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CFD and Statistical Approach for Optimization of Operating Parameters in a Tangential Cyclone Heat Exchanger

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ABSTRACT

Present work optimizes the operational parameters such as solid particle diameter, inlet air velocity and inlet air temperature on heat transfer rate by Taguchi method. Operational parameters play an important role in the performance of cyclone heat exchanger thus the parameter optimization is deemed important. The parameters have been analyzed under varying solid particle diameter (300 and 400 µm), inlet air temperature (323, 373, 423 and 473 K) and inlet air velocity (5, 10, 15 and 20 m/s). Results of heat transfer rate by varying the operational parameters have been found from Computational Fluid Dynamics (CFD) software Ansys Fluent. Orthogonal array of Taguchi, the signal-to-noise ratio and analysis of variance have been employed to found the optimal parameter values and the effect of parameters on heat transfer rate. Mixed level factor and L32 array is chosen for the design of analysis in Taguchi. Result of statistical analysis shows that the developed approach yields worthy results when comparing with predicted simulation values with confidence level of 99.5%. Taguchi analysis reveals that optimized levels of parameters are 300 µm, 473 K & 20 m/s for solid particles diameter, inlet air temperature and inlet air velocity respectively. Confirmation test was conducted in simulation and experiment for optimized parameters and result shows that maximum heat transfer rate was obtained with optimized parameter among the chosen operational parameters.

Keywords: CFD; Optimization; Taguchi method; Cyclone heat exchanger.

NOMENCLATURE

B_d	diameter of the bin
B_h	height of the bin
C_D	particle drag coefficient
C_d	diameter of dust outlet
C_{ps}	specific heat capacity of solid particle
D	body diameter
d	particle diameter
Da	diameter of gas inlet
De	diameter of gas exit
Ds	diameter of solid particles inlet
F_D	drag force
Fx	additional force
Gk	generation of turbulent kinetic energy
g	gravitational acceleration
H	height of the rectangular inlet section
k	turbulent kinetic energy
Lc	length of the cone
Lb	length of the cyclone body
Lp	length of the pipe
Ls	length of the solid cone
Lcc	length of the transition piece
m_s	mass flow rate of the solid particle
P	the mean pressure in Pascal
Q	heat transfer rate
Re	Reynolds number
S	length of the vortex finder in mm
Ts_{in}	inlet temperature of solid particle
Ts_{out}	outlet temperature of solid particle
t	time in seconds
u	gas velocity
W	width of the rectangular inlet section
ρ_p	density of solid particles
μ	dynamic viscosity
μ_{eff}	effective dynamic viscosity of gas
u_i	flow velocity component in i direction
u_j	flow velocity component in j direction

α_k	inverse effective Prandtl number for turbulent kinetic energy
α_ε	inverse effective Prandtl number for turbulent dissipation rate
ε	turbulent dissipation rate
ρ	fluid density

Subscript

d	diameter
h	height
S	solid particles
a	gas inlet
e	gas exit
c	cone
b	cyclone body
p	pipe
cc	transition piece
in	inlet
out	outlet
k	turbulent kinetic energy
ε	turbulent dissipation rate

1. INTRODUCTION

Cyclones are static device which are used widely in various industries to remove dispersed particles from carrying gas due to centrifugal force of mixture. Cyclone is one of the oldest methods of particle separation and mainly used by their advantages like operation at high loading conditions (Temperature, pressure and load) low maintenance cost, no moving parts which make the cyclone very attractive. Heat exchangers are used for effective heat exchange between two medium. In cyclone heat exchanger transfer of heat takes place between gas and solid particles which enters tangentially in to the cyclone, swirls inside the cyclone due to centrifugal force till it reaches the end of conical part after that solid particles are collected in the bin whereas gas stream moves up and exit through vortex finder pipe. Although cyclone heat exchanger has many advantages, its studies are minimum with respect to optimization of inlet parameters.

The influence of operational parameters on heat transfer of cyclone is studied by (Karagoz and kaya 2007; Jain *et al.* 2006). The effects of geometrical parameters on cyclone performance are reported in (Elsayed and Lacor 2011, 2013; Raoufi *et al.* 2008; Xiang and Lee 2005; Lim *et al.* 2009). Parameters influencing on collection efficiency in a cyclone is discussed by Patterson and Munz (1989). Altmeyer *et al.* (2004) presented software cyclone which is used to measure efficiency of a cyclone for known model or to select model for a required efficiency. Ficici *et al.* (2010) found the effect of vortex finder on pressure drop. Several works are carried out to minimize pressure drop (Noriler *et al.* 2004; Fassani and Goldstein 2000; Kharoua *et al.* 2011; Elsayed and Lacor 2010; Derksen and Van den Akker 2008). Avci and Karagoz (2001) theoretical analyze the pressure losses under the consideration of geometrical and flow parameters. Many researchers analyzed the effect of operational parameter on pressure drop (Avci and Karagoz 2003; Derksen *et al.* 2006, Fassani and Goldstein 2000). Model was created to calculate pressure drop by Chen and Shi (2007), Karagoz and Avici (2005). Azadi *et al.* (2010) concluded that with increase in cyclone size the pressure drop and cut off diameter increased. Li Xiaodong *et al.* (2003) found that separation efficiency decreases with an increase in turbulence intensity and increases with decrease in the thickness of the boundary layer. Wang *et al.* (2006) studied numerically and experimentally gas-solid flow inside the cyclone separator for separation efficiency of particles at different entries. Hoekstra *et al.* (1999) uses laser-Doppler velocimetry to analyze geometric swirl numbers and concluded that swirl number has effect on mean flow characteristics and maximum tangential velocity is influenced by vortex dimension. Shukla *et al.* (2011) analyzed various numerical schemes in cyclone separator for dispersed phase. Mothilal and Pitchandi (2015, 2014) experimentally and computationally analyzed the impact of inlet air and solid particles on holdup mass in cyclone heat exchanger by varying the inlet operating parameters and proposed empirical correlation for Nusselt number and holdup mass from computational result. Liming shi *et al.* (2007) developed tangential lift-off boundary condition via a user-defined function and it predicts accurately than other boundary conditions.

Above literature work discuss the effect of mass flow rate of gas mixture (air & solid) on pressure drop, heat transfer characteristics and collection efficiency in a cyclone separator. Performance of cyclone heat exchanger depends on the rate of heat transfer between air to solid particles within the cyclone heat exchanger. Present work analyzes and optimizes the different inlet parameters that affects heat transfer rate by numerically and mathematically.

2. NUMERICAL MODEL DESCRIPTION

2.1. Governing Equations

Fluid flow in cyclone heat exchanger modeled mathematically by RANS equation. The continuity and momentum equation for steady and incompressible flow is given in Eq. (1 & 2) (Karagoz and Kaya 2007; Mothilal and Pitchandi 2015).

$$\frac{\partial \rho u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial}{\partial x_i}\left(\rho u_i u_j\right) = -\frac{\partial P}{\partial x_i} + \rho g_i + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) \tag{2}$$

Table 1 Geometrical dimensions of cyclone heat exchanger

Description	Cd	De	S	Ds	Da	Ls	Lb	Lc	Lp	D	Lcc	Bd	Bh	W	H
Dimension	37.5	50	50	36	36	100	150	250	200	100	50	50	50	20	50

2.2. Turbulent Equations

Several turbulence models available in FLUENT software to evaluate the high Reynolds flow of primary phase. RNG k-ε was employed for present work and its transport equation is shown in Eq. (3) (Karagoz and Kaya, 2007; Mothilal and Pitchandi, 2015).

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\alpha_k \mu_{eff} \frac{\partial k}{\partial x_j}\right) + G_k - \rho\varepsilon \tag{3}$$

$$\frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left(\alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} - R_\varepsilon \tag{4}$$

Constants values used in Eq. (4) are $C_{1\varepsilon} = 1.42$, $C_{2\varepsilon} = 1.68$.

2.3. Discrete Phase Model (DPM)

Solid particles in cyclone heat exchanger act as discrete secondary phase which follows the Eulerian and Lagrangian approach. Dispersed phase solid particles solved by large number of particles tracking through the primary phase. The main assumption followed in DPM is lower volume fraction (10 - 12 %) and all particles are considered as spherical. Solid particles loading in cyclone heat exchanger are very small (3 – 5 %) (Fassani F and Goldstein 2000, Shukla *et al.* 2011 and Mothilal and Pitchandi 2015) which don't affect the gas phase (one way coupling). The interaction between the particles in a flow is neglected and their effects are calculated by force balancing Eq. (5) (Mothilal and Pitchandi, 2015).

$$\frac{du_p}{dt} = F_D(u - u_p) + \frac{g_x(\rho_p - \rho)}{\rho_p} + F_x \tag{5}$$

Where F_D is drag force experienced by particles is given by Eq. (6)

$$F_D = \frac{18\mu}{\rho_p d_p^2}\frac{c_D \text{Re}}{24} \tag{6}$$

Fluid Reynolds number (Re) is given by Eq. (7)

$$\text{Re} = \left(\frac{\rho d_p (u_p - u)}{\mu}\right) \tag{7}$$

2.4. Configuration of Cyclone Heat Exchanger

Numerical simulation of cyclone heat exchanger performed on Stairmand high efficiency cyclone which collects more particles compared to other cyclone design (Ficici *et al* 2010; Fassani and Goldstein, 2000; Karagoz and Avci, 2005). Table.1 shows the dimension of various parts of cyclone and its schematic 2D diagram is displayed in Fig. 1. Modeling of cyclone is constructed using SOLIDWORKS modeling software.

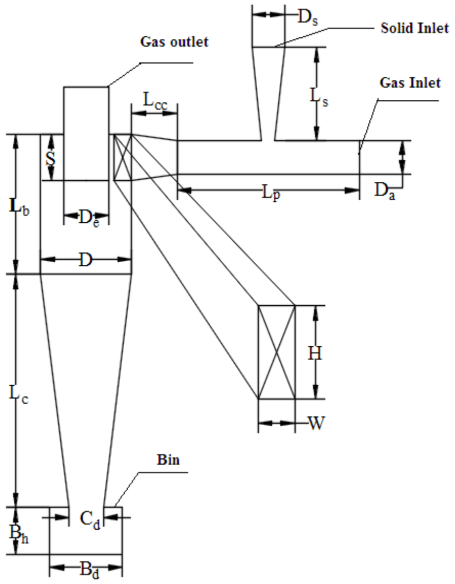

Fig. 1. 2D model of cyclone heat exchanger.

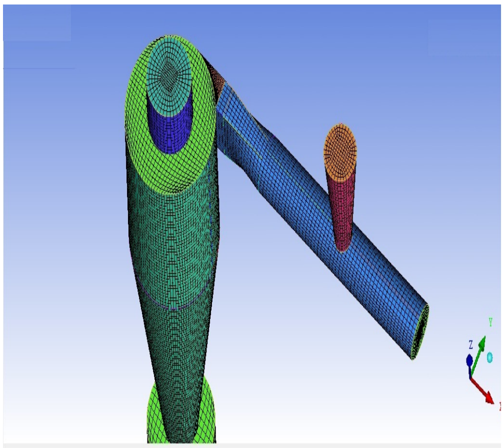

Fig. 2. Grid generated cyclone heat exchanger.

2.5. Mesh Generation and Boundary Conditions

Mesh was generated using Hybrid mesh elements (Karagoz and Kaya, 2007) in cyclones by using ANSYS ICEM CFD (Mothilal and Pitchandi, 2015) software. Mesh consists of 197789 elements, 25030 nodes was generated in cyclone heat exchanger shown in Fig. 2. The boundary condition at gas entrance and solid entrance was given as velocity inlet. Intensity of turbulent flow in cyclone is set as 5% (Fassani and Goldstein, 2000; Shukla *et al.* 2011, Mothilal and Pitchandi 2015) and hydraulic diameter at gas and solid inlet is 0.036 m. Outflow boundary condition was set at gas outlet and trap

Table 2 Solver methodologies

S. No	Description	Scheme
1	Pressure description	Standard
2	Pressure velocity coupling	SIMPLE
3	Momentum	Second order upwind
4	Turbulent kinetic energy	Second order upwind
5	Turbulent dissipation rate	Second order upwind

DPM condition was applied at the bin in order to track all particles. In wall boundaries, no slip condition was set and co efficient of restitution of particles is 0.8 (Shukla *et al.* 2011; Mothilal and Pitchandi 2015).

2.6. Grid Independence

Grid refinement test was performed to confirm solutions are grid independent. Four levels of grid systems (91264, 143273, 197789 and 238427 elements) are generated in ICEM environment and meshes are imported to ANSYS FLUENT software and RNG k-□ turbulence model utilized. Pressure drop of air for different grid elements of cyclones shown in Fig. 3. Maximum difference between the pressure drops is less than 1% for two grid systems between 197789 and 238427 elements. Considering the computational time and accuracy cyclone model with 197789 elements is taken for simulation.

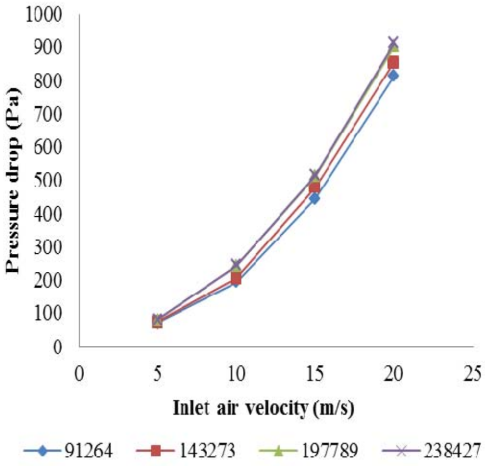

Fig. 3. Comparison of inlet air velocity and pressure drop for various grids.

2.7. Solver Settings

Gas flow is steady, incompressible and three dimensional solved by Reynolds Average Navier Stokes equation. The methodologies used for simulation is displayed in Table. 2.

3. RESULT AND DISCUSSION

3.1. CFD Analysis

Heat transfer rate was found by varying the inlet parameters such as mass flow rate of air, air temperature and solid particles diameter. Simulation was done by Ansys Fluent software and results are found for various inlet parameters which affect heat transfer rate. Heat transfer rate of cyclone heat exchanger was found out by Eq. (8)

$$Q = m_s * C_{ps} * \left(T_{sout} - T_{\text{sin}}\right) \tag{8}$$

The effect of heat transfer rate with respect to the inlet parameters is shown in the Fig. 4. Heat transfer rate is increased with rise in inlet air velocity and inlet air temperature but decreases with rise in solid particles diameter. The increase in heat transfer rate is occurred due to increase in exit solid temperature with rise in inlet air temperature and inlet air velocity.

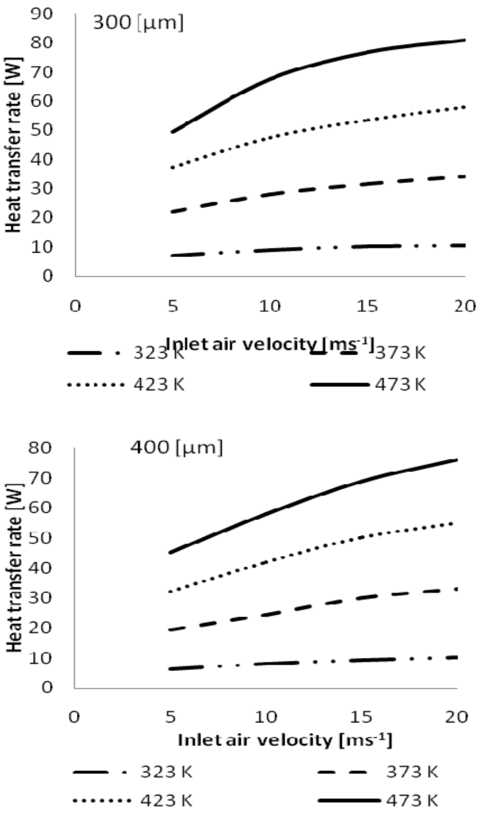

Fig. 4. Effect of inlet air velocity and inlet air temperature on heat transfer rate for different solid particles diameter.

3.2. Design of Experiments

Design of experiment is considered as a useful method for prediction of optimal parameters of an experiment. The Taguchi method for three factors and four levels was used for the study of optimization of operating parameters. The factors and their levels of present work used for the analysis are shown in the Table 3. The parameters selected for the analysis are solid particle diameter, inlet air velocity and inlet air temperature. From the literature review, gas properties and solid particles properties are more significant on the performance of cyclone heat exchanger. The experiment was conducted according to 3 Factor and Mixed level L_{32} array. Two levels of solid particle diameter (300 & 400 µm), four levels of inlet air temperature (323, 373,423 & 473 K) and four levels of inlet air velocity (5, 10, 15 & 20 m/s) were used to find the optimum parameters. To obtain the optimal performance parameter of cyclone heat exchanger "Larger is better" quality character is chosen for the Taguchi analysis.

Table 3 Levels of the variables used in the experiment

S.No	Control Factors	Levels			
		I	II	III	IV
1	Solid particles diameter	300	400	-	-
2	Inlet air temperature	323	373	423	473
3	Inlet air velocity	5	10	15	20

3.3. S/N Ratio Analysis

Taguchi Signal to Noise (S/N) ratio is used as a performance index for analyzing the various responses. Taguchi analysis uses three quality characteristics of the S/N ratio are smaller is better, larger is better and nominal is better. "Larger is better" quality characteristics are used for the response of heat transfer rate. Taguchi experimental design is orthogonal, the effects of different parameters are separately found out in the analysis. The S/N Ratio of heat transfer rate is shown in Table 4 and corresponding main effect plot is shown in Fig. 5. The plot shows the variation of individual response with the process parameters. The x axis in the plot shows value of each parameter at three different levels and y-axis the response value (mean S/N ratio). From Table 4, it is observed that the inlet air velocity influences more on heat transfer rate followed by inlet air temperature and solid particles diameter. The optimal parameters level for the heat transfer rate is observed from Table 4 and values are 300 µm, 473 K and 20 m/s.

The main effect plot for mean S/N ratio on heat transfer rate for inlet parameters is shown in Fig. 5. It is observed that heat transfer rate accelerate with increase in inlet air temperature and inlet air velocity but decelerate with increase in solid particle diameter. The interaction plot for heat transfer rate at different operating parameters is shown in Fig. 6. The plot shows the different interaction at single graph in order to understand the effect of operating parameter of cyclone heat exchanger on heat transfer rate.

Table 4 Response table for S/N ratio of heat transfer rate

Levels	Solid particle diameter (µm)	Inlet air Temperature (K)	Inlet air Velocity (m/s)
1	29.65*	26.72	18.73
2	28.79	28.96	28.73
3	-	30.24	33.28
4	-	30.95*	36.14*
Delta	0.86	4.24	17.41
Rank	3	2	1

*Optimal Parameter

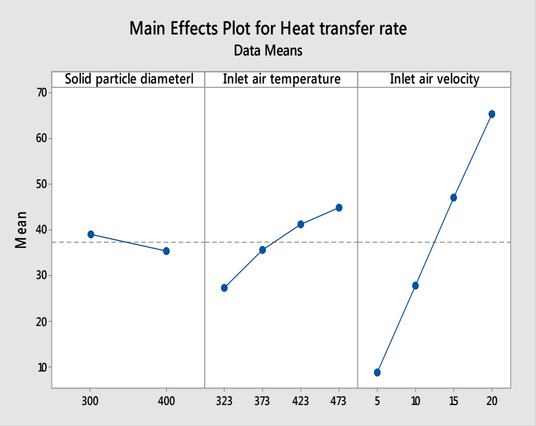

Fig. 5. Main effect plots for S/N ratio of heat transfer rate.

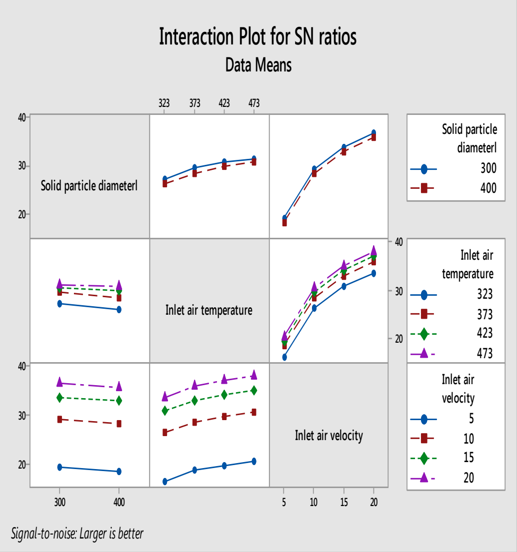

Fig. 6. Interaction Plot for S/N ratio of heat transfer rate.

3.4. Analysis Of Variance (ANOVA)

The computational results of heat transfer rate were analyzed using Analysis Of Variance (ANOVA) to identify the most significant parameter of cyclone heat exchanger on response. Source of variation, degrees of freedom (DF), sum of square (SS), mean square (MS), F-values (F), P value for different inlet parameters on heat transfer rate are shown in

Table 5 Analysis of variance for heat transfer rate

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Solid particle diameter	1	100.9	100.92	4.54	0.043
Inlet air temperature	3	1397.5	465.84	20.98	0.000
Inlet air velocity	3	14276.2	4758.73	214.27	0.000
Error	24	533	22.21		
Total	31	16307.6			

Table 5. The analysis was carried out for a confidence level of 95% (significance level of $\alpha = 0.05$).

The principle of the F test is that the larger the F value for a particular parameter, the greater the effect on the performance characteristics due to the change in that process parameter. The other important factor is R^2 (determination coefficient) in the ANOVA, which is defined as the ratio of the explained variation to the total variation. When R^2 approaches to unity, it indicates that there is a good fit among inlet parameters and response.

From the Table 5 it is concluded that inlet air velocity parameter has the larger F value (214.27) compared to other two parameters which indicate that inlet air velocity has maximum influence on heat transfer rate. The coefficient of determination (R^2) for the heat transfer rate is 96.73 % which shows that better prediction of response and good fit of the model with computed data.

3.5. Confirmation Test

The final step in the analysis of design of experiment is validating the optimized inlet parameter response with experimental result. Experimental set up of cyclone heat exchanger was fabricated with Stairmand high efficiency ratio and it is shown in Fig. 7. Mass flow rate of air and solid particles were controlled by inlet valves.

Fig. 7. Experimental setup of cyclone heat exchanger.

Air from the atmosphere was fed into the cyclone heat exchanger by using air blower and solid particles are fed by magnetic feeder. Air and solid were mixed in the inlet duct and flows into the cyclone tangentially. Temperature of air was increased by industrial heater and transfer of heat is take place between hot air and solid particles. Temperature of inlet and outlet solid particles was calculated by K-type thermocouple and amount of heat transfer was found out by Eq. (8). The optimized parameters (300 µm, 473 K and 20 m/s) were set in the experiment and heat transfer rate was calculated. Experimentally calculated heat transfer rate was compared with numerically calculated heat transfer rate and shown in Fig. 8. The Fig. 8 confirms that the optimized level parameter results from simulation and experimental has similar trend.

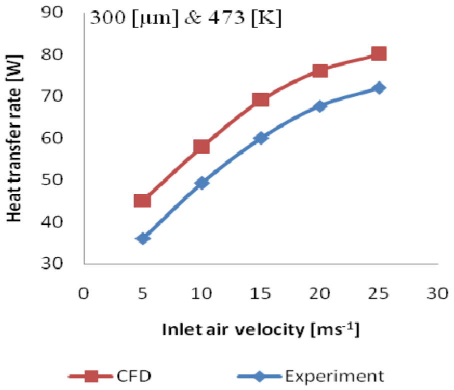

Fig. 8. Comparison of experimental and simulation result for the optimized level of inlet parameters.

4. CONCLUSION

Present work discussed the Taguchi statistical analysis on inlet operating parameters of cyclone heat exchanger for response of heat transfer rate. The response of heat transfer rate in cyclone heat exchanger was found by computational fluid dynamics, Ansys Fluent 12 software. The obtained heat transfer rate values are used for Taguchi statistical optimization test in Minitab 17 software. The statistically tested design of experiment uses, Taguchi L_{32} orthogonal array to analyze the inlet parameters like solid particles diameter, inlet air temperature and inlet air velocity on heat transfer rate. The ANOVA also tested for the same inlet parameters on response, the results of statistical test is shown below:

1. The Taguchi S/N ratio was calculated for the

"Larger is better" quality characteristic. The S/N ratio values of the study reveals that 300 µm, 473 K and 20 m/s are optimized values of solid particle diameter, inlet air temperature and inlet air velocity among the levels chosen.

2. The ANOVA test had been carried for the response to found most significant inlet parameter among the parameters used. The F tests in ANOVA employed to found the most significant parameter, larger the F value stronger the significant. From the result inlet air velocity had larger F value (214.27) compared to other parameter F value which shows that inlet air velocity has most significant effect on heat transfer rate.
3. The coefficient of determination R^2 has been found for varying inlet parameters on heat transfer rate. The R^2 value is 96.73 % which shows the good fit among the parameters chosen on response.
4. Confirmation test was conducted in simulation and experiment for the optimized parameters to check the efficiency of the Taguchi analysis. It was found that both the data matches with deviation of 15-20 %. Deviation in the result due to assumption made in numerical analysis like co efficient of restitution, particle interaction, wall temperature, additional forces acting on particles etc.

5. FUTURE SCOPE

1. This wok can be extended to find the generalized optimization by considering all the input parameters on performance of cyclone heat exchanger.
2. This work can also be extended to find the optimized cyclone geometry for maximum heat transfer rate in cyclone heat exchanger.

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