Optimization of cyclone geometry for maximum collection efficiency

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Abstract. This paper presents the results obtained from the application of both computational fluid dynamics (CFD) Fluent 6.3 and Design Expert codes to modelling and optimizing a gas-solid cyclone separator based upon its geometrical parameters. A pre-processor software GAMBIT was employed to set up the configuration, discretisation, and boundary conditions of the cyclone. A commercial CFD code FLUENT 6.3 was employed to simulate the flow field and particle dynamics in the cyclone. The optimization study was performed under either a constant gas inlet flow rate of 0.075 m3/s or a constant inlet gas velocity of 18 m/s. A response surface methodology with three levels (-1, 0, and +1) was employed as the experimental design. Independent variables to be optimized include the ratio of inlet gas width to diameter of the cyclone, W/D, the ratio of conical length to diameter, Lc/D and the ratio outlet diameter to cyclone diameter De/D. The response variables of collection efficiency and pressure drop were correlated in the forms of quadratic polynomial equations. The simultaneous optimization of the response variables has been implemented using a desirability function (DF) approach, computed with the aid of Design Expert software. The results of investigation showed that at constant flow rate, the following optimum ratios of W/D =0,28, Lc/D =1,5, and De/D =0,52 were obtained to give a collection efficiency of 90% and a pressure drop of 155 Pa. At the constant inlet gas velocity, the following optimum ratios of W/D =0,25, Lc/D =1,5, and De/D =0,57 were obtained to give a collection efficiency of 90% and a pressure drop of 190 Pa. This findings indicate that gas inlet treatment at either constant flow rate or constant inlet gas velocity does not produce significant difference on the collection efficiency, but does give significant influence on the pressure drop.

Key words: cyclone, optimization, response surface methodology, desirability function, efficiency.

Introduction

Cyclones are one of the most common equipment used for controlling dust emissions of gaseous flow in industrial processes. Although current engineering developments have enabled to employ cyclone for example as dryers and reactors, their main application remains in the area of air pollution control where high efficiencies are required to meet the stringent regulations. In comparison with other equipment used for air pollution control, cyclones are more preferable due to their simplicity in the design, inexpensiveness to manufacture, low maintenance costs, and adaptability to a wide range of operating conditions such as high temperature and pressure. Despite they are frequently used as final collectors where large particles to be removed, it has been also a common practice to employ cyclones as pre-cleaners for a more efficient collector such as an electrostatic precipitator, scrubber or fabric filter (Swamee, 2009).

The main performance of a cyclone is primarily judged from its collection efficiency and pressure drop. In order to describe the cyclone performance (pressure drop and collection efficiency) there are three approaches, mathematical models, experimental Investigation, and computational fluid dynamics (CFD). The cyclone performance is affected by several parameters, viz.: cyclone geometry (dimensions, shape of inlet section, number of inlets and vortex finder shape), inlet velocity (volume flow rate), dust mass loading, surface roughness.

In recent years, the response surface methodology (RSM) has become one of the most popular optimization methods used for optimizing a process when the independent variables have an interaction effects on the desired response (Tang et al.., 2010). The RSM is a collection of mathematical and statistical technique that has been widely used in optimization studies of biomass densification (Yunardi et al., 2011), cyclone performance (Leith, 1993), and cyclone performance with respect to its pressure drop (Elsayed and Lacor, 2010). The present study was aimed at optimizing the cyclone efficiency from the geometry point of view. A number of simulation and experimental studies have shown that the efficiency of a cyclone is much affected by the ratios of inlet width to cyclone diameter, length of conical section to the cyclone diameter, and the outlet diameter to the cyclone diameter (Elsayed dan Lacor, 2010).

Methodology

Experimental Procedure and Design

The independent variables being studied were ratio of inlet width to cyclone diameter, X_1 = W/, ratio of length of conical section to the cyclone diameter, X_2= L_c/D and ratio of the outlet diameter to the cyclone diameter, X_3= D_e/D. The dependent variables analyzed were collection efficiency and pressure drop of the cyclone. However, due to limitation space, pressure drop in the cyclone is excluded from discussion in this paper. The simulation experiment was carried out using a commercial CFD code Fluent 6.3 keeping the flow rate of gas coming to the cyclone constant, with a dust loading of less than 10%. The level and code investigated in this study is presented in Table 1.

Table 1. Experimental range and levels of independent variables

	Coded level and range		
Independent variable	-1	0	+1
ratio of inlet width to cyclone diameter, X_1	0.2	0.25	0.3
ratio of length of conical section to the cyclone diameter, X_2 (mesh)	1.5	2.0	2.5
ratio of the outlet diameter to the cyclone diameter, X_3 (%)	0.4	0.5	0.6

A number of 17 runs were randomly performed to optimize the process variable, as shown in Table 2 together with the simulated experimental and predicted results of the dependent variable, the collection efficiency. The experimental data were analyzed by RSM with the aid of Design Expert software (Version 6.06, State-Ease Inc, Minneapolis, USA) to fit the following second order polynomial equation:

$$Y_k = \beta_o + \sum_{i=1}^{3} \beta_i X_i + \sum_{i=1}^{3} \beta_{ii} X_i^2 + \sum\sum_{i<j} \beta_{ij} X_i X_j + \varepsilon_j \qquad [1]$$

where Y is the predicted response and X_1, X_2, and X_3 are coded independent variables corresponding to the ratio of inlet width to cyclone diameter, ratio of length of conical section to the cyclone diameter and ratio of the outlet diameter to the cyclone diameter, respectively. The constants β_o, β_i, and β_{ij} are linear term, quadratic term and cross product term coefficients, respectively. The coded values are related to the real values through Equation 2 presented below.

$$Z = X - X^o \big/ \Delta X \qquad [2]$$

where Z is the coded value (-1, 0, or +1) and X is the corresponding original un-coded value, while X^o the mid value of the domain. ΔX represents as the increment of X for every unit of Z.

For the purpose of optimizing multiple response variables, it is necessary to establish the optimum criteria in accordance to the desirability function (DF) approach, as proposed by Derringer dan Suich [3]. The maximum or minimum value of the variable response is determined on the basis of technical and/or economical considerations. The general approach is to first convert each response Y_i, into an individual desirability function d_i , that may vary over the range $0\leq d_i \leq 1$, where if the response yi meets the goal or target value, then $d_i = 1$, and if the response falls beyond the acceptable limit, then $d_i = 0$.

Table 2. Box-Behnken design matrix along with experimental data and predicted efficiency

Run	W/D, X_1	L_c/D, X_2	D_e/D X_3	Collection efficiency,%		
				Simulation Experiment	Model Prediction	Error, %
1	+1	+1	0	78,36	78,72	0,455
2	+1	-1	0	94,77	88,93	-6,158
3	-1	-1	0	78,36	78,72	0,455
4	0	0	0	78,36	78,72	0,455
5	+1	0	+1	75,50	74,02	-1,958
6	0	+1	+1	53,70	58,25	8,471
7	-1	0	-1	70,74	69,19	-2,197
8	0	0	0	78,36	78,72	0,455
9	0	0	0	82,87	85,14	2,735
10	0	-1	-1	51,28	54,08	5,468
11	0	-1	+1	78,36	78,72	0,455
12	+1	0	-1	61,92	57,78	-6,687
13	0	0	0	64,46	62,37	-3,244
14	-1	0	+1	76,28	78,47	2,872
15	-1	+1	0	66,00	70,50	6,817
16	0	0	0	65,66	70,51	7,391
17	0	+1	-1	50,05	46,26	-7,566

Results and Discussion

Model for Response Variable

Table 2 presented the design matrix in the coded units in conjunction with the results of simulation experimental data and the predicted values of response variable using the model (cyclone collection efficiency). The predicted values of the response were calculated from quadratic model fitting techniques utilizing Design Expert software. The simulation experimental data, the cyclone collection efficiency were utilized to develop the statistical model using multiple regression analysis method. The resulted relationship between the response variable of collection efficiency and independent variables of ratio of inlet width to cyclone diameter, ratio of length of conical section to the cyclone diameter and ratio of the outlet diameter to the cyclone diameter is shown in Equation 3.

$$Y_2 = -426{,}41 + 3325{,}95X_1 + 41{,}99X_2 + 166X_3 - 327{,}3X_1X_2 + 576{,}5X_1X_3 + 9{,}15X_2X_3 - 5549{,}5X_1^2 + 6{,}265X_2^2 - 357{,}875X_3^2 \quad [3]$$

The statistical significance of the statistical model of Equation 3 was evaluated by the F-test analysis of variance (ANOVA) presented in Table 3. In Table 3, the value of " Prob>F" less than 0.0500 revealed that the quadratic model of the response variable is statistically significant at 95% confidence level. The model showed a significantly high determination coefficient (R^2=0.9239) and low the coefficient of variation (CV=7.10%). The closer the determination coefficient to unity, the better agreement of the model suits the experimental data, showing less the difference between the calculated and measured values. Inspection of the value of R^2 indicates that around 7.6% variation is not explained by the model. Myers and Montgomery (2002) also suggested that the model adequacy can be evaluated not only from R^2, but also from adjusted R^2, predicted R^2, and prediction error sum of squares (PRESS). A good model is indicated by a large R^2 and a low PRESS. In this case, R^2=0.9239; adjusted-R^2=0.8260; predicted-R^2=-0.2182; and adeq precision=11.068. A negative "Pred R-Squared" implies that the overall mean is a better predictor of the response than the current model. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The current study showed a value of 11.068 which is greater than 4.0, indicating an adequate signal, confirming this model can be used to navigate the design space.

The coefficient of the model, its significance and its standard error can be verified by Prob>F-value, also shown in Table 3. Observation of Table 3 showed that most of terms including their interactions are significant. Values of "Prob>F" greater than 0.1 indicate the model terms are not significant.

Table 3. Analysis of variance (ANOVA) for the quadratic polynomial model

Source	Sum of squares	DF	Mean squares	F Value	Prob>F	Remarks
Model	2153,1	9	239,23	9,44	0,0037	significant
X_1-W/D	683,39	1	683,39	27	0,0013	significant
X_2-Lc/D	208,08	1	208,08	8,21	0,0242	significant
X_3-De/D	69,384	1	69,384	2,74	0,1420	Not significant
X_1X_2	267,81	1	267,81	10,6	0,0140	significant
X_1X_3	33,235	1	33,235	1,31	0,2898	Not significant
X_2X_3	0,8372	1	0,8372	0,03	0,8609	Not significant
X_1^2	810,45	1	810,45	32	0,0008	significant
X_2^2	10,329	1	10,329	0,41	0,5436	Not significant
X_3^2	53,926	1	53,926	2,13	0,1881	not. ignificant
Residual	177,44	7	25,349			
Lackof Fit	177,44	3	59,147			
Pure Error	0	4	0			

R^2=0,9239; adj R^2 = 0,8260; pred. R^2=-0.2182; C.V = 7.10%; Adeq Precision=11,068

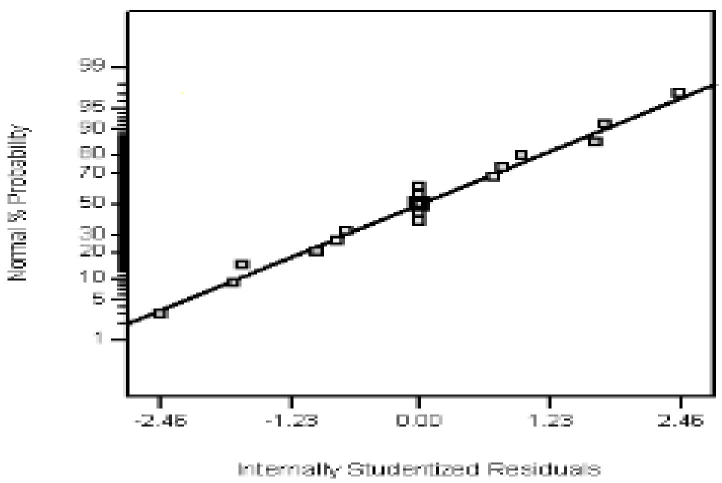

Figure 1. Comparison of predicted and experimental values of collection efficiency (symbol – simulated experimental data; line – predicted model)

Figure 1 presented comparison of predictions of cyclone collection efficiency compared to the simulated experimental measurements using Fluent 6.3. The solid line represents the calculation based on the statistical model shown in Equation 3, while the symbol depicts the simulated experimental values. It is clearly seen that most of the experimental data are falling on or having in contact with the prediction line, confirming an excellent agreement between the predictions and experimental data. All the above discussions indicate outstanding adequacy of the proposed quadratic model to represent the relationship between the response variable, collection efficiency and independent variables of ratio of inlet width to cyclone diameter, ratio of length of conical section to the cyclone diameter and ratio of the outlet diameter to the cyclone diameter.

Optimization of the response variable

The determination of optimum operating conditions for the independent variable is aimed at obtaining highest collection efficiency of solid particles in the cyclone. A parameter desirability function, DF is used to judge the optimum operating condition. As mentioned earlier that if DF is closer to unity, the response of the target is the best. Table 4 presented alternative solution with different DF values. The highest DF value is 90 per cent obtained at a condition of W/D=0.25, Lc/D=1.5 and De/D=0.57. The lowest DF value of 0.59 is obtained at a condition of W/D=0.26, Lc/D=1.5 and De/D=0.59. Both conditions produce a similar efficiency of 90 per cent. Applying the desirability function (DF) method, the Design Expert software produced a number of 8 solutions, as shown in Table 4. On the consideration of DF value, the solution number 1 is selected to represent the optimum reponse variable.

Table 4. Alternative solutions for optimization of process parameters

Solution number	W/D, X_1	L_c/D, X_2	D_e/D X_3	Desirability function, DF	Collection Efficiency
1	0,25	1,5	0,57	0,90	90
2	0,27	1,51	0,56	0,89	90
3	0,27	1,52	0,56	0,88	90
4	0,27	1,52	0,55	0,87	90
5	0,26	1,5	0,51	0,83	90
6	0,27	1,53	0,51	0,79	90
7	0,26	1,5	0,49	0,78	90
8	0,26	1,5	0,44	0,59	90

Conclusions

A desirability function approach has been utilized to optimize the process variables of ratio of inlet width to cyclone diameter, ratio of length of conical section to the cyclone diameter and ratio of the outlet diameter to the cyclone diameter on the collection of solid particles in a cyclone. The optimum conditions to produce high collection efficiency of a cyclone were obtained at a ratio of inlet width to cyclone diameter of 0.25, ratio of length of conical section to the cyclone diameter of 1.5 and ratio of the outlet diameter to the cyclone diameter of 0.57. With a minimum number of experimental runs, this technique is an efficient one for the solution of cyclone optimization problems.

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