The Effect of Solid Rate on Cyclones Pressure Drop and Erosion Rate at Coal Boiler Plant Using Computational Fluid Dynamics

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***Abstract*— Gas-solid separation systems with turbulent swirl flow that occur inside the cyclone will cause pressure drop and erosion on the cyclone wall. Both of these can cause a decrease in performance and increase maintenance costs for cyclones. CFD simulation is carried out on the actual cyclone dimensions used in the coal boiler industry. It was performed using the Reynolds Stress Model (RSM) for turbulent flow in the gas phase and Oka erosion model for its erosion model. The inlet velocity is fixed 6 m/s with variations in the solid rate ranged from 30 to 40 kg/s. This study will analyze the pressure drop and erosion rate on the cyclone walls in various solid rate variations. The simulation results show that the higher the solid rate with the same speed will reduce the pressure drop by 4% and at selected local area, increase the erosion rate on the cyclone wall by about 19%.**

***Keywords*— Cyclone, Pressure Drop, Erosion Rate, CFD, Coal Boiler Industry.**

I. INTRODUCTION

SINCE the late 1980s, cyclone separator has been used for the removal of solid particles for both air pollution control and process use on many industries such as chemical industry, food industry, power generation industry (coal boiler plant) and any other industries. Cyclone separator has simple design, no moving components (static parts), low installation, operational and maintenance costs, be able to operate at high temperature, pressure and amount of solid particles [1]. Because of its several advantages compared with the other equipments, cyclone separators are the most widely and commonly used equipments in industries for gas-solid separation.

There are many numbers of different types and geometrical designs of cyclones which are at present in use but the conical reverse flow cyclone with a tangential inlet is most commonly employed. The main parts of cyclone separator consist of a cylindrical and conical section which together form the body of the cyclone, tangential inlet, outlet for cleaned gas (called vortex finder), solid particle outlet and solid particle collector or bin.

In Figure 1 shows the basic principle of the cyclone separator. Gas-solid stream entering tangential inlet cyclone separator with high angular velocity and forms swirling flow [2]. Gas flow (which contains solid particles) are forced radially outward to the wall by centrifugal force and move downwards along the cylindrical and conical wall towards the bottom of the cyclone and into the solid particle outlet. The cleaned gas swirls upwards in the centre of the cyclone and leaves the cyclone upwards through a vortex finder [3].

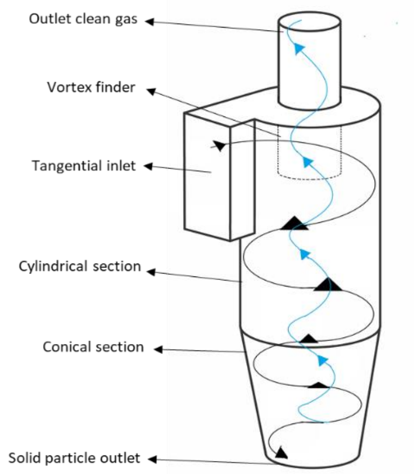


Figure 1. Basic Principle of Cyclone

Generaly, there are two parameters in order to carry out an assessment of a cyclone performance. These parameters are the collection efficiency of particle and pressure drop through the cyclone. The pressure drop across the cyclone is an important parameter in the evaluation of cyclone performance. It is a measure of the amount of work that is required to operate the cyclone at given conditions, which is important for operational and economical reasons. The total pressure drop over a cyclone consists of losses at the inlet, outlet and within the cyclone body. The main part of the pressure drop, i.e. about 80%, is considered to be pressure losses inside the cyclone due to the energy dissipation by the viscous stress of the turbulent rotational flow [4].

Besides pressure drop, there is another main problem that often occurs on the cyclone separator, it is an erosion at the wall caused by friction between solid particles and cyclone's wall. This erosion can results operational and also financial consequences. Before modeling the erosion model on the wall of the cyclone, the hydrodynamic flow must be known first. Even though the design and geometric construction of cyclone separator is very simple but the phenomenon that occurs in cyclone is not that simple. The swirling flow including particle motion inside cyclone separator has three dimensional nature of the flow, high turbulence level, strong anisotropy and interaction between fluid, solid particles and the cyclone separator's wall [5].

Computational fluid dynamics (CFD) has a great potential to understanding the complex fluid dynamics and how it is influenced by changes in both design and operating conditions. In early 80s, Boysan was the first person presented CFD techniques to cyclone simulation. After that, several studies were done on turbulence modeling in order to predict the fluid flow characteristics, particle trajectories, pressure drop, erosion rate and any other phenomena in cyclones [6].

Many previous studies have been carried out to determine hydrodynamic of cyclone separator, pressure drop and erosion rates, both experimental and simulation methods but mostly carried out on small scales. As was done by Masnadi regarding the distribution of gas-solid multiphase flow in a cyclone or study of the impact of changes in cyclone geometry on cyclone performance carried out by Kepa, Hsiao and also by Brar.

Brar, et. al used CFD simulation with Reynold stess turbulance model for continuous gas flow and discrete phase models. Explain in their study that cyclone geometry is an important factor that influences the performance of the cyclone (based on the pressure drop) [7].

Mazdak Parsi, et. al did his research on erosion in elbow piping systems due to the flow of sand particles using the CFD method. It was carried out through the Lagrangian approach, using 4 different types of erosion equation model approaches namely Oka, DNV (Det Norske Veritas), Zhang and Mansouri's erosion models with a One-Way coupling [8].

Sedrez, et. al conducted a study on erosion in cyclone by CFD methods as well as experiments. Sedrez uses the Eularian-Lagrangian approach with RSM (Reynolds Stress Model) with two-way coupling and uses 2 types of erosion modeling namely DNV and Oka. In addition, Sedrez also conducted experiments as a validation of the results of his CFD simulation. Based on the simulation results and experimental validation, erosion rate increases as the gas velocity increases and the rate of erosion rate decreases as the ratio of solids increases [9]. In this study, CFD simulation was using the actual geometry of cyclone separator and operational condition datas from the coal boiler plant (industrial scale).

II. METHOD

A. Design of The Cyclone Separator

Geometry and cyclone dimensions used in the coal boiler plant shown in Figure 2 and Table 1

B. CFD Based Simulation of Cyclone Separator

CFD is a numerical algorithm that can be used as a method to simulate fluid flow, mass transfer, heat transfer or other phenomena using computer simulations [10]. To be able to calculate, analyze and simulate a system, CFD requires data variables, among others, input data, outputs, equations and boundary conditions of the system that we want to simulate. In general, a CFD code consists of three main elements: pre-processor, solver and post processor.

The data used in this CFD simulation is the actual data from the coal boiler plant. Silica sand sample (as a solid particle dispersed in a continuous gas phase) was taken in the inlet cyclone separator then the sample is processed to determine the particle distribution as shown in Table 2. Taking cyclone wall samples is also done to find out their physical properties. In addition to sampling inlet sand and cyclone walls, operational condition data was collected in the form of inlet velocity and solid particle rate during the coal boiler plant operation. All data that has been obtained is used as input data for CFD simulation.

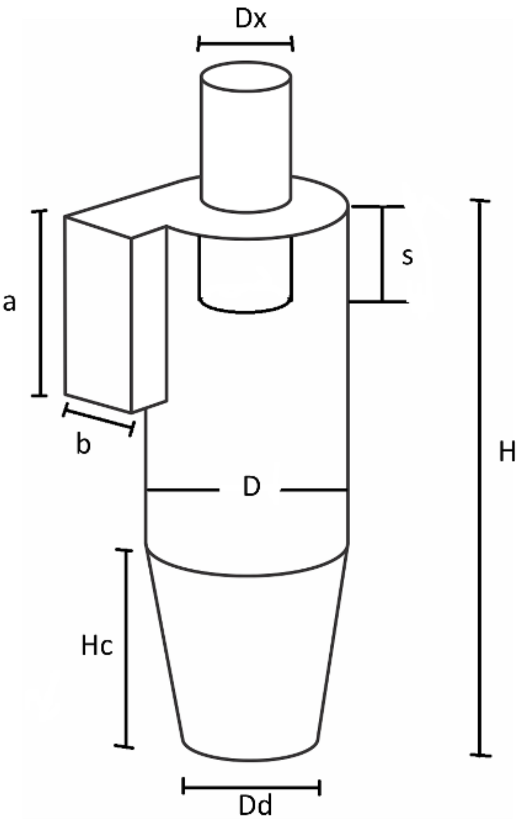


Figure 2. Geometry of Cyclone Separator

Table 1.
Dimension of Cyclone Separator

Dimension	Size (mm)
Cyclone diameter (D)	5120
Cyclone height (H)	13970
Vortex finder diameter(Dx)	2200
Vortex finder length (s)	2310
Tangential inlet height (a)	4620
Tangential inlet width (b)	2333
Conical cyclone height (Hc)	5200
Dust exit diameter (Dd)	3320

Table 2.
Solid Particle Sample Size Distribution

Size (Micron)	Percentage of Total Weight (%)	Size (Micron)	Percentage of Total Weight (%)
2000	0.14	180	17.1
1000	0.3	150	8.8
710	0.3	125	6.8
425	7.24	106	4.2
355	8.6	<75	4.92
212	41.6		

We have to do flow modeling and particle tracking before we calculate the pressure drop and erosion rate. For the calculation of the continuous flow field the time-averaged Navier-Stokes (RANS) equations are solved in an Eulerian framework with continuity and momentum transport equations and for the calculation of Newton's law motion equations are solved in a Lagrangian framework, using two-way coupling with the continuous phase. This calculation is used to predict the trajectory and particle velocity as a discrete phase. The gas streamlines in cyclone separator have high curvature and the flow field has high swirl intensity, large radial shear, adverse pressure gradients and recirculation zones. Those flow characteristics mean that turbulent models cannot be solved by first order turbulence closure equation including the k-epsilon model, which assume that the turbulence structure is isotropic. In order to capture the real flow details in cyclone separators, the Reynolds stress model (RSM) was applied by various researchers [11]. Discrete random walk model (DRW) used to model the turbulence fluctuation velocity components on the particle trajectories [9].

C. Mathematical Models

The gas-solid flow is simulated using Eulerian equations with the continuous phase as the gas phase, while the discrete phase as the solid phase. The equation used is as follows:

Eularian equation – Continuous Phase

Continuity:

$$\frac{\partial}{\partial t}\left(\rho_g\right)+\nabla\left(\rho_g v_g\right)=0 \tag{1}$$

Momentum:

$$\frac{\partial}{\partial t}\left(\rho_g v_g\right)+\nabla\left(\rho_g v_g v_g\right)=-\nabla P_g - \nabla\left(T^V+T^R\right)+\rho_g g+S_v 0 \tag{2}$$

Where, the index g represents the gas phase, v is a velocity vector,

Lagrangian equation – Discrete phase

$$\frac{dx_p^{(i)}}{dt}=v_p^{(i)} \tag{3}$$

$$\frac{dv_p^{(i)}}{dt}=\left(\frac{\rho_p-\rho_g}{\rho_p}\right)g+\frac{18\mu_g}{\rho_p\left(d_p^{(i)}\right)^2}\frac{C_D^{(i)}\operatorname{Re}_p^{(i)}}{24}(v_g-v_p^{(i)}) \tag{4}$$

with,

$$C_D^{(i)}=a_1+\frac{a_2}{\operatorname{Re}_p^{(i)}}+\frac{a_3}{\left(\operatorname{Re}_p^{(i)}\right)^2}$$

$$\operatorname{Re}_p^{(i)}=\frac{\rho_g d_p^{(i)}\left|v_g-v_p^{(i)}\right|}{\mu_g}$$

Then for turbulence flow used RSM approach as follows in equation (5).

$$\frac{\partial}{\partial t}\left(T^R\right)+\nabla v_g\left(T^R\right)=\Psi+\Pi+D_T+D_M-\frac{2}{3}\sigma\rho_g\varepsilon_g \tag{5}$$

Stress Production,

$$\Psi=-\rho_g\left|v'_g v'_g.\left(\nabla v_g\right)^T+\left(\nabla v_g\right)v'_g v'_g.\right| \tag{6}$$

Pressure Strain,

$$\Pi=-\rho_g\varepsilon_g\left[C_{s1}b+C_{s2}\left(b.b-\frac{1}{3}b:b\delta\right)\right]-C_{r1}\Psi.b+C_{r2}\rho_g k_g S_d-C_{r3}\rho_g k_g S_d\sqrt{b:b}+C_{r4}\rho_g k_g\left(b.S_d^T+S_d b^T-\frac{2}{3}b:S_d\delta\right)+C_{r5}\rho_g k_g\left(b.\Omega^T+\Omega.b^T\right) \tag{7}$$

Where,

$$b=\frac{v'_g v'_g}{k_g}-\frac{2}{3}\delta$$

$$S_d=\frac{1}{2}\left[\nabla v_g+\left(\nabla v_g\right)^T\right]$$

$$\Omega=\frac{1}{2}\left[\nabla v_g-\left(\nabla v_g\right)^T\right]$$

$$k_g=\frac{1}{2}v'_g v'_g$$

Turbulence Diffusion

$$D_T=\nabla\left(\frac{\mu_{t,g}}{\sigma_{k,g}}\nabla v'_g\, v'_g\right) \tag{8}$$

With,

$$\mu_{t,g}=\rho_g C_\mu\left(\frac{k_g^2}{\varepsilon_g}\right)$$

Molecular Diffusion

$$D_M=\nabla\left(\mu_g\nabla v'_g\, v'_g\right) \tag{9}$$

$$\frac{\partial}{\partial t}\left(\rho_g\varepsilon_g\right)+\nabla\left(\rho_g\varepsilon_g v_g\right)=\nabla\left[\left(\mu_g+\frac{\mu_{t,g}}{\sigma_\varepsilon}\right)\nabla\varepsilon_g\right]+C_{\varepsilon1}\frac{1}{2}P\frac{\varepsilon_g}{k_g}-\rho_g C_{\varepsilon2}\frac{\varepsilon_g^2}{k_g} \tag{10}$$

Erosion Model (Oka Erosion Model) [12][13]

$$E^{(I)}=1x10^{-9}E_V.\rho_W.m_p \tag{11}$$

With,

$$E_V=f(\alpha)E_{90}$$

$$E_{90} = L(H_V)^{k1}\left(\frac{v_p^{(i)}}{v'}\right)^{k2}\left(\frac{d_p}{d'}\right)^{k3}$$

$$f(\alpha) = (sen\,\alpha)^{n1}\left(1 + H_V(1 - sen\,\alpha)\right)^{n2}$$

III. RESULTS AND DISCUSSION

As mentioned earlier, on the modeling of the turbulence swirl flow that occurs in the cyclone separator , the Reynolds stress model (RSM) was used due to its capability to predict the strong turbulent swirling flow with anisotropic behavior. In a turbulent flow, the particle trajectories can be affected by fluctuations of the velocity

Simulations results in Figure 3, there are 2 projection forms of velocity vector. In point (a) is the velocity vector projection based on plane and in point (b) the projection of the velocity vector is based on a streamline for the continuous gas phase. It can be seen that the flow pattern that occurs in the cyclone is in accordance with the main principle of the cyclone. The inlet gas enters through the tangential inlet and then swirls downward inside the cyclone and also forms a reverse flow towards the vortex finder and exits through the outlet gas.

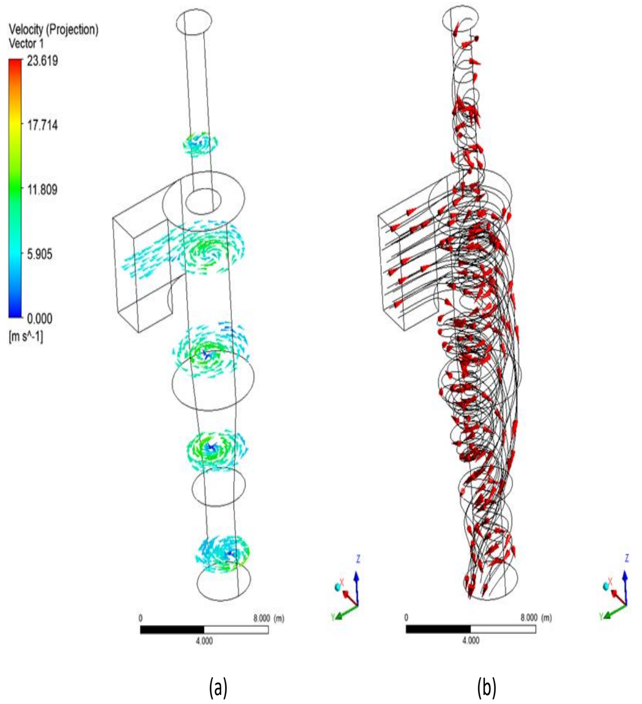


Figure 3. Velocity Vector Projection Based on (a) plane (b) continous gas phase

Figure 4 shows the solid particle distribution, the higher solid rate, more particles that enter the cyclone separator, more likely, solid particle collides with the cyclone wall and the erosion that occurs on the cyclone wall will increase because there is more friction between particles of solids with the cyclone wall.

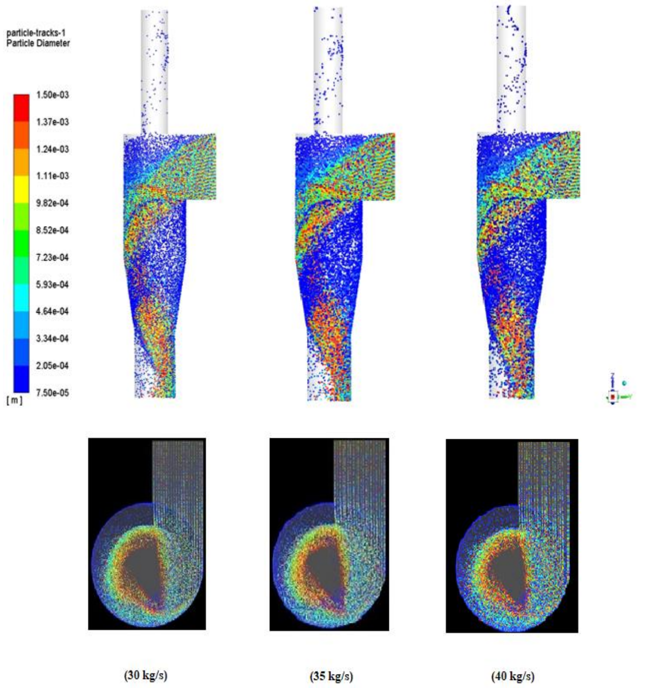


Figure 4. Distribution of Solid Particles Inside Cyclone with Solid Particle Diameter between 0,075 and 1,5 mm and inlet velocity 6 m/s with (a) solid rate 30 kg/s, (b) Solid rate 35 kg/s, (c) Solid rate 40 kg/s

Figure 5 shows the the dependence of the pressure drop on the solid rate. For the same inlet gas velocity , increasing the solid rate will decrease the pressure drop, about 4 %. The reduction in the pressure drop in cyclones with increasing solids loading ratio caused by 2 reasons. In the former case, the turbulent rotational flow responsible for about 80% of the pressure losses inside the cyclone due to the energy dissipation. The other reason is collision between particles. It produces a pressure drop due to the interaction between the particles that collide with each other, hindering the transport of the solids by the gas.

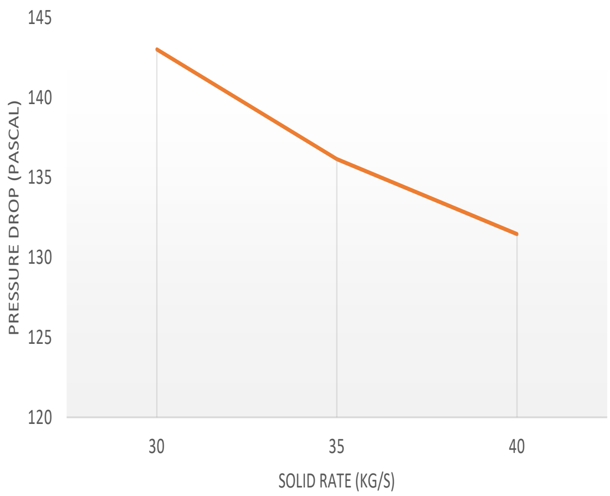


Figure 5. Pressure Drop with Inlet Velocities 6 m/s and solid rate ranged from 30 to 40 kg/s.

For the erosion rate simulation on the cyclone wall will be calculated using the oka erosion model. Erosion rate simulation result can be seen in the Figure 6,7,8 and 9.

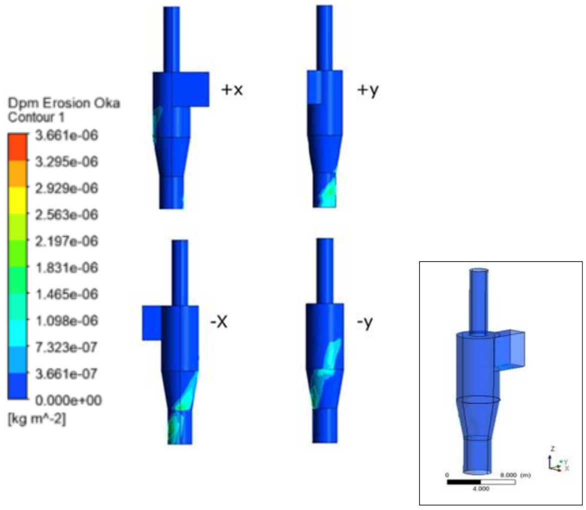


Figure 6. Erosion Rate Contour with Inlet Velocities 6 m/s and solid rate 30 kg/s.

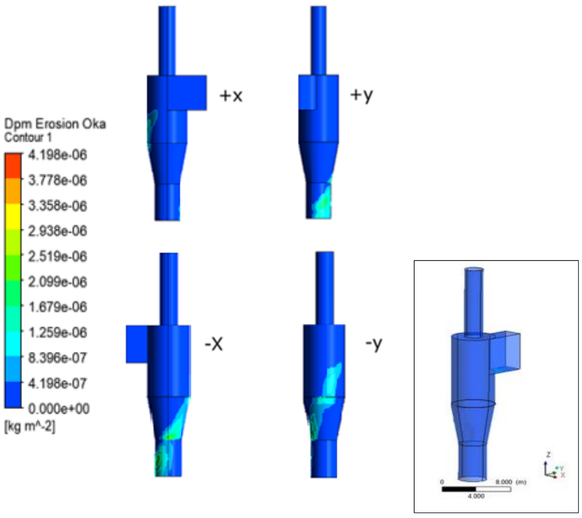


Figure 7. Erosion Rate Contour with Inlet Velocities 6 m/s and solid rate 35 kg/s.

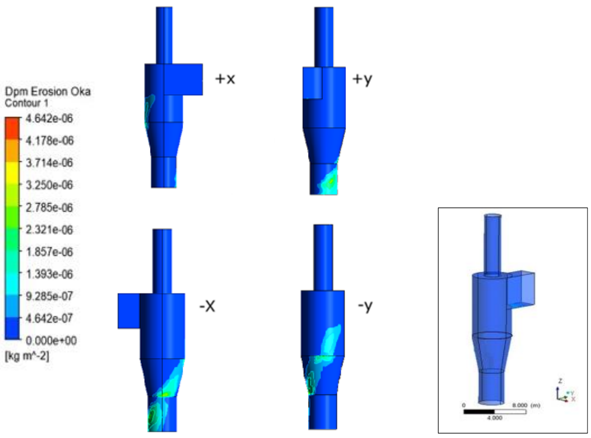
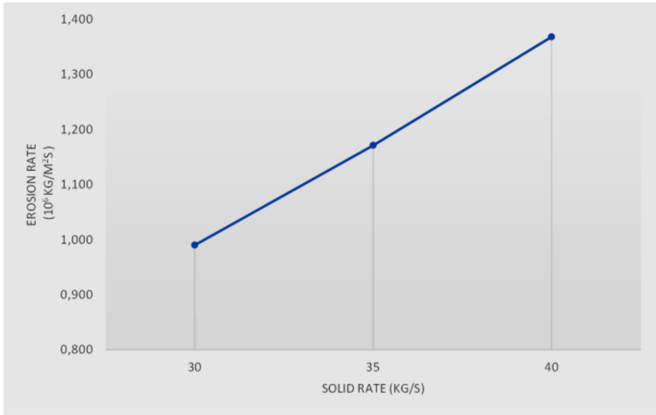


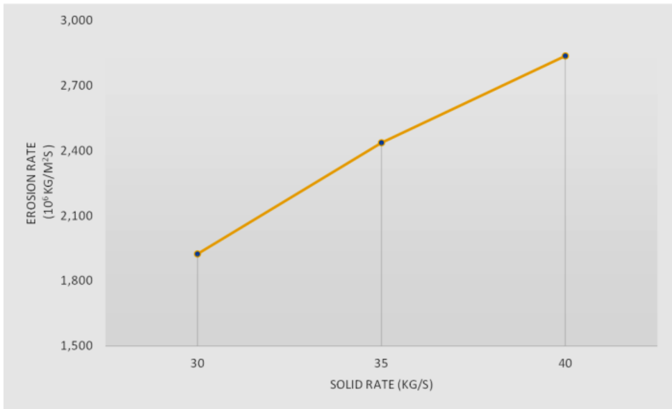
Figure 8. Erosion Rate Contour with Inlet Velocities 6 m/s and solid rate 40 kg/s.

Figure 6,7,8 shows the simulation results of erosion in the form of erosion contours in the entire cyclone wall, to be able to see erosion contours, the simulation results are shown in 4 directions, namely -X, -Y, + X and + Y. By contour, the erosion rate increase with increasing solid rates. The discussion will focus on the worst erosion in 2 areas, cylindrical section and conical section. The most severe erosion in the cylindrical section area can be seen in the impact zone cylindrical section (+Y direction). Impact zone is an area where initial collisions occuran then the direction of flow changes from tangential inlet flow to angular or swirl flow. Unlike the cylindrical section, for the most severe erosion of the conical section is at the end of the conical section (+Y direction). The highest erosion rate is obtained for solid rate 40 kg/s, at the cylindrical section of 1.368 x 10^{-6} kg/m^{-2}.s and the conical section of 2.837 x 10^{-6} kg/m^{-2}.s

The comparison of erosion rates for various solid rate can be seen in figure 9. In point a) shows the erosion rate comparison that occurs in cylindrical sections and point b) in the conical section. On average, the erosion rate increases for the variation of the solid rate, the average of erosion rate increase at cylindrical sections by 16.49% and at the conical section by 21.82%.



(a)



(b)

Figure 9. Most Severe Erosion Rate with Inlet Velocities 6 m/s and solid rate ranged from 30 to 40 kg/s at (a) Cylindrical Section, (b) Conical Section

IV. CONCLUSION

In this study, CFD simulation is supported by actual data in the coal boiler plant used to determine the cyclone performance (based on pressure drop) and erosion phenomenon that occurs in the cyclone separator. This can be useful for investigating erosion that occurs in industries that use cyclone as a solid-gas separator system so that it can be improvised in the cyclone system to reduce the potential loss due to pressure losses and erosion that occurs.

Based on the results of simulations carried out by CFD, Both of the pressure drop and the erosion is dependent on the solids rate.The pressure drop decrease with an increase in the solid rate and the erosion rate increases with an increase in the solid rate.

As the future extension of this study, to complete the results already obtained, it is necessary to do variations in inlet velocity and validate data on actual pressure drop and erosion rate in the coal boiler plant. In addition, several important factors need to be included that have not been included in this simulation, including collisions between particles, heat energy in the cyclone system and other factors.

NOMENCLATUR

Cs1,Cs2	
Cr1,Cr2	
Cr3,Cr4	
Cr5, Cμ	
Cε1, Cε2	Constant
a1,a2,a3	
k1,k2,k3	
n1,n2	
L	
D	Cyclone diameter
H	Cyclone height
Dx	Vortex finder diameter
S	Vortex finder length
A	Inlet height
B	Inlet width
Hc	Conical Cyclone height
Dd	Dust Exit Diameter
DM	Molecular diffusion term
DT	Turbulent diffusion term
e	error
N	Total number of cells
v	Vector velocity
vg	Gas velocity in inlet cyclone
vp	Particle impact velocity
v′	Standard velocity
v′	Velocity fluctuation pressure
Tv	Stress tensor
TR	Reynolds stress
g	Gravity
Sv	Source term
Sd	Strain rate
FD	Interface coefficient
CD	Drag coefficient
Re	Reynolds Number
x	Position vector
E	Erosion rate
ER	Mass flux of erosion
Ev	Volumetric erosion
E90	Erosion damage to normal impact angle
k	Turbulent kinetic energy
Hv	Vickers hardness
m	Mass flow rate
K	Material constant
k	Turbulent kinetic energy
f(α)	Function of impact angle
n	Exponent velocity
p	Apparent order
q	Poisson's ratio
r	Grid refinement factor
Y	Young's modulus
TL	Lagrangian integral time
t	Time
Δt	Time step

Greek letters

ρ	Density
μ	Viskosity
α	Impact angle
γ	Elastic load limit
σε ,σk	Constant
δ	Tensor unit
ε	Dissipation rate of the kinetic energy
τe	Characteristic lifetime of the eddy
τ	Particle relation time
Π	Pressure-strain
Ω	Vorticity
Ψ	Stress production

Subscripts

g	Refers to gas phase
p	Refers to solid phase
t	Refers to turbulence
w	Refers to wall

Superscripts

(i)	Refers to particel i
a	Refers to absolute

REFERENCES

[1] Danyluk, W. J. Shack, and J. Y. Park, “The erosion of a type 310 stainless steel cyclone from a coal gasification pilot plant,” *Wear*, vol. 63, no. 1, pp. 95–104, 1980.

[2] A. C. Hoffman and L. E. Stein, *Stein, Gas Cyclone and Swirl Tubes*, Second Edi. 2008.

[3] K. S. Lim, H. S. Kim, and K. W. Lee, “Characteristics of the collection efficiency for a cyclone with different vortex finder shapes,” *J. Aerosol Sci*, 2004.

[4] A. Ogawa, *Separation of particles from air and gasses*, First and. Florida: CRC, 1984.

[5] I. Karagoz and A. Avci, “Modelling of the pressure drop in tangential inlet cyclone separators,” *J. Aerosol Sci.*, 2005.

[6] R. Utikar *et al.*, “Hydrodynamic Simulation of Cyclone Separators,” 2010.

[7] L. S. Brar, S. R.P, and K. Elsayed, *The effect of the cyclone length on the performance of stairmand high-efficiency cyclone*. Birla institute of technology, 2015.

[8] M. Parsi *et al.*, “CFD simulation of sand particle erosion in gas-dominant moltiphase flow,” *J. Nat. Gas Sci. Eng.*, 2015.

[9] T. A. Sedrez, R. K. Decker, M. . da Silva, D. Noriler, and H. F. Meier, *Experiments and CFD-based erosion modeling for gas-solids flow in cyclones*. University of Blumenau, 2017.

[10] B. Zhao, Y. Su, and J. Zhang, “Simulation of gas flow pattern and separation efficiency in cyclone with conventional single and spiral double configuration,” *Chem. Eng. Res. Des*, 2006.

[11] F. Parvaza, S. H. Hosseinib, K. Elsayedc, and G. Ahmadid, *Numerical investigation of effects of inner cone on flow field, performance and erosion rate of cyclone separators*. Semnan University, 2018.

[12] Y. I. Oka, K. Okamura, and T. Yoshida, “Practical estimation of erosion damage caused by solid particle impact, Part 1: effects of impact parameters on predictive equation,” *Wear*, vol. 259, 2005.

[13] I. Oka, K. Okamura, and T. Yoshida, “Practical estimation of erosion damage caused by solid particle impact, Part 2: mechanical properties of materials directly associated with erosion damage,” *Wear*, vol. 259, 2015.