CFD ANALYSIS ON THE EFFECT OF PARTICLES DENSITY AND BODY DIAMETER IN A TANGENTIAL INLET CYCLONE HEAT EXCHANGER

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This work presents the effect of particles density and body diameter on holdup mass and heat transfer rate in cyclone heat exchanger by using computational fluid dynamics (CFD) analysis. Performance of cyclone heat exchanger is based on operational and geometrical parameters which mainly depend on inlet air velocity and solid particles parameters. Present work studies the effect of particles density, diameter of cyclone, inlet air velocity and temperature on performance of cyclone heat exchanger. RNG k-ε turbulence model was adopted in ANSYS Fluent 12.0 software to analyze the flow field and discrete phase model (DPM) is adopted to predict tracking of solid particles in cyclone. Solid particles density ranges from2050 to 8950 kg/m^3 for different materials fed at 0.5 g/s flow rate and inlet air velocity ranges from 5 to 25 m/s at three inlet air temperature 373, 473 and 573 K for 100, 200 and 300 mm body diameter cyclone heat exchangers. Results conclude that increase in diameter of cyclone increases holdup mass and heat transfer rate whereas increase in density of particles decreases the holdup mass and heat transfer rate. Experimental setup was built for Stairmand high efficiency cyclone and good agreement was found between simulation and experimental result. New correlation was proposed for non-dimensional holdup mass. Correlation compared with experimental holdup mass and predicts experimental value within an error band of -3 to 6%.

Key words: *Particles density, Holdup mass, cyclone heat exchanger, RNG k-ε model, discrete phase model, correlation*

1. Introduction

In various industries such as cement production, fertilizer, chemical processing and powder industries cyclones are used to remove dispersed particle from carrying gas. Cyclones are one of the oldest methods of particle separation and it can operate at high loading conditions (Temperature and pressure). Heat exchangers are used for efficient transfer of heat through convection between two fluids. In tangential inlet cyclone heat exchanger fluid and solid mixture enters the cyclone tangentially which generate the swirling motion of the gas stream, in turn forces particles toward the outer wall where they spiral in the downward direction. The solid particles gain relative motion in the radial direction and get separated from the gaseous stream which is collected in the bin of the cyclone heat exchanger. The gaseous stream migrates inwards axially along the cylinder and finally exit through the vortex finder tube. Swirl induces a centrifugal force (driving force) on solid particles and particles are dispersed by turbulence, thus swirl and turbulence are the two competing phenomena in the cyclone. The mechanism of swirl consists of inner vortex moving toward the cyclone exit and an outer vortex moving in the opposite direction. Due to presence of particles, the intensity of swirl and turbulence gets reduced. The reduction of swirl is mostly felt in the free-vortex part as the particle concentrations are much higher than in the core. In case of a cyclone heat exchanger holdup mass of the particles i.e. amount of particle undergoing heat transfer at any instance of time within the cyclone body, has not been discussed so far. Although cyclone heat exchanger has these many credentials, the studies on the subject are at a very minimum extent.

Azadi *et al.* [1] analyzed numerically flow patterns on different cyclone size and observe enhance in cut off diameter and pressure drop with increase in cyclone size. Gas-solid flow inside the cyclone separator was analyzed numerically and experimentally for separation efficiency of particles at different entries [2]. Numerous studies have been performed on cyclone pressure drop by varying operational and geometrical parameters [3-5]. Khairy Elsayed and Chris lacor [6-9] analyzed different geometrical parameters like inlet height, dust outlet and cone tip diameter of cyclone on its flow patterns and performance. Karagoz and kaya [10] studied the structure of vortices and variation of local heat transfer by varying inlet velocity of gas and particle feed rate. Correlation for dimensional nusselt number was predicted by varying inlet parameters of cyclone heat exchanger [11]. Bohnet *et al*. [12] developed a model, in which temperature dependent wall friction coefficient was introduced and re-entrainment of separated particles were considered. Dust load has strong influence on collection efficiency and loading effect are stronger at high temperature [13]. Zhu and Lee [14] carried experiment on collection efficiency in small cyclones by changing exit tube length and cylinder height at high flow rates and observed that flow rate plays significant role in cyclone collection efficiency. Hoekstra *et al*. [15] experimentally analyzed different geometric swirl numbers by laser-Doppler velocimetry. Geometry swirl number has influence on mean flow characteristics and maximum tangential velocity influences vortex size. Different numerical schemes for dispersed phase were evaluated in cyclone separator [16]. Xiang and Lee [17] numerically evaluated different cyclone height for flow pattern and separation efficiency. Mothilal and Pitchandi [18] analyzed numerically effect of inlet mass flow rate of air and solid on holdup mass and heat transfer rate, found new correlation for holdup mass by varying inlet air velocity and particle feed rate. The effect of mass flow rate of inlet air on holdup mass experimentally observed [19].Geometries of cyclone heat exchanger such as vortex finder diameter, inlet height and cone tip diameter are varied to find its effect on flow field, holdup mass and heat transfer rate [20, 21].The entire models developed were reviewed for the flow field inside inverse flow cyclone separator [22].

Performance of cyclone heat exchanger depends on holdup mass of the solid particles within the cyclone. The present work elaborates the holdup mass and heat transfer characteristics at the various particles density, inlet velocity of air and temperature on three different cyclone (C1, C2&C3) heat exchangers. Previous work applies the cyclone principle to separate particles from dust laden gas whereas present work makes the first attempt to analyze the cyclone as a heat exchanger and predicts the correlation for holdup mass

2. Numerical descriptions

2.1. Governing Equation for Gas Phase

Fluid flows are mathematically described by Reynolds-Average Navier-Stokes (RANS) equation. For steady and incompressible flow the equation for continuity and momentum is given as [10,18]

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

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

2.2. Turbulent Equations for Gas Phase

For swirling turbulent flow in cyclone heat exchanger there are several turbulence models available in FLUENT. RNG k-ε model well predicts the experimental results [10, 18] therefore RNG k-ε was employed for present work and its transport equation is shown below

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

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

Where $C_{1\varepsilon}$ = 1.42, $C_{2\varepsilon}$ = 1.68 [18,23].

2.3 Model equation for particles phase

In this study spherical particles gets dispersed and diluted into gas phase, gas-solid interaction and effect of the dispersed particles volume fraction on gas phase is negligibly small. As the particle volume fraction(less than 1%) and mass loading is lower in a cyclone, Lagrange approach is used to simulate particle transport in CFD analysis[1, 2, 4, 6].The Eulerian–Lagrangian approach adopts a continuum description for the fluid phase and tracks the discrete phase using Lagrangian particle trajectory analysis. Generally particles loading in cyclone is small (3-5%), so flow field in the cyclone is not affected by the presence of particles, therefore one way coupling is adopted for simulation [4, 16]. Interaction among the particles is neglected due to dilute flow. Discrete phase model (DPM) is used to simulate the particles motion in the cyclone [5, 16, 18]. Trajectories of particles are obtained by integrating the force balance on the particles. Equation of motion of small particles in terms of the Eulerian-Lagrangian approach is given by [16, 18].

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

F_D is the drag force per unit particles mass and

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

Here, u is the fluid phase velocity, u_p is the particles velocity, μ is the molecular viscosity of the fluid, ρ is the fluid density, ρ_p is the density of the particles, and d_p is the particles diameter. R_e is the relative Reynolds number is given by

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

Fx denotes the additional forces per unit mass such as Staffman lift force, Brownian force, Basset and virtual force [7,16]. Due to low value of gas to particle density ratio, low inertia and particle size, neglects Basset force, Staffman lift force and Brownian motion of the particles respectively when compare to the drag force of the particle [7,16]

2.4. Turbulent Dispersion of Particles

Reynolds average (RANS) turbulence model provide only the average velocity field, as small particles are injected, the effect of instantaneous fluctuation of gas velocity on turbulent dispersion of small particles has to be considered and therefore it is necessary to include a turbulence dispersion model. The dispersion of particles due to turbulence in the fluid phase is predicted using the stochastic tracking model [7, 16]. The stochastic tracking (random walk) model includes the effect of instantaneous turbulent velocity fluctuations on the particle trajectories through the use of stochastic methods. The turbulent dispersion of small particles was taken into account by integrating the trajectory equations for individual particles using the instantaneous fluid velocity [7, 16].

$$u = \bar{u} + u' \tag{8}$$

Where u is instantaneous velocity,$\bar{u}$ mean gas velocity,u'fluctuation gas velocity.

2.5. Geometrical descriptions

Numerical simulation of cyclone heat exchanger performed on Stairmand high efficiency cyclone which collects more particles [3,4,18]. Dimension of various parts of three different cyclones are shown in tab.1, and 2D view is shown infig.1. 3D model of cyclone is constructed by SOLIDWORKS modeling software.

2.6. Discretization of cyclone and Boundary conditions

Mesh was generated using Non uniform Hybrid mesh [10] in cyclones by using ANSYS ICEM CFD [18,24] software. Grid of 197789 cells, 25030 nodes for C1, 219140cells, 38781 nodes for C2 and 330673 cells, 82212 nodes for C3. Mesh generated cyclones are shown in fig. 2. The boundary condition at gas entrance and solid entrance was given as velocity inlet which means that the velocity and direction is specified. Intensity of cyclone is set as 5% [4,16,18] and hydraulic diameters in gas and solid for C1 is 0.036 m, C2 is 0.072 m and C3 is 0.108 m. Outflow boundary condition was set at gas outlet and trap 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 [16,18].

2.7. Numerical methods and Grid Independence

Gas flow is steady, incompressible and three dimensional solved by Reynolds Average Navier Stokes equation. The methodologies used for simulation is displayed in tab. 2. Mesh independence study has been done for tested cyclones. For each cyclone four levels of meshes (91264, 143273, 197789 & 238427 elements)) for C1, (98583, 145267, 219140 & 245161 elements) for C2 and (225611, 277777, 330673 & 372003 elements) for C3 was generated in ICEM [24] environment respectively. These grids are imported to CFD software and single phase gas flow is analyzed for pressure drop. Static pressure of C1, C2 and C3 were predicted at gas outlet for inlet air velocity of 10 m/s Maximum difference between the pressure drops is lesser than 1% for grid systems 197789 and 238427 elements for C1, 219140 and 245161 elements for C2 and 330673 and 372003 for C3 respectively. Considering the computational time and accuracy, cyclone model with 197789, 219140 and 330673 elements for cyclones C1, C2, C3 respectively were taken for simulation.

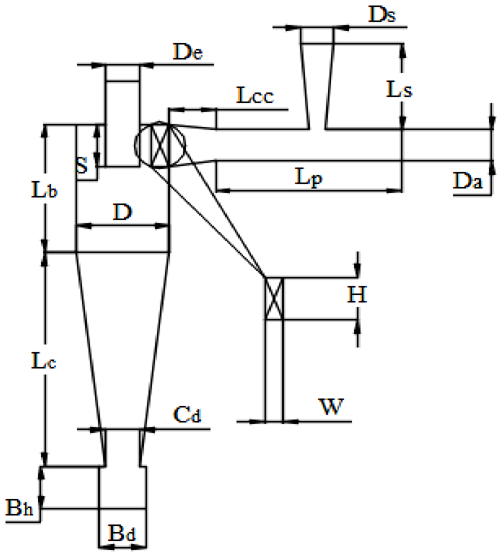

Figure 1. 2D View of the Cyclone heat exchanger

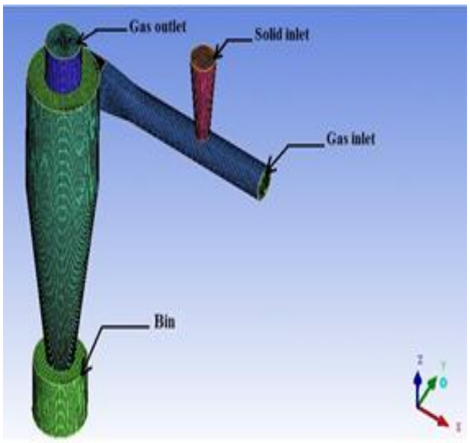

Figure 2. Mesh generation of cyclone heat exchanger

Table 1. Details of cyclone Heat Exchanger geometry (All dimensions are in mm)

	C_d	D_e	S	D_s	D_a	L_s	L_b	L_c	L_p	D	L_{cc}	B_d	B_h	W	H
C1	37.5	50	50	36	36	100	150	250	200	100	50	50	50	20	50
C2	75	100	100	72	72	200	300	500	400	200	100	100	100	40	100
C3	112.5	150	150	108	108	300	450	750	600	300	150	150	150	60	150

2.8. Comparison of experimental and simulation result

Simulation result of cyclone C1 is compared with A. Jain *et al.* [11], cyclone C2 is compared with B. Wang *et al.* [2] and C3 cyclone is compared with Karagoz *et al.* [10], for same inlet parameters and present simulation value well similar with literature values shown in fig. 3.Pressure drop in cyclone C2 under predicts the experimental pressure drop whereas in cyclone C3 above 15 m/s simulation over predicts experimental value. Deviation in results is quite acceptable due to three dimensional flow complexity, instrumental error, assumption made and losses due to friction.

Table 2. Methodologies for simulation

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

3. Result and discussion

Present study evaluates the effect of different particle densities, cyclone diameter and inlet air velocity & temperature on holdup mass and heat transfer rate. Physical properties of particles used in this study are shown in tab.3.

Table 3. Different particles density and its specific heat capacity

S.No	Materials	Density [kgm^{-3}]	Specific heat capacity [$Jkg^{-1}K^{-1}$]
1	Sulfur	2046	634
2	Dolomite	2872	910
3	Steel	8030	502.48
4	Copper	8978	381

3.1. Effect of particles density on holdup mass

To study the effect of solid particles density on holdup mass, particles are fed at different densities ranging from 2046 - 8930 kg/m^3at constant particle feed rate (0.5 g/s) and diameter, inlet air velocity varied from 5 - 25 m/s and temperature of air from 373- 573 K. Holdup mass is the total mass of the solid particle present inside the cyclone at any instant of time and it depends upon residence time (t_R) and mass flow rate of solid particles [18, 20, 21] and was obtained using eq. (9).

$$M_h = m_s \times t_R \tag{9}$$

Effect of different solid particles density and air temperature on holdup mass for cyclone heat exchangers C1, C2 and C3 is shown in fig. 4-6, respectively. Decrease in density of particles enhances holdup mass. When comparing copper with steel in C1, holdup mass increases from 1.5 - 3.5%and with sulfur holdup mass increases from 6 to 9%, while increasing the velocity from 5 - 25 m/s. This shows that with decrease in particle density holdup mass increases. Similar result was found for cyclone C2&C3.In C1 holdup mass of sulfur is 0.5 g at 5 m/s and 0.65 g at 25 m/s, similarly for C2is 0.75 g at 5 m/s and 1.15 g at 25 m/s and for C3 is 1.05g at 5 m/s&1.20g at 25 m/s. This shows that holdup mass increases with increase in cyclone body diameter in a range of 5 to 18%. Similar trend was observed for all particle materials at all inlet air velocities.

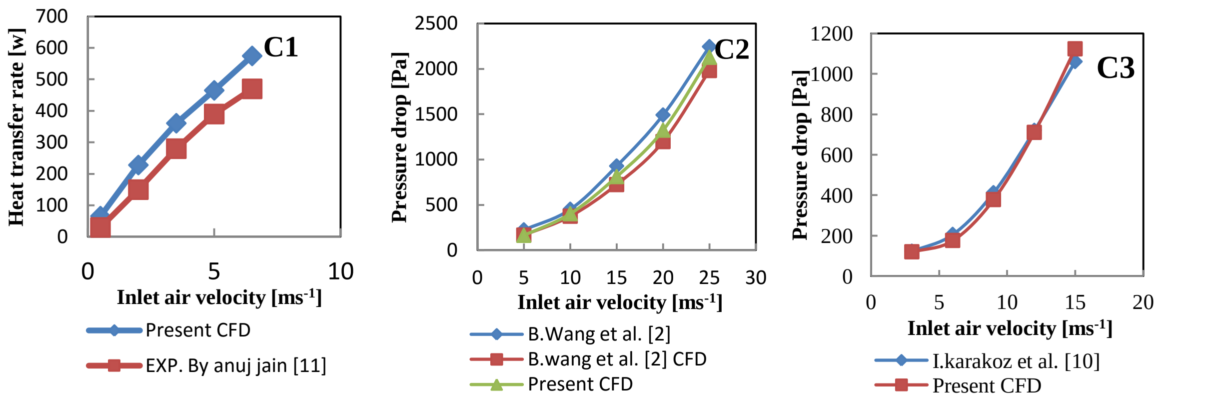

Figure 3. Comparison of Experimental and CFD results for cyclone C1, C2 and C3

Holdup mass increases with increase in inlet air velocity and temperature. Increase in inlet air velocity increases the centrifugal force as well as swirling rotation of particles which carry more amounts of particles inside the cyclone. At all inlet air temperature (373 - 573 K) For C1 maximum holdup mass of 0.64 - 0.65 g, for C2 1.15 - 1.2 g and for C31.32 - 1.46 g is obtained at 25 m/s. Thus the holdup mass increases with inlet air temperature. Particle trajectories of residence time for copper and sulphur particle in C1 cyclone are shown in fig 7. The colored legends indicate the residence time of the particles. Copper particle takes 0.86 seconds to reach bin whereas sulphur particle needs 0.93 seconds to reach bin. Number of swirling rotation decreases with increase in density of particles .Increase in density of particles raises drag force acting on particles, which lead to loss in swirling rotation inside cyclone and residence time of particles (Time taken by the particles to reach the bin from its inlet). Similar trend of results were observed for C2 and C3 cyclones.

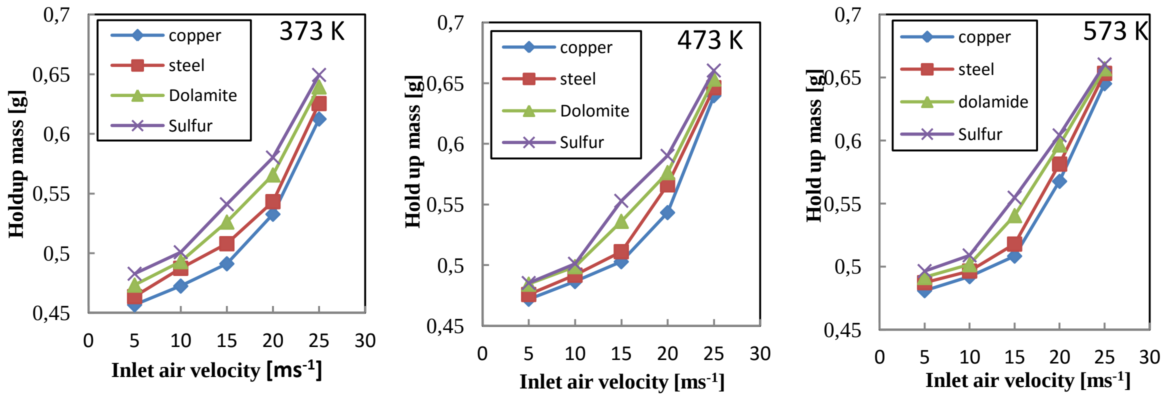

Figure 4. Effect of solid particles density on holdup mass at different inlet air temperature for C1

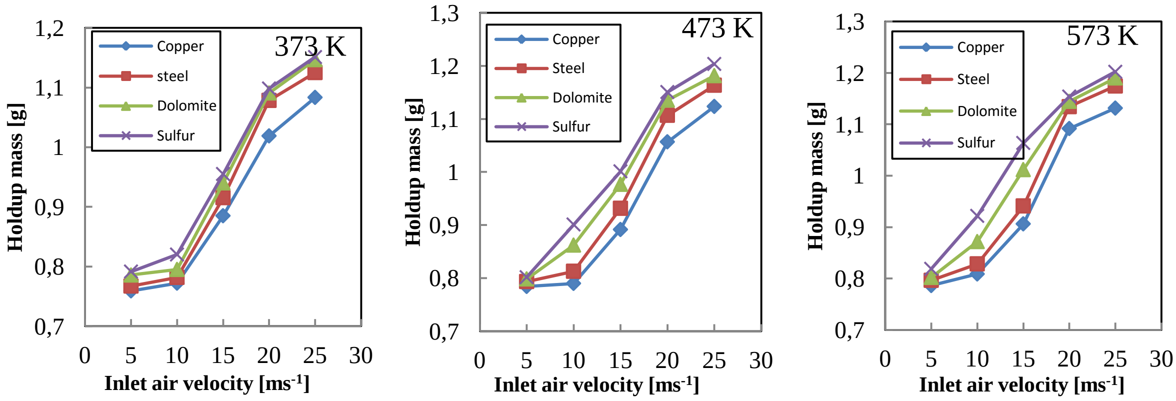

Figure 5. Effect of solid particles density on holdup mass at different inlet air temperature for C2

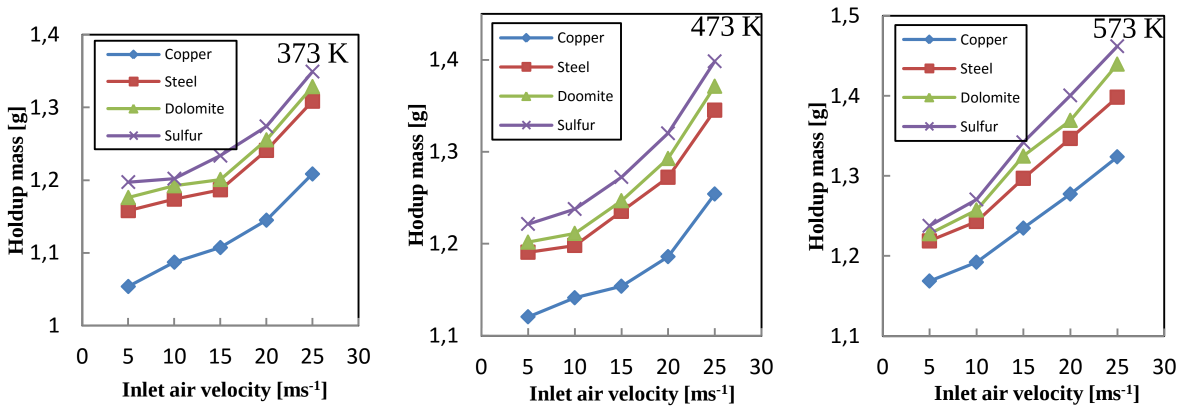

Figure 6. Effect of solid particles density on holdup mass at different inlet air temperature for C3

3.2. Effect of particles density on heat transfer rate

Heat transfer rate of the particles is related with mass flow rate, specific heat capacity and temperature difference between inlet and outlet temperature of particles [11, 25] and shown in eq. (10).

$$q = m_s C_{ps}(T_{sout} - T_{sin}) \quad (10)$$

The effect of particles density of C1, C2 and C3 on heat transfer rate is shown in fig.8, respectively. Heat transfer rate increases with rise in heat capacity of particles and high for dolomite compared to other particles even though particle residence time is less than steel, which indicates that heat transfer rate depends upon heat capacity of particle than particle residence time and holdup mass. Increase in diameter of cyclone increases the contact time between particles and air, thus the heat transfer rate increased. Increasing the cyclone diameter from C1 to C2 the heat transfer rate increased to 20% at 373 K and similar result was observed for C2 to C3 for all particles and temperatures.

It is also clear that increase in inlet air velocity increases the heat transfer rate due to increase in mass flow rate of air which increases the availability of air for heat transfer. Maximum heat transfer rate occurs at 5 - 10 m/s(15 – 25%) for all particles in C1 and similar result was observed for C2 and C3. Increasing the temperature of inlet air from 373 - 473 K, heat transfer rate increases 1.2 - 1.5 times and when increasing 473 - 573 K, heat transfer rate increases 0.5 - 0.8 times in C1. Similar result was observed for C2 and C3 cyclone for all particles.

3.3. Experimental Description

Experimental setup of present work is displayed in fig. 9. It consists of an air inlet pipe connected with blower, solid particles feeder, cyclone separator, valve arrangements and bin. Feeder section consists of an electromagnetic vibrator connected to a particle discharge unit. Particles are fed in to inlet pipe through a hopper and inlet pipe is joined to cyclone with a geometrical transition part from circular to rectangular. To calculate temperature of air and solid particles, thermocouples are placed at various parts of cyclone body. Setup is fitted with instruments to measure flow rate of air and solid particles. Experiment is insulated with asbestos rope in order to prevent the heat loss. Pressure gauges are used to measure pressure drop at inlet and outlet. Air and solid feed rate was controlled by varying the inlet valves respectively. Uncertainty in the measurement of exit temperature is ±1 ºC. The collected solids are weighed on Infra digital precision balance having model number IN200 manufactured by Infratech, India, with a least count of 0.01 g.

3.4. Experimental Procedure

Desired flow rate of air was set by inlet valve and atmospheric air is drawn from the blower which enters heater through inlet pipe. Solid particles fed to the hopper through electromagnetic arm imparting machine which is fitted in the inlet pipe. Steady solid feed rate is achieved for particular combination of gas velocity, particle size and funnel opening. Mixture of gas and solid phase enters tangentially into the exchanger where heat transfer takes place between gas to solid. Temperature of air from inlet to outlet was measured using thermocouples at various parts of cyclone heat exchanger. Solid particles are collected in bin. At any instant of time holdup mass in cyclone heat exchanger was calculated by closing both inlet and outlet valve of gas and particles flow simultaneously. Particles collected in bin are weighted to calculate the mass (holdup mass) of solid particles. In order to ensure the reliability of data, four random measurements were taken for each experimental reading.

3.5. Prediction of new correlation for dimensionless holdup mass

Correlation is developed from obtained computational result by dimensional and regression analysis. Correlation coefficients and exponents were estimated using regression analysis Holdup mass is a function of flow rate of air, flow rate of solid particles, cyclone body diameter, diameter of particle and particle density [18].

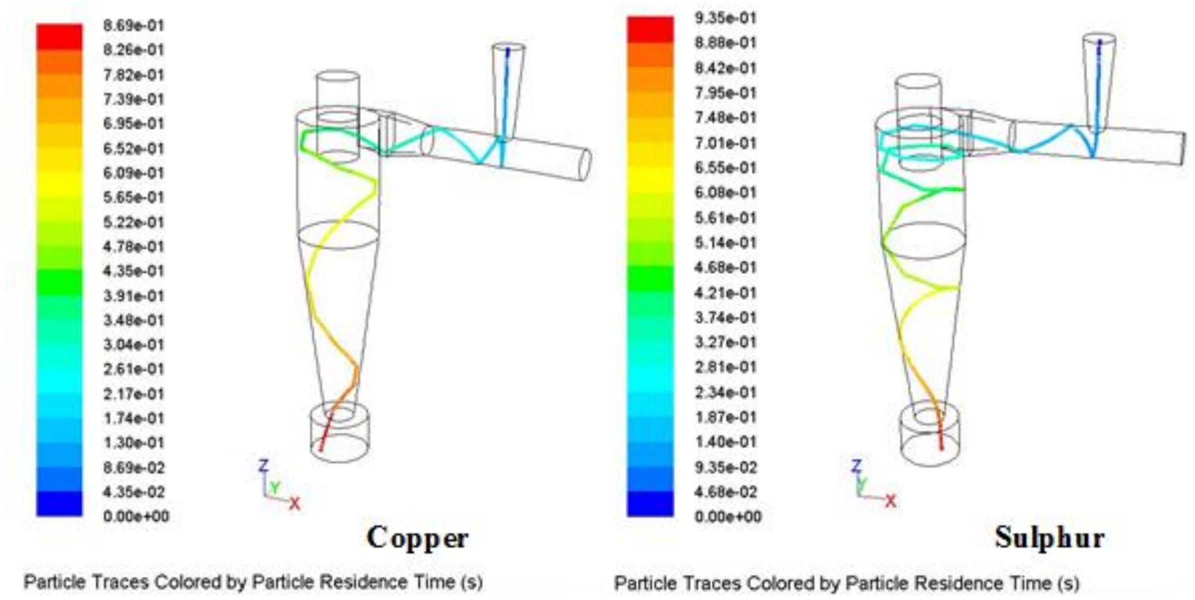

Figure 7.Single particle trajectories for different materials.

$$M_h = f\,(m_g, m_s, D, d, \rho_p) \qquad (11)$$

Variables are grouped into non dimensional group by using Buckingham Π solution theorem. Three Π values are generated from Dimensional analysis [11,18]

$$\Pi 1 = M_h/\ \rho_p\ D^3 \qquad (12)$$

$$\Pi 2 = m_s/m_g \qquad (13)$$

$$\Pi 3 = d/D \qquad (14)$$

Where Π 1 is a dimensionless holdup and Π values are arranged together to derive correlation [18].

$$M_h/\ \rho_p\ D^3 = (m_s/m_g)^{\,a1}\ (d/D)^{\,a2} \qquad (15)$$

Coefficient values of eq.(14) obtained by regression technique are grouped to form the equation

$$M_h/\rho_p D^3 = 165.574\ (m_s/m_g)^{-0.13013}\ (d/D)^{\,2.6054} \qquad (16)$$

The above correlation is valid for mass flow rate of solid (m_s) to air (m_g) ratio from 0.00401 - 0.8019, density of particles from 2050 - 8978 kg/m^3 and ratio of diameter of particles (d) to diameter of cyclone (D) varies from 0.001 - 0.003. Predicted correlation compared with experimental Π1 value and result is displayed in fig.10. It indicates good relation between proposed correlation Π1and experimental Π1, with error band of -3 to +6%.

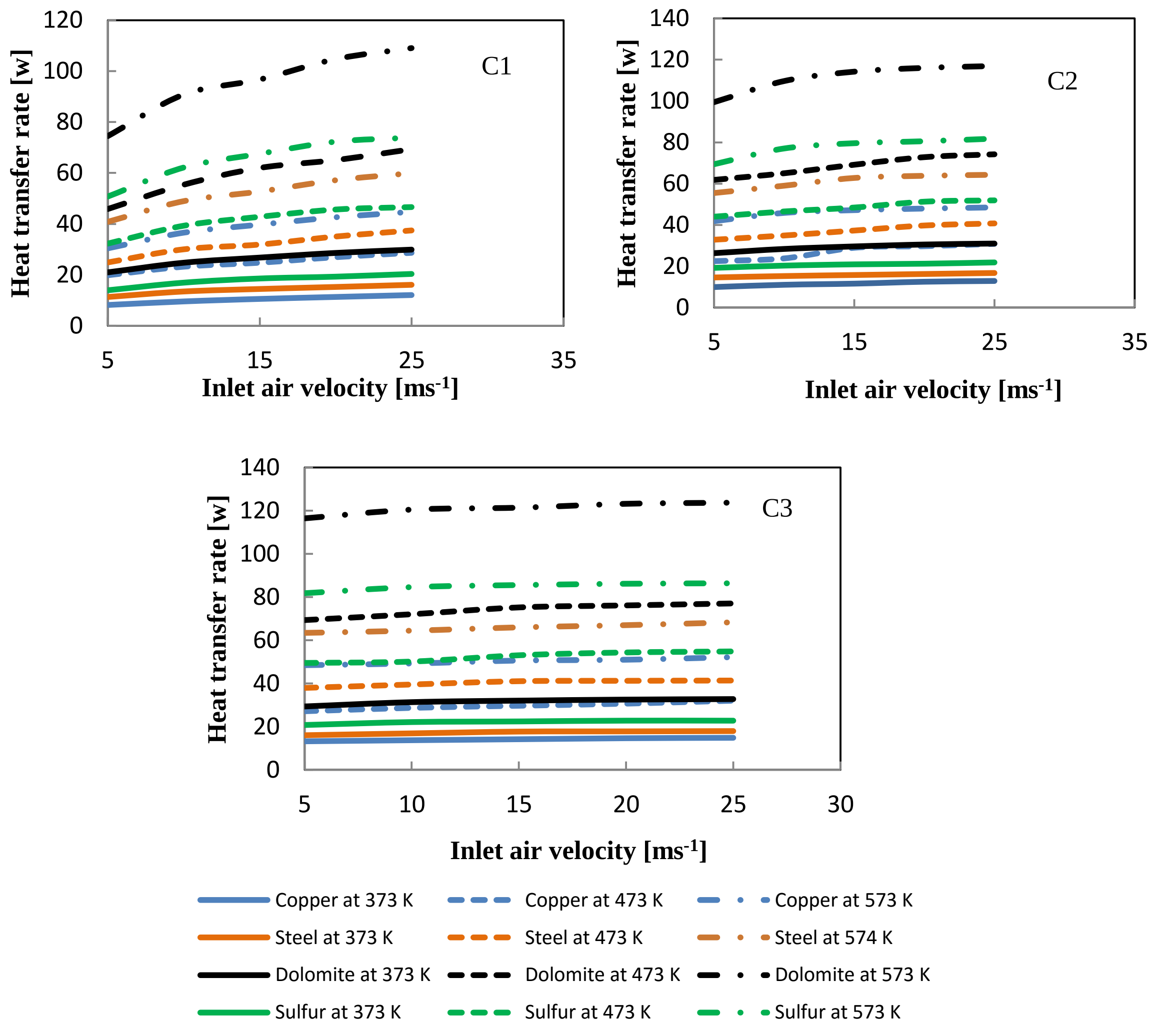

Figure 8. Effect of particles density on heat transfer rate for C1, C2 and C3

Figure 9. Experimental setup of cyclone heat exchanger

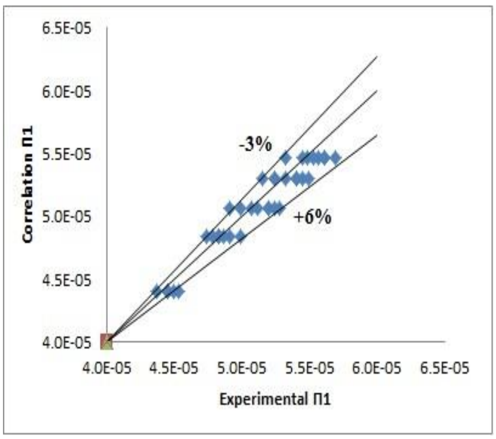

Figure 10. Comparison of experimental and correlation Π1 value

4. Conclusions

In this paper the simulation done in k-ε RNG turbulence model and DPM for particle trajectory to find effect of particles density and diameter of cyclone heat exchanger on holdup mass &heat transfer rate in the Stairmand high efficiency cyclone. Holdup mass of the particles decreases with increase in inlet particle density whereas increases with increase in cyclone diameter. Heat transfer rate increases with decrease in density of particles as well as increase in specific heat capacity of particles and body diameter of cyclone. Correlation is predicted for non-dimensional holdup mass and it is compared with experimental holdup mass that predicts experimental value within an error range of -3 to +6%.Correlation is valid only for mass flow rate of solid to air ranges from 0.00401 - 0.8019, diameter of particles to diameter of cyclone ranges from 0.001 - 0.003.This work can be extended to find generalized correlation for holdup mass without compensating collection efficiency by varying cyclone geometry dimensions.

Nomenclature

B_d	-Bin diameter, [mm]
B_h	-Bin height, [mm]
C_d	-Gas outlet, [mm]
d	-Diameter of solid particles [micron]
C_D	-Drag Coefficient
D	-Cyclone diameter, [mm]
D_e	-Gas outlet, [mm]
D_s	-Solid particle inlet diameter, [mm]
D_a	-Gas inlet diameter, [mm]
G_k	-Generation of turbulence kinetic energy
g_x	-Gravitational acceleration,[ms^{-2}]
H	-Height of rectangle inlet, [mm]
k	-Turbulent kinetic energy,[m^2s^{-2}]
L_b	-Cyclone body length, [mm]
L_c	-Cone length, [mm]
L_{cc}	-Connector length, [mm]
L_p	-Duct length, [mm]
L_s	-Particle hopper length, [mm]
m_g	-Mass flow rate of the air, [kgs^{-1}]
M_h	-Holdup mass, [grams]
m_s	-Mass flow rate of the solid particles, [kgs^{-1}]
P	-Mean pressure, [Pa]
S	-Vortex pipe height, [mm]
t_R	-Particle Residence time, [s]
W	-Width of the rectangle inlet, [mm]
D_H	-Hydraulic diameter of inlet duct,[m]
Y_m	-Fluctuating dilatation in compressible turbulence
C_{ps}	-Specific heat of solid particle, [$Jkg^{-1}K^{-1}$]
T_{Sin}	-Inlet temperature of solid particle,[K]
T_{Sout}	-Outlet temperature of solid particle, [K]
q	-Heat transfer rate, [W]

Greek Letters

ε	-Turbulent dissipation rate, [m^2s^{-3}]
μ	- Molecular viscosity of fluid, [$kgm^{-1}s^{-1}$]
ξ	-Drag coefficient defined as per the equation
α_k	- Inverse effective Prandtl number for k
α_{ε}	- Inverse effective Prandtl number for ε
ρ_p	-Density of solid particles [kgm^{-3}]

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