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# A CFD Study of the Effect of Vortex Finder Thickness on Gas Cyclone Separator Performance

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**Abstract:** Three-dimensional, time-dependent Eulerian-Lagrangian simulations of the turbulent gas-solid flow in a cyclone separator have been performed. The effects of geometrical and operational variables on the separation efficiency in a cyclone separator have been investigated. The flow features are examined in terms of flow field, pressure drop, particle trajectories and separation efficiency. In the Computational Fluid Dynamics (CFD) modeling of gas cyclone, the Reynolds Stress Model (RSM) that is a suitable turbulence model was used. The trajectory of the discrete phase particle is obtained by integrating the force balance on the particle which can be written in a Lagrangian reference frame. In this study, grade efficiencies have been computed and compared with the experimental values for cyclones of different vortex finder thickness. The results show that the separation efficiency will be changed with the change of the vortex finder thickness and the main reason of it is the reduction of particle escaping to centric upward flow and inlet flow momentum improvement in the cylinder zone of cyclone.

**Key words:** Vortex finder thickness, cyclone separator, overall efficiency, pressure drop, turbulence modeling, dense medium separation

## INTRODUCTION

Cyclones are by far the most widely used type of particulate control equipment. Their simple design, low maintenance costs and adaptability to a wide range of operating conditions make them one of the most widely used particle removal devices. By using suitable materials and methods of construction, cyclones may be adapted for use in extreme operating conditions such as in high temperature, high pressure and corrosive environment. With no moving parts involved and mainly consisting of a drum with a funnel at the bottom, inlet and exit ports, a cyclone separator is fairly simple to build and inexpensive (Zhao *et al*., 2004).

Many researchers have contributed to the large volume of work on improving the efficiency of cyclone by introducing new design and operation variables. However, in most cases, the improvement in efficiency is marginal and in some cases in association with complex structure and additional operating costs. However, there is a potential for improving cyclone separators as discussed in the following. During recently years, a number of variation and modifications of geometrical variables to the basic design of gas cyclone and hydrocyclone have been examined by various investigations to find out optimal models for different industrial applications (Avci and Karagoz, 2003; Rahmani and Mahvi, 2005; Xiang and Lee, 2005; Yoshida *et al*., 2006; Chuah *et al*., 2006; Lee *et al*., 2006; Wang and Yu, 2006; Bhaskar *et al*., 2007; Neesse *et al*., 2007). Also many researches have been focused on operational variables like feed inlet pressure, particle concentration, gas velocity, temperature, turbulence intensity, etc. (Mukherjee *et al*., 2003; Xiaodong *et al*., 2003; Cilliers *et al*., 2004; Neesse *et al*., 2004; Yang *et al*., 2004a; Doby *et al*., 2005; Bernnan *et al*., 2007; Shi and Bayless, 2007; Chen and Shi, 2007).

However, very little information is available on the modeling and simulation of the effects of the vortex finder thickness on the performance and hydrodynamics of cyclone. The effects of the vortex finder thickness have been neglected or taken in negligible order by most of the researchers. This work highlights the fundamental significance of the thickness of the vortex finder, showing how small changes in thickness have meaningful effects on mass recovery and particle size distribution in cyclone separator.

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## COMPUTATIONAL FLUID DYNAMICS APPROACH

Fluid flows have long been mathematically described by the Navier-Stokes equations. With the current technology, it is not possible to solve the Navier-Stokes equations for turbulent flow to the required accuracy (Yang *et al*., 2004b). A practical way of simulating fluid flows in engineering applications is to use turbulence models and solve for the mean fluid velocity and pressure.

**Turbulence closure model:** The multiphase flow in a cyclone is quite complicated and different treatments may have to be used for different phases. In this study, the fluid flow is modeled as turbulent, described by the Reynolds stress model (RSM) that can reasonably predict the swirling flows (Bounegta *et al*., 2010; Elhadi *et al*., 2002). It is regarded as the most applicable turbulent model for cyclone flow even though it has the disadvantage of being computationally more expensive (Narashima *et al*., 2007). When using the Reynolds stress turbulence model, beside the momentum and continuity equations, the transport equations of Reynolds stresses can be written as:

$$\frac{\partial}{\partial t}\left(\rho\, \overline{u_i' u_j'}\right)+\frac{\partial}{\partial x_k}\left(\rho\, u_k \overline{u_i' u_j'}\right)=D_{ij}+P_{ij}+\Pi_{ij}+\varepsilon_{ij}+S \qquad (1)$$

Where the left two terms are the local time derivative of stress and convective transport term, respectively right five terms are;

The stress diffusion term:

$$D_{ij}=-\frac{\partial}{\partial x_k}\left[\rho\, \overline{u_i' u_j' u_k'}+\left(\overline{p' u_j'}\right)\delta_{ik}+\left(\overline{p' u_j'}\right)\delta_{jk}-\mu\left(\frac{\partial}{\partial x_k}\overline{u_i u_j}\right)\right] \qquad (2)$$

The shear production term:

$$P_{ij}=-\rho\left[\overline{u_i' u_j'}\frac{\partial u_j}{\partial x_k}+\overline{u_j' u_k'}\frac{\partial u_j}{\partial x_k}\right] \qquad (3)$$

The pressure strain term:

$$\Pi_{ij}=p\left(\overline{\frac{\partial u_j'}{\partial x_j}+\frac{\partial u_j'}{\partial x_i}}\right) \qquad (4)$$

The dissipation term:

$$\varepsilon_{ij}=-2\mu\,\overline{\frac{\partial u_i'}{\partial x_k}\frac{\partial u_j'}{\partial x_k}} \qquad (5)$$

and the source term: S.

**Particle tracking method:** In this phase modeling technique, the second phase is introduced as a discrete phase that can be simulated in a Lagrangian frame of reference by defining the initial position, velocity and size of individual particles. The second phase consists of particles dispersed in the continuous phase that are assumed to be spherical (Dorfeshan and Marghzar, 2011).

The particle loading in a sampling cyclone is typically small (3-5% volume fraction) and therefore, it can be safely assumed that the presence of the particles does not affect the flow field (one-way coupling).

In the gas cyclone system operating since the particulate is very dilute, its effects on the flow field was not considered. The continuous gas flow was solved first. The discrete particulate phase is predicted based on the fixed continuous phase flow field.

**The equation of motion for the particles:** In the three-dimensional cylindrical coordinates the trajectory of the discrete phase particle is obtained by integrating the force balance on the Particle. for a particle, only gravity, drag force, centrifugal force and the force resulting from the velocity gradient (the Saffman force) are considered and the equation of motion can be written in a Lagrangian reference frame:

$$\frac{du_p}{dt}=\frac{1}{\tau_r}\left(u+u'-u_p\right)+\frac{v_p^2}{r}-F_{saff} \qquad (6)$$

$$\frac{dv_p}{dt}=\frac{1}{\tau_r}\left(v+v'-v_p\right)+\frac{u_p v_p}{r} \qquad (7)$$

$$\frac{dv_p}{dt}=\frac{1}{\tau_r}\left(w+w'-w_p\right)-g \qquad (8)$$

Here, $\tau_r$ is the relaxation time of the particle which is defined as:

$$\tau_r=\frac{\rho_p d_p^2}{18\mu f} \quad \text{and} \quad f=\frac{C_D}{24/\mathrm{Re}} \qquad (9)$$

The values of the drag coefficient in the turbulent fluctuation flow, $C_D$ can be expressed as the drag coefficient used in this study was that of Sartor and Abbot;

$$C_D=\begin{cases}\dfrac{24}{\mathrm{Re}_p}, & 0<\ \mathrm{Re}_p\le 0.1\\[2mm] \dfrac{24}{\mathrm{Re}_p}(1+0.0916\mathrm{Re}_p), & 0.1<\mathrm{Re}_p\le 5\\[2mm] \dfrac{24}{\mathrm{Re}_p}(1+0.158\mathrm{Re}_p^{2/3}), & 5<\mathrm{Re}_p\le 1000\end{cases} \qquad (10)$$

where, $Re_p$ is the particle Reynolds number and can be written as:

$$Re_p = \frac{\rho_f \left|\overrightarrow{u_p} - \vec{V}\right| d_p}{\mu} \tag{11}$$

$F_{saff}$ is the Saffman force which can be calculated as follow;

$$F_{saff} = 9.66 \frac{(\mu \rho g)^{0.5} (v_g - v_p)}{\pi\, d_p} \left|\frac{dv}{dr}\right|^{0.5} \tag{12}$$

In the last equation the part of dv/dr is the gradient of the tangential velocity.

**Particles in turbulent flows:** Because the particle diameter is in the range of 1-10 μm, the effect of the instantaneous turbulent velocity fluctuations on the particle trajectories can not be ignored .The dispersion of particles due to turbulence in the fluid phase was predicted using the stochastic tracking model. The stochastic tracking (or ‘‘random walk’’) model includes the effect of instantaneous turbulent velocity fluctuations on the particle trajectories through the use of stochastic methods. The particles are assumed to have no direct impact on the generation or dissipation of turbulence in the continuous phase.

**Numerical scheme:** The physical problem was numerically discrete using finite-volume approximation in three-dimensional Cartesian coordinate system. The decoupled solver was chosen for the governing Navier-Stokes equations which are solved iteratively in sequential manner until the defined values of convergence are met. Although the first-order upwind scheme discrete yields better convergence, it generally will yield less accurate results (Azwadi and Idris, 2010). According to this, the QUICK discrete scheme was used in calculating momentum and turbulence kinetic energy and its dissipation rate equations. The first-order upwind scheme discrete was used on the Reynolds stress equations. SIMPLEC arithmetic was used in pressure-velocity coupling in order to accelerate the convergence of the continuity equation (Qian *et al.*, 2006). The PRESTO! (PREssure STaggering Option) scheme which uses the discrete continuity balance for a “staggered” control volume about the face to compute the “staggered” pressure, is used for discrete of pressure. The grids consist of about 96000 control volumes for the cyclone. Grid refinement tests are conducted in order to make sure that the solution is not grid dependent. The CFD simulation was performed with a Pentium IV Core2 Due 2.67GHz with 1GB RAM-memory and 250GB hard disc memory.

## RESULT AND DISCUSSION

**Flow field characteristics:** The most important economical parameters of a cyclone separator are separation efficiency and pressure drop. To assess factors that contribute to performance, the components of the velocity field must be understood.

**Effect of the vortex finder thickness on the pressure patterns:** Cyclone pressure drop is essentially a consequence of the vortex energy, the solid loading and the gas-wall friction. The main contribution is the former, but it cannot be reduced because it may affect separation efficiency.

The pressure drop across cyclone is commonly expressed as a number gas inlet velocity heads ΔH named the pressure drop coefficient which is the division of the pressure drop by inlet kinetic pressure $\rho_g v_2^i/2$.

In this study, four empirical models in the literature have been chosen to predict the pressure drop over a cyclone, namely Shepherd and Lapple, Dirgo, Casal and Martinez and Coker (Gimbun *et al.*, 2005). In these four models, the total pressure drop in cyclone is either assumed equal to the static pressure drop or as a function of cyclone dimension and pressure drop coefficient. Generally cyclone pressure drop is proportional to the velocity head and can be written in the form of:

$$\Delta P = \alpha \frac{\rho_g v_i^2}{2} \tag{13}$$

In the Shepherd and Lapple model, α is obtained by assuming static pressure drop given as:

$$\alpha = 16 \frac{ab}{D_e^2} \tag{14}$$

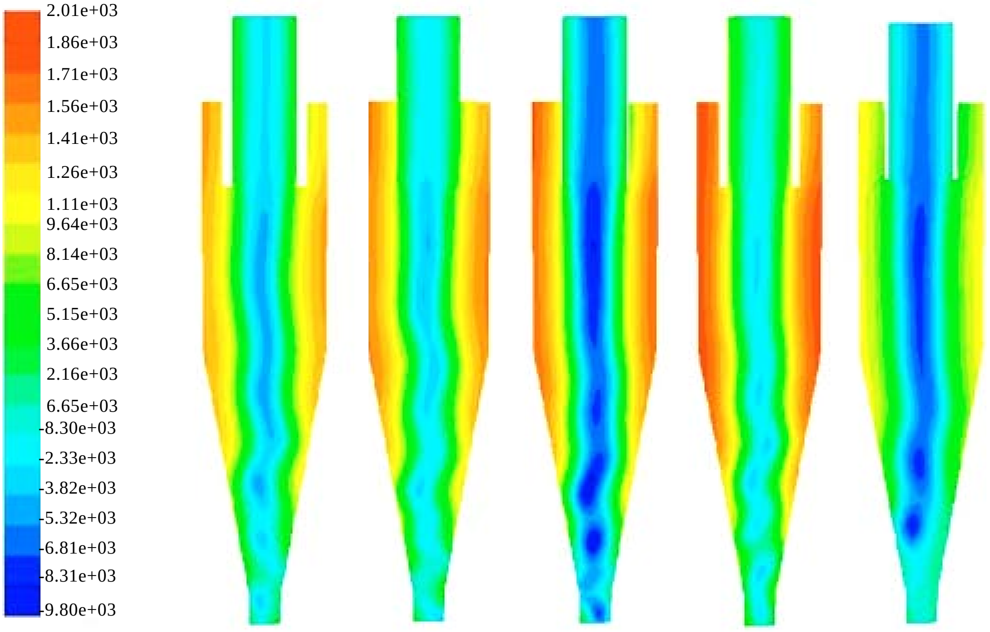
In Dirgo model, α is a function of cyclone dimension given as:

$$\alpha = 20 \left(\frac{ab}{D_e^2}\right) \left[\frac{S/D}{(H/D)(h/D)(B/D)}\right]^{\frac{1}{3}} \tag{15}$$

In Casal and Martinez, α is derived from the statistical analysis on experimental data given as:

$$\alpha = 11.3 \left(\frac{ab}{D_e^2}\right)^2 + 3.33 \tag{16}$$

In Coker, α is given as:



Conventional $t/D_e = 0.05$ $t/D_e = 0.1$ $t/D_e = 0.15$ $t/D_e = 0.2$

Fig. 1: Evolution of pressure drop for inlet velocity of 20m/s. comparison between conventional and new design cyclones

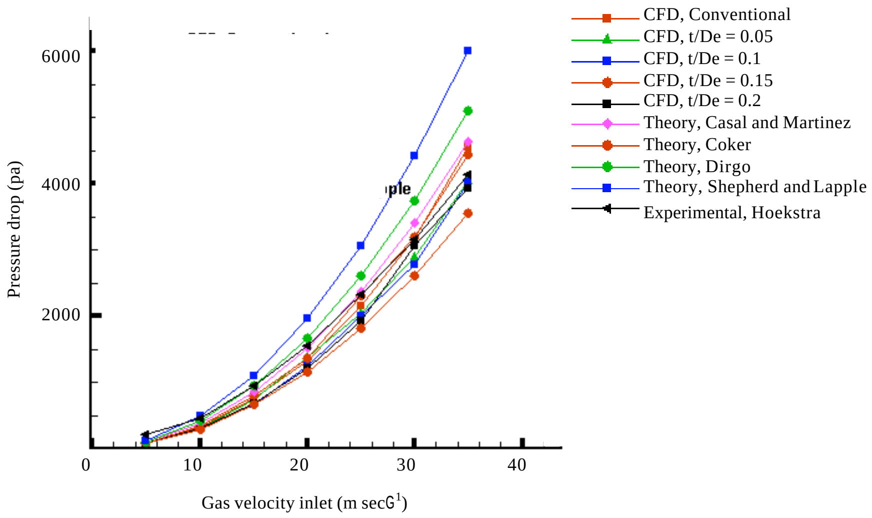


Fig. 2: Evolution of pressure drop with inlet velocity. Comparison between data presented by Hoekstra, the predictions of CFD and four empirical models

$$\alpha = 9.47\frac{ab}{D_e^2} \qquad (17)$$

In order to examine vortex finder thickness effects on cyclone performance, the ratio of vortex finder thickness to outlet diameter has been defined as a thickness ratio. In this study the ratios of 0.05, 0.1, 0.15 and 0.2 has been examined.

Figure 1 shows the effect of the vortex finder thickness on pressure patterns for a cyclone diameter of 200 mm that the static pressure decreases radial from wall to centre and a negative pressure zone appears in a centre. The pressure gradient is the largest along radial direction, as there is a highly intensified forced vortex.

Figure 2 shows the relationship between the pressure drop and the inlet gas velocity and compares the CFD results with four theoretical methods.

From Fig. 2, the new design cyclone with thickness ratio of $t/D_e$ = 0.1 will produce the slightly increased pressure drop. This can be explained by the balance between the effect of thickness on the velocity inlet and the flow turbulence in the cylinder and cone body of cyclone.

**Tangential velocity:** Tangential velocity distribution is similar to the dynamic pressure distribution. This means the most evident velocity component inside a cyclone is the tangential velocity. The centrifugal force field necessary for classification inside the system will be generated by the tangential velocity component of the continuous phase.

The flow field in the cyclone indicates the expected forced/free combination of the Rankine type vortex. Moreover, because the cyclone has only one gas inlet, the axis of the vortex does not coincide with the axis of the geometry of cyclone (Su, 2006).

Figure 3 indicate that the tangential velocity increases with increasing radial distance from the axis till a maximum tangential velocity values is achieved. However, at further increase in radial distances approaching towards the walls, the values decrease.

Figure 4 shows the experimental and calculated tangential velocities at the cylindrical section of the cyclone. The measured profiles show that the central region in the cyclone rotates like a solid body where the tangential velocity is increasing with an increasing radius. The maximum tangential velocity of approximately 1.65 times the inlet velocity is reached at radius range of 53 to 63% from the centre of the cyclone. Then, the tangential velocity starts to decrease and reaches zero velocity at the wall. Comparison with the new design data shows that the inverse tangential velocity has maximum and minimum value at thickness ratio of 0.1 and 0.15, respectively. The simulation results are in good agreement with the experimental results.

**Cyclone collection efficiency:** Separation efficiency in a cyclone is the fraction of the inlet solid flow rate separated in the cyclone.

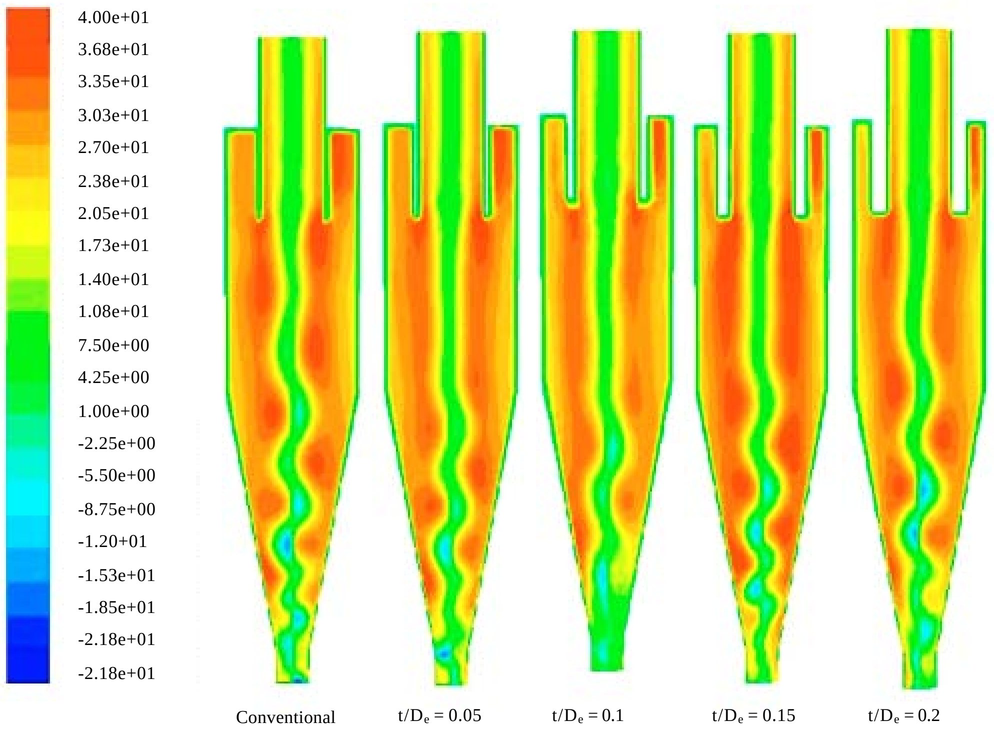


Fig. 3: Distribution of tangential velocity (anti-clockwise is positive and clock wise is negative): comparison between conventional and new design cyclones

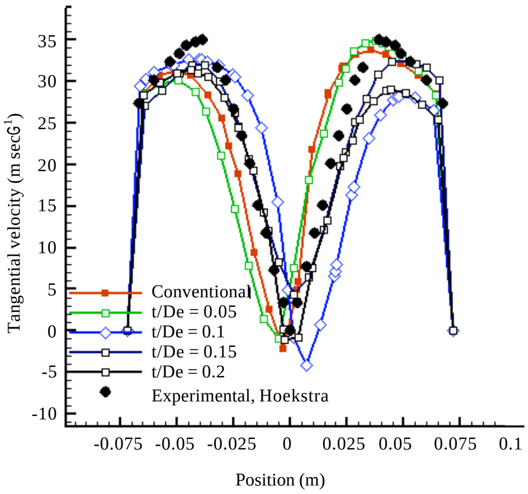


Fig. 4: Comparison of tangential velocity distribution between conventional and new design cyclone at the cylindrical section of the cyclone body

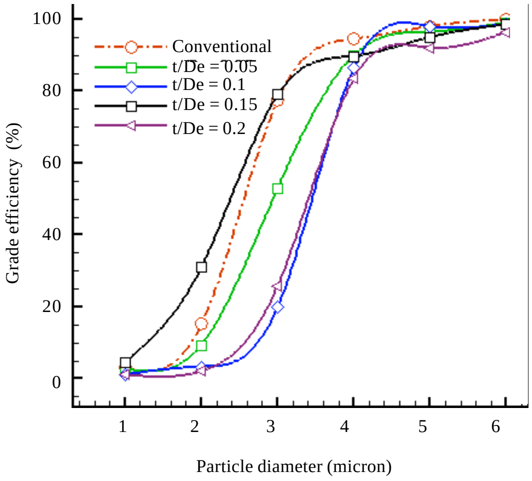


Fig. 5: Comparison of cyclone grade efficiency curves for conventional cyclone and cyclones with different vortex finder thickness

In this study to obtain the optimum vortex finder thickness, grade efficiencies of four thickness ratio have been computed and compared with conventional cyclone values.

The efficiency of cyclone for the particle diameters less than 5 micron is an important subject. Therefore at the velocity inlet of 20 m $sec^{-1}$, the effects of particle diameter on the grade efficiency have been studied.

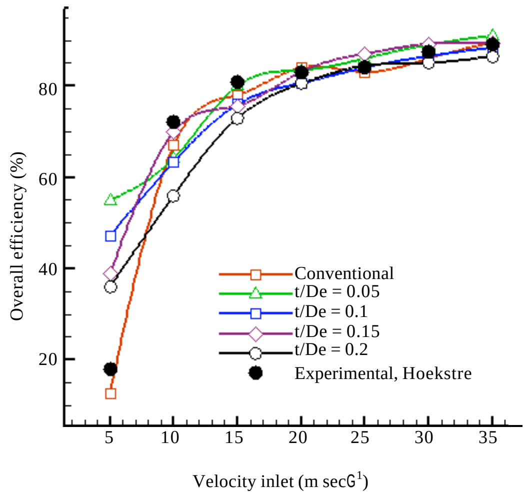


Fig. 6: Overall efficiency of cyclone at different inlet velocities and 4 micron particle diameter

**The relationship between grade efficiency and Particle diameter:** Collection efficiency test results are presented in Fig. 5, as a function of particles diameter, for six different diameters. It is usually expected that collection efficiency increase with the particle diameter. However, the grade efficiency of the cyclone with thickness ratio of 0.15 was higher than the efficiency of the cyclone with conventional design at the three smaller particle diameters but the other ratios have been negative effects. As expected, the grade efficiencies of all the cyclones are seen to increase with increase in particle size. The shapes of the grade collection efficiency curves of all models have a so-called ‘‘S’’ shape.

These effects of vortex finder thickness contribute to the increase in grade efficiency of the cyclone by 2-17% in the tested particle diameter range.

**The relationship between overall separation efficiency and Gas velocity inlet:** Figure 6 shows the measured overall efficiencies of the cyclones as a function of flow rates or inlet velocities. It is usually expected that collection efficiency increase with the entrance velocity.

Totally, the overall efficiency of the cyclone with thickness ratio of 0.05 was approximately higher than the efficiency of the cyclone with other design at the same velocity. These effects of vortex finder thickness contribute to the average increase in overall efficiency of the cyclone by 8.3% in the tested velocity range.

## CONCLUSIONS

In order to increase the cyclone separator efficiency, the effects of vortex finder thickness on separation performance was examined by simulation.

The collection efficiency was evaluated for various thicknesses. The results indicate that the vortex finder thickness has significant effects on upward flow zone and therefore, the escaping of particle to centric upward flow will be change. The cyclone with thickness ratio of 0.05 had higher overall efficiency rather than other ratios.

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