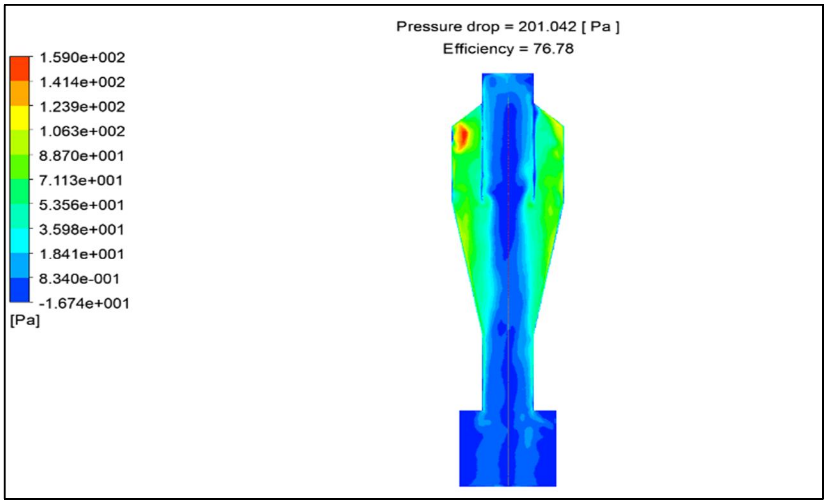


Fig 7. CFD result of set-6.

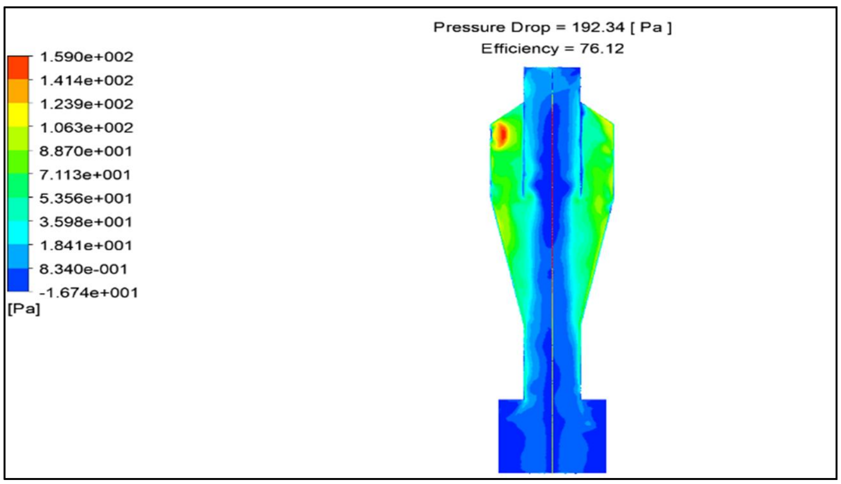


Fig 8. CFD result of set-7.

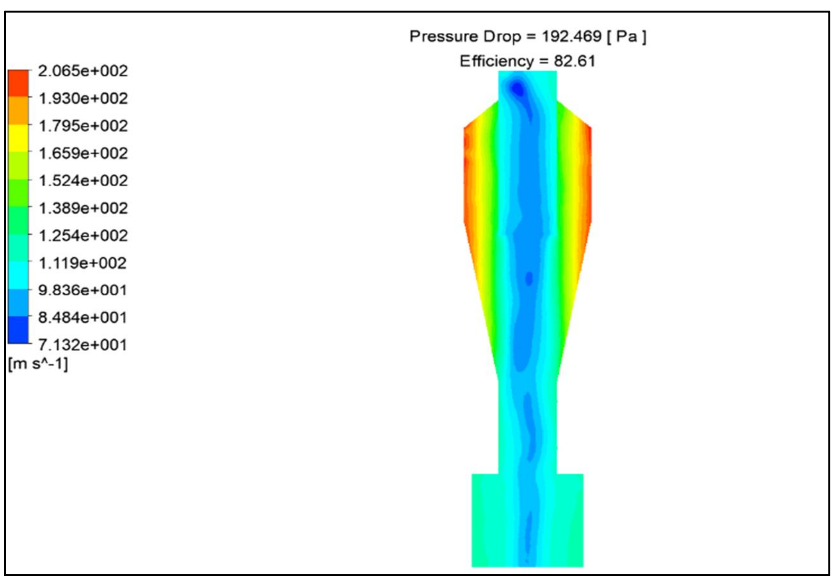


Fig 9. CFD result of set-8.

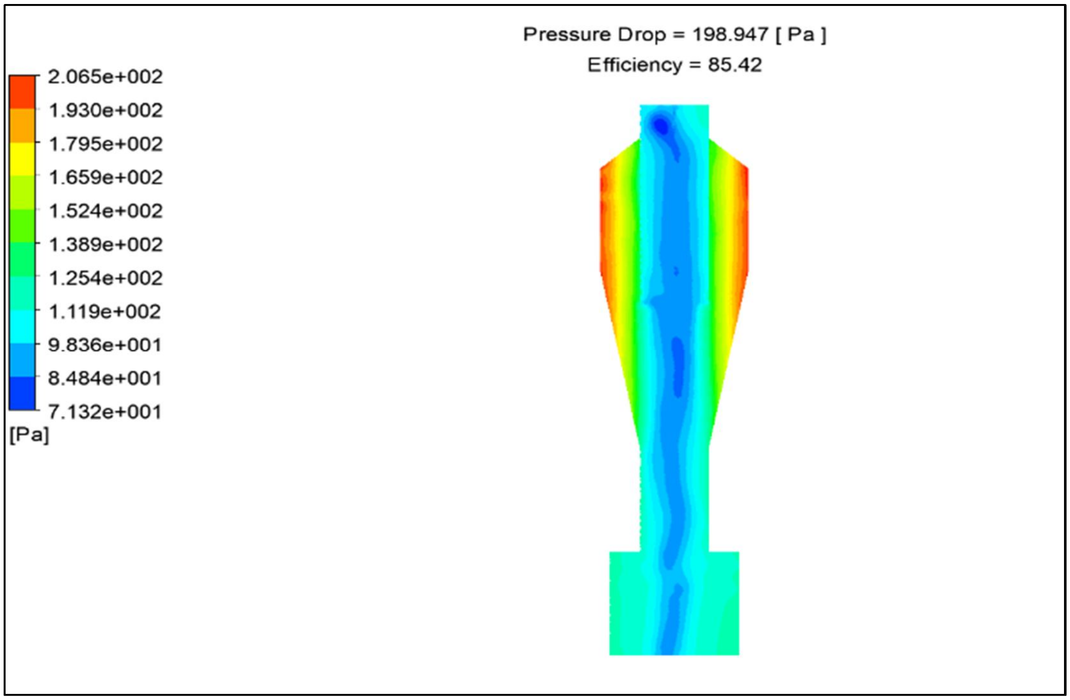


Fig 10. CFD result of set-9.

Table 4. DOE combination for optimization.

S. No.	Cone height (mm)	Inlet height (mm)	Outlet height (mm)	Pipe length (mm)	Pressure drop (Pa)	Efficiency (%)
1	300	123	80	450	200.727	77.85
2	300	153	90	470	191.222	81.2
3	300	173	100	490	185.943	83.21
4	340	123	90	490	200.673	79.24
5	340	153	100	450	198.678	81.23
6	340	173	80	470	201.042	76.78
7	390	123	100	470	192.34	76.12
8	390	153	80	490	192.469	82.61
9	390	173	90	450	198.947	85.42

B. Taguchi analysis and Calculation of S/N ratio

Study of the effect of different design parameters (cone height, Inlet height, outlet height and pipe length) on the pressure drop and efficiency was conducted with a so-called S/N response table, through MINITAB 17.0 statistical software. The analysis are formulated according to the OA in order to relate the influence of the input parameters on the pressure drop and efficiency. The pressure drop and efficiency values were obtained from CFD analysis for all the nine combinations. Further analysis has been performed employing Taguchi technique in Minitab software. The pressure drop and efficiency values were obtained from CFD analysis and their corresponding S/N ratio values are presented in Table 5.

Table 5. Design of experiment employing L9 orthogonal array and S/N Ratios.

S. No.	Cone height (mm)	Inlet height (mm)	Outlet height (mm)	Pipe length (mm)	Pressure drop (Pa)	Pressure drop S/N Ratios	Efficiency (%)	Efficiency S/N Ratios
1	300	123	80	450	200.727	-46.0521	77.85	37.8252
2	300	153	90	470	191.222	-45.6308	81.2	38.1911
3	300	173	100	490	185.943	-45.3876	83.21	38.4035
4	340	123	90	490	200.673	-46.0498	79.24	37.9789
5	340	153	100	450	198.678	-45.9630	81.23	38.1943
6	340	173	80	470	201.042	-46.0657	76.78	37.7050
7	390	123	100	470	192.34	-45.6814	76.12	37.6300
8	390	153	80	490	192.469	-45.6872	82.61	38.3407
9	390	173	90	450	198.947	-45.9747	85.42	38.6312

C. Taguchi Analysis: Pressure drop versus Cone height, Inlet height, Outlet height, Pipe length

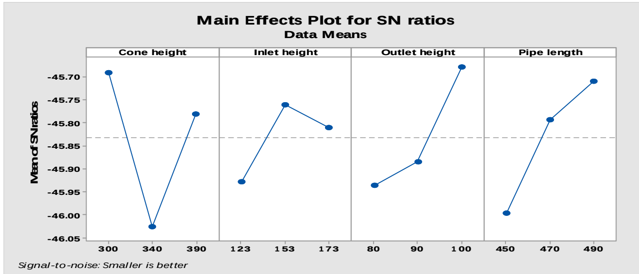
Table 6. The Signal to Noise ratios response table for pressure drops (smaller is better).

Factor	A	B	C	D
Level	Cone height	Inlet height	Outlet height	Pipe length
1	-45.69	-45.93	-45.94	-46.00
2	-46.03	-45.76	-45.89	-45.79
3	-45.78	-45.81	-45.68	-45.71
Delta	0.34	0.17	0.26	0.29
Rank	1	4	3	2
Optimum Level	$A_2B_1C_1D_1$			

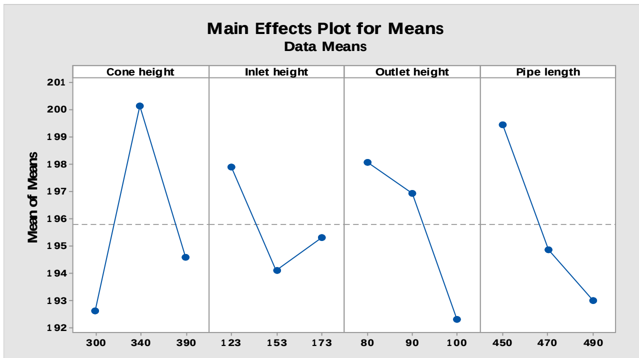
Table 7. The response table for means (smaller is better).

Factor	A	B	C	D
Level	Cone height	Inlet height	Outlet height	Pipe length
1	192.6	197.9	198.1	199.5
2	200.2	194.1	196.9	194.9
3	194.6	195.3	192.3	193.0
Delta	7.6	3.8	5.8	6.4
Rank	1	4	3	2
Optimum Level	$A_2B_1C_1D_1$			

The response table for each response characteristic such as S/N ratio and mean are estimated by Minitab software. Which factors has the largest impact on the response and which level of factor is related to higher or lower response characteristic values can be indicated by the response table. The strongest control factors for pressure drop and collection efficiency are presented in Tables 6 and 7. The optimal design parameters of all four control factors could be determined from the S/N graphs in Figs 10 and 11 for pressure drop and collection efficiency, respectively. Different between the highest and lowest value for a factor is called delta. Amongst the all factors, A has highest value so it is ranked first, factor D has second highest value and ranked second, factor C is third highest so ranked third and factor D has least value compared to other factors so it is ranked fourth.



(a)



(b)

Fig 10. Main effects plots for (a) S/N ratios and (b) Means of pressure drop.

Using the signal to noise ratio the optimum value of pressure drop is obtained by the MINITAB. The lowest pressure loss was achieved corresponding to: cone height: 340 mm, inlet height: 123 mm, outlet height: 80 and pipe length: 450 mm.

D. Taguchi Analysis: Efficiency versus Cone height, Inlet height, Outlet height, Pipe Length

Table 8. The Signal to Noise Ratios Response Table for Efficiency (Larger is better).

Factor	A	B	C	D
Level	Cone height	Inlet height	Outlet height	Pipe length
1	38.14	37.81	37.96	38.22
2	37.96	38.24	38.27	37.84
3	38.20	38.25	38.08	38.24
Delta	0.24	0.44	0.31	0.40
Rank	4	1	3	2
Optimum Level	$A_3B_3C_2D_3$			

Table 9. The response table for means (Larger is better).

Factor	A	B	C	D
Level	Cone height	Inlet height	Outlet height	Pipe length
1	80.75	77.74	79.08	81.50
2	79.08	81.68	81.95	78.03
3	81.38	81.80	80.19	81.69
Delta	2.30	4.06	2.87	3.65
Rank	4	1	3	2
Optimum Level	$A_3B_3C_2D_3$			

The Tables 8-9 it has been found that the Factor B has highest value so it is ranked first, factor D has second highest value and ranked second, factor C is third highest so ranked third and factor A has least value compared to other factors so it is ranked fourth.

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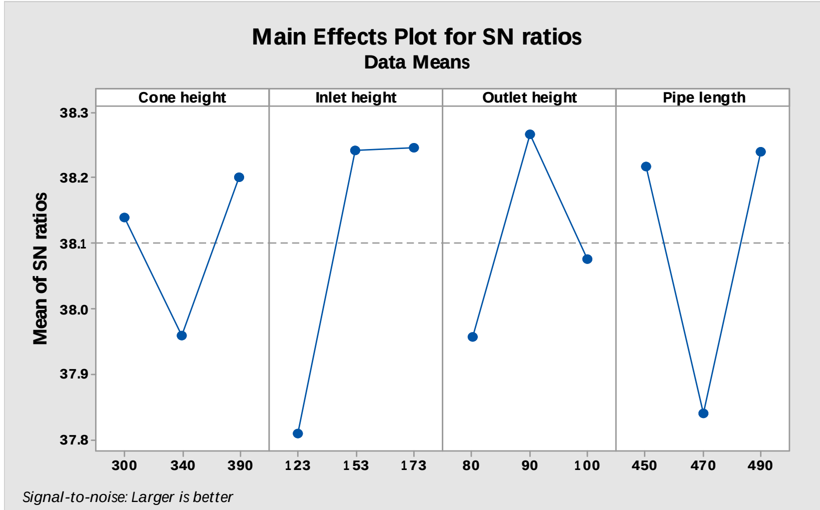
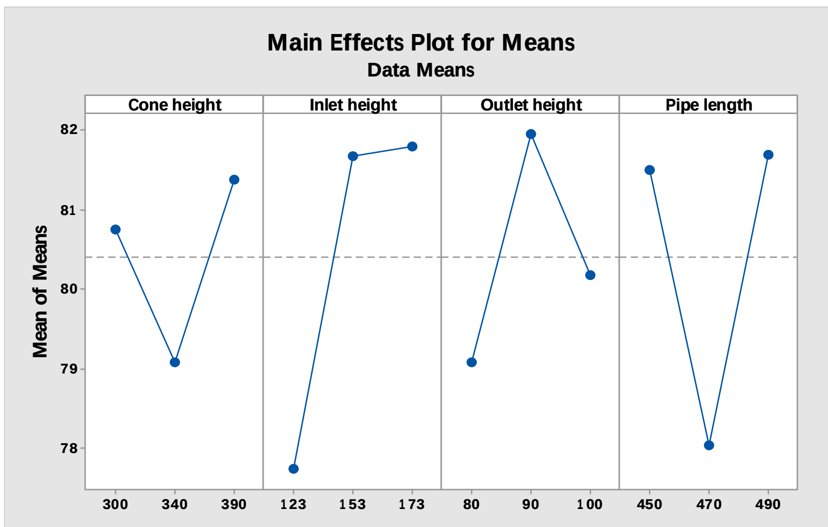
Using the signal to noise ratio the optimum value of efficiency is obtained by the MINITAB. The highest efficiency was achieved corresponding to: cone height: 390 mm, inlet height: 173 mm, outlet height: 90 and pipe length: 490 mm.



(a)



(b)

Fig. 11. Main effects plots for (a) S/N ratios and (b) Means of Efficiency.

VI. CONCLUSION

In this work, Taguchi method has been applied to analyse the effect of design parameters (cone height, inlet height, outlet height and pipe length) on the response parameters (pressure drop and efficiency) values on the cyclone precipitator. The following observation can be drawn based on the above experimental results of this study:

The outcomes revealed that the primary factor affecting the pressure drop and efficiency is inlet height, subsequently followed by cone height, pipe length and outlet height.

1) Using the signal to noise ratio the optimum value of pressure drop is obtained by the MINITAB. The optimum pressure drop is at :-

Cone height = 340 mm, inlet height = 123 mm, outlet height = 80 and pipe length = 450 mm.

2) Using the signal to noise ratio the optimum value of efficiency is obtained by the MINITAB. The optimum efficiency is at :-

Cone height = 390 mm, inlet height = 173 mm, outlet height = 90 and pipe length = 490 mm.

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