Effect of vortex finder dimension on holdup mass and heat transfer rate in cyclone heat exchanger-CFD approach

T. Mothilal*

Department of Mechanical Engineering,
T.J.S. Engineering College,
Peruvoyal, Chennai, India
Email: haimothi@yahoo.co.in
*Corresponding Author

K. Pitchandi

Department of Mechanical Engineering,
Sri Venkateswara College of Engineering,
Sriperumpudur, Chennai, India
Email: pitch@svce.ac.in

Abstract: This work investigates the effect of vortex finder dimensions on solid cyclone heat exchanger using Reynolds stress turbulence model (RSTM) in CFD code FLUENT 12. Seven cyclones were tested to find the holdup mass and amount of heat transferred from the inlet gas to solid particles. Tangential and axial velocity of cyclone reduces with increase in vortex diameter whereas increase in vortex finder length reduces tangential velocity slightly and not much variation is observed with axial velocity. The experimental data used for the validation of simulations were obtained from the literature study. Previous works done in varying the dimensions of vortex finder does not predict the holdup mass and heat transfer rate in cyclone. This work presents effect of vortex finder dimensions on holdup mass and heat transfer rate on solid cyclone heat exchanger. Holdup mass and heat transfer rate decreases with increase in both vortex finder diameter and vortex finder length. Results indicate that change in vortex finder diameter has more impact of about 25% to 48% than change in vortex finder length on holdup mass and about 3% to 5% on heat transfer rate.

Keywords: cyclone heat exchanger; CFD; RSTM; vortex finder dimension; holdup mass.


Biographical notes: T. Mothilal is an Associate Professor in Department of Mechanical Engineering at TJS Engineering College, affiliated to Anna University Chennai. He is pursuing his PhD from Anna University Chennai. His area of research includes computational fluid dynamics, heat exchanger, heat transfer, etc. He has published various articles in national and international journals and participated in various conferences.
1 Introduction

In various industries such as cement production, fertiliser, chemical processing and powder industries, cyclones are used to remove dispersed particles from carrying gas. Cyclones are one of the oldest methods of particles separation in power plants and industries. Heat exchangers are used for efficient transfer of heat through convection between two fluids and the convection takes place even though the mediums are separated by a wall region. This study discusses the effect of geometrical parameters while using cyclone separator as a heat exchanger as it is deemed to have a higher popularity for the past two decades. Various studies on effect of mass flow rate of fluid (air and solid) on pressure drop, heat transfer characteristics and collection efficiency in a cyclone separator has been done. In case of a cyclone heat exchanger holdup mass of the particles is the amount of particles undergoing heat transfer at any instance of time within the cyclone body.

Karagoz and Kaya, (2007) investigated influence of inlet velocity in tangential inlet cyclone on heat transfer characteristics and found that input flow rate mostly affects swirl rotation in inside vortex whereas its effect on outer vortex is negligible. Jain et al. (2006) carried experiments in cyclone heat exchanger and found that heat transfer rate and heat transfer coefficient between gas and particles increases with increase in solid feed rate. The effects of geometrical parameters on cyclone performance are reported in many articles (Elsayed and Lacor, 2011a, 2012, 2011b, 2013, 2008; Xiang and Lee, 2005; Lim et al., 2004). The influence of geometrical parameters of a cyclone viz., Inlet height, dust outlet and diameter of cone tip on flow patterns and cyclone performance are found by Elsayed and Lacor (2011; 2011a; 2012; 2013). Optimisation of cyclone vortex diameter by numerical simulation was done by Elsayed and Lacor (2008). Xiang and Lee (2005) numerically evaluated different cyclone height for flow pattern and separation efficiency. Lim et al. (2004) analysed experimentally characteristics of collection efficiency in cyclone for different vortex finder diameter and shape. Parameters influencing on collection efficiency in a cyclone is discussed by Patterson and Munz (1989) found that dust load has more effect on collection efficiency and at high temperature the loading effects are stronger. 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. The influence by velocity on pressure drop is experimentally studied by Ficici
et al. (2010). By varying vortex finder diameter and observed linear relation between drop in pressure and vortex finder length. Noriler et al. (2004). introduced new mechanical device in cyclone to reduce the pressure drop which is obtained by breakdown of swirling flow.

The above-mentioned study does not predict influence of geometrical parameters on holdup mass in cyclone heat exchanger. The present work elaborates the effect of vortex finder dimension on holdup mass and Heat transfer rate which has not been discussed so far.

2 Description of numerical model

2.1 Governing equations

Fluid flows are mathematically evaluated by Reynolds-average navier-stokes formulae. For steady and incompressible flow the equation for continuity and momentum is given as (Karagoz and Kaya, 2007).

\[
\frac{\partial \rho u_i}{\partial x_i} = 0
\]  

\[
\frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \rho g_i + \frac{\partial}{\partial x_i}\left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho u_i u_j^\prime\right)
\]

2.2 Transport equation of RSTM model

\[
\frac{d}{dt}\left(\rho u_i^\prime u_j^\prime\right) + \frac{d}{dx}\left(\rho u_i u_j^\prime\right) = -\frac{d}{dx}\left[\frac{\rho u_i u_j}{\partial x_i}\right] + \frac{\rho}{\partial x_i}\left[\mu \frac{\partial u_i}{\partial x_i}\right] - \rho\left(\frac{u_i u_j^\prime}{\partial x_i} + u_i^\prime u_j^\prime\frac{\partial u_i}{\partial x_i}\right) -\rho\beta\left(g_i u_j^\prime + g_j u_i^\prime\right)
\]

\[
+p\frac{\partial u_i^\prime}{\partial x_j} + \frac{\partial u_j^\prime}{\partial x_i} - 2\mu\frac{\partial u_i^\prime}{\partial x_i}\frac{\partial u_j^\prime}{\partial x_k}\]

\[+2\rho\frac{\partial\Omega}{\partial x_i}\left(u_i^\prime u_m^\prime e_{ikm} + u_i^\prime e_{ikm}^\prime + u_m^\prime e_{ikm}\right) + S_{user}
\]

2.3 Numerical description of solid particles

Lagrangian discrete phase model (DPM) follows the Eulerian – Lagrangian method in FLUENT software. Discrete phase modelling is analysed by collecting solid particles through flow field. Particles phase fraction is less than 10%. Trajectory of solid particles calculated individually at specified time interval during primary phase calculation. Usually solid loading is small in cyclones (3%–5%) (Elasyed and Lacor, 2011; Mothilal and Pitchandi, 2015) presence of second phase (solid phase) does not affect the primary phase (gas phase) and flow field (one way coupling) in cyclone heat exchanger.
Interactions between particles are neglected and trajectory is computed by force balancing on particles. Discrete phase model gives the particles velocity, size and position at inlet to simulate the motion of particles. Equation of DPM model is given below

\[
\frac{du_p}{dt} = F_D(u - u_p) + g\left(\frac{\rho_p - \rho}{\rho_p}\right) + F_x
\]  

(4)

where \(F_x\) is acceleration (force/unit particles mass) term and \(F_D\) is drag force

\[
F_D = \frac{18\mu \ c_D R_e}{\rho_p d_p^2 24}
\]

(5)

where \((R_e)\) Reynolds number of fluid which is formulated as

\[
R_e = \left(\frac{\rho d_p (u_p - \mu)}{u}\right)
\]

(6)

### 3 Generation of model

The configuration of cyclones was based on stairmand high efficiency cyclone, which gives more collection efficiency of particles. Cyclone body diameter is the important dimension in designing of cyclones. So the design of different vortex finder dimensions is based on the ratio of cyclone body diameter and other dimensions are taken as reference from stairmand high efficiency cyclone. The vortex finder dimensions of different cyclones are displayed in Table 1 and 2D view is shown in Figure 1. 3D modelling was done by using Solid works modelling software.

**Figure 1**  Cyclones with different vortex dimensions

Note: *D3 and S3 is same dimension*
Table 1  Dimension description of different cyclones

<table>
<thead>
<tr>
<th>Cyclone description</th>
<th>Dimension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclone diameter</td>
<td>100</td>
</tr>
<tr>
<td>Inlet height</td>
<td>50</td>
</tr>
<tr>
<td>Inlet width</td>
<td>20</td>
</tr>
<tr>
<td>Barrel height</td>
<td>150</td>
</tr>
<tr>
<td>Cone height</td>
<td>250</td>
</tr>
<tr>
<td>Cone tip diameter</td>
<td>37.5</td>
</tr>
<tr>
<td>Gas inlet</td>
<td>36</td>
</tr>
<tr>
<td>Solid inlet</td>
<td>36</td>
</tr>
<tr>
<td>Vortex finder diameter</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>30</td>
</tr>
<tr>
<td>D2</td>
<td>40</td>
</tr>
<tr>
<td>D3*</td>
<td>50</td>
</tr>
<tr>
<td>D4</td>
<td>60</td>
</tr>
<tr>
<td>Vortex finder length</td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>30</td>
</tr>
<tr>
<td>S2</td>
<td>40</td>
</tr>
<tr>
<td>S3</td>
<td>50</td>
</tr>
<tr>
<td>S4</td>
<td>60</td>
</tr>
</tbody>
</table>

Note: *D3 and S3 is same dimension.

4 Boundary condition and grid independence

A velocity inlet boundary condition is used at gas and solid inlet whereas outflow condition was applied at gas outlet. The density of the air is 1.225 kg/m$^3$ and the turbulent intensity (I) is 5% and hydraulic diameter is 0.036 m. Carbon particles with density of 2000 kg/m$^3$ is used for analysis. The co-efficient of restitution of particles is assumed to be 0.8 (Mothilal and Pitchandi, 2015).

The grid was generated by using ICEM CFD software for all seven cyclones. Three levels of grids tested in every cyclone heat exchanger to confirm the obtained results are grid independent. Table 2 shows three different grids 111519, 144605 and 196429 elements for D2 and their pressure drop in cyclone heat exchanger. Result shows that difference between 196429 and 144605 is less than 1% and considering computational timing cyclone domain 144605 elements chosen for holdup mass and heat transfer rate analysis. Similar study was done for other six cyclones and similar range of mesh size was selected for analysis.
Table 2  
Grid independent study of D2 cyclone heat exchanger

<table>
<thead>
<tr>
<th>Number elements</th>
<th>Pressure drop (Pascal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>111519</td>
<td>118.04</td>
</tr>
<tr>
<td>144605</td>
<td>123.38</td>
</tr>
<tr>
<td>196429</td>
<td>124.32</td>
</tr>
<tr>
<td>% difference(^a)</td>
<td>4.52</td>
</tr>
<tr>
<td>% difference(^b)</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Note: Where % difference\(^a\) is difference between 111519 to 144605 elements  
% difference\(^b\) is difference between 144605 to 196429 elements.

5  Results and discussion

5.1  Flow pattern of cyclone heat exchanger

Static pressure in cyclone heat exchanger decreases with increase in vortex finder dimensions. Rise in vortex dimension reduces the pressure and even negative region appeared in vortex finder. Gas entering the cyclone classified into three velocities namely tangential, axial and radial. Impact of radial velocity is negligible compared to tangential and axial velocities. Maximum tangential velocity rises with decrease in vortex finder dimension. Axial velocity rises with increase in both vortex finder dimensions.

5.2  Validation of simulation result with experimental result

In order to validate the present CFD simulation, result of heat transfer rate was compared with the experimental heat transfer rate stated by Jain et al., (2006). In simulation outlet temperature of particles measured and heat transfer rate was calculated. The result shows that heat transfer rate rises with rise in inlet air flow rate. Heat transfer rate predicted from the simulation result have similar trend to that of heat transfer rate predicted by Jain et al. (2006) is shown in Figure 2. Deviation in heat transfer is due to friction between wall and fluid is not considered, variable heat transfer coefficient and variable wall temperature. Considering the complexity of the turbulent swirling flow in the cyclones, the agreement between the simulations and measurements is considered to be quite acceptable.

Figure 2  
Comparison between simulation and experimental heat transfer rate
Figure 3  Influence of vortex finder dimensions on holdup mass

Figure 4  Single particle trajectories of vortex finder diameters (see online version for colours)
5.3 Effect of vortex finder dimension on holdup mass

Holdup mass of the particles is predicted by using the following equation (Mothilal and Pitchandi, 2015)

\[ M_h = m_t \times t_p \]  

(7)

The residence time \( t_p \) of particles is defined as particles travelling time in cyclone heat exchanger from inlet to the bin. Residence time has a greater influence on holdup mass. Influence of vortex dimension on holdup mass was studied at 10 m/s air velocity, uniform particles size of 200 micron and constant solid flow rate of 0.5 g/s. The effect of vortex dimension on holdup mass is shown in Figure 3. Result shows that with increase in vortex finder diameter and vortex finder length the holdup mass decreases. It is due to loss in tangential velocity which is directly proportional to centrifugal force of particle. Figure 4 shows single particle trajectory for various cyclones with respect to that of the different vortex diameter. Due to the loss of centrifugal force, swirling rotation gets reduced which decreases residence time of particles hence the holdup mass reduces with rise in vortex finder dimension.

5.4 Effect of vortex dimension on heat transfer rate

Effect of vortex finder dimension on heat transfer rate was evaluated with inlet air temperature of 500 K. In order to find the effective heat transfer rate, the particles outlet temperature was obtained by tracking the solid particles at the solid outlet surface (bin) and calculated using equation (8).

\[ q = m_t C_p \left[ T_{out} - T_{inr} \right] \]  

(8)
Increase in vortex finder dimension reduces the swirling motion of particles therefore contact time between solid particles and air in cyclone decreases which in turn decreases heat transfer rate. Comparing vortex finder diameter and length, the change in vortex finder diameter has more impact on heat transfer rate.

6 Conclusions

Reynolds stress turbulence model (RSTM) has been used to evaluate effect of vortex dimension on holdup mass and heat transfer rate. Seven cyclones have been analysed and following conclusion is obtained.

- Vortex finder dimension has a significant effect on flow pattern. Pressure drop decreases with increase in both vortex finder diameter and length.
- Increasing the vortex finder dimension in cyclones decreases the tangential velocity and axial velocity. Negligible variation in radial velocity was observed when increasing vortex finder dimension.
- Holdup mass of cyclone decreases with increase in both vortex finders dimensions. Holdup mass decreases more with change in vortex finder diameter than change in vortex finder length and has impact of 25% to 48% higher than vortex finder length.
- Heat transfer rate increases with decrease in both vortex finder diameter and vortex finder length. But change in vortex finder diameter has more impact on heat transfer rate comparing with vortex finder length.

References


Effect of vortex finder dimension on holdup mass and heat transfer rate


Nomenclature

\( C_{ps} \) solid particles heat capacity in kJ/kg K

\( g_i \) gravitational acceleration

\( J \) diffusion flux in moles/cm²s

\( M_h \) holdup mass in g

\( m_s \) solid particles flow rate in kg/s

\( P \) mean pressure in Pascal

\( q \) effective heat transfer rate in W

\( t_p \) particles Residence time in s

\( T_{sin} \) inlet solid temperature in K

\( T_{sout} \) exit solid temperature in K

\( u \) inlet velocity of gas in m/s

\( \rho_p \) density of solid particles in kg/m³

\( \mu \) viscosity of fluid in kg/ms.