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Erosion Reduction and Enhancement in Performance of A Novel Cyclone Separator Using CFD Analysis

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Abstract: Assessment of erosion phenomenon in standard and novel cyclones is compared in this paper using CFD analysis. Conventional Standard cyclone used is modelled by using the design of stairmand cyclone and a novel cyclone is designed by having the same volume of standard cyclone except it will have a slot on the body of the cyclone, function of novel of cyclone is to store the particles at the slot and particles entering the cyclone will impinge on the particles stored in the slot, this is to avoid erosion at the cyclone body. Novel cyclone by having a slot on the body, which stores the particles in the slot and particles entering the cyclone will impinge on the particles stored in the slot. This avoids erosion at the cyclone body. The erosion rate is determined computationally by varying the gas velocity at a constant mass flow rate of the solid particles. By comparing the results of cyclones, novel cyclone pressure drop reduces by 29.15% in comparison with the standard cyclone. Standard cyclone pressure drop is in good agreement with the previously published results. Mass erosion rate of a novel cyclone is 45.5% lesser than the standard cyclone, no of swirl path taken by particles inside the novel cyclone is 7, and that of the conventional standard cyclone is 6. As the particles are impinging against the particles itself in the novel cyclone, the erosion rate is reduced by 45.5%. The novel cyclone can be used by the process industries to prevent erosion to a great extent.

Keywords: Cyclone Separator, Novel Cyclone, Erosion Rate, Pressure Drop.

1 Introduction

Cyclone separators used for separating solid particles from the gas phase. They are simple in construction and fabrication is less expensive. They are used specifically for the removal of solid particles from gas. The fluid dynamics and flow structure in cyclone separators are complex. The driving force in a cyclone separator is strong swirling turbulent flow. The upper part of cyclone consists of the tangential inlet through which gas and solid particles enter. Its tangential inlet produces the swirling motion of the gas. The particles pushed to the cyclone wall. Both the phases swirl down the cyclone wall. The solid particles get collected at the bottom of the cyclone through a duct. Then the gas swirls upwards in the middle of the cone. The dust-free gas then leaves the cyclone through vortex finder. Therefore, the turbulence characteristics and the particle interaction ultimately determine the performance of a cyclone separator. Experimental and numerical studies have been carried out for the last few years for a better understanding of the flow inside the cyclone separators [1].

The particles which move at high-speed cause surface damage to the material of construction of the cyclone and it is called erosion. The erosion caused in the cyclone are due to the particles impingement against the wall due to their swirling motion. The erosion mainly depends on the velocity of particles. If the cyclone material surface is harder than particle, then the rate of erosion will be less [2]. As the cyclone design handles particles of different diameter and characteristics, it is difficult to handle the problem of erosion by modifying the material of the cyclone alone.

Two types of wear are involved in the erosion of metals which occur due to large and small impingement angles [3]. For low impact angles, hard and brittle steel acts as erosion resistant material. For high impact angles, soft and ductile materials act as erosion resistant material. This reveals that the mechanical properties of eroded materials and their type play a significant role in erosion in a typical cyclone [4]. During the collision, deformation takes place initially, and when the elastic limit exceeded, the repeated collision of particles will lead the material to plastically deformed state. The resulting deformation hardening increases the elastic limit and further plastic deformation limit will eventually become equal to the strength of the material. It will become relatively hard and also brittle, and it cannot be plastically deformed. With further increase in load, the elastic limit (i.e. the strength) of the material exceeded, and the surface layer gets destroyed [5]. Tube failures that occur in boilers caused due to the erosion of ash particles. Many investigations had been done on heat exchange tube erosion. Investigations with a large number of boilers where the erosion occurs revealed that one-third of the tubes became faulty due to erosion [6].

The erosion wear is directly proportional to the impact velocity of particles to the power 2.5[7]. The extensive wear takes place in the oil and gas industry during hydrocarbon processing and transport equipment. To compute erosion rate, modern techniques like Computational fluid dynamics (CFD) are used [8].

The conventional cyclones are the root cause for the problems in the operation of Fluid Catalytic Cracking(FCC) units. Inview of erosion, some of the components of FCC unit have to be replaced, which require unscheduled shut down during operations and hence the cost of operation increases. Under such circumstances, unscheduled shutdown can be reduced by using longer barrels/hoppers. A cost-effective solution can also be considered for improving cyclone technology with volatile stabilizer. Potential cost savings can be achieved by reusing the existing vessels. The operating cost can also be reduced by catalyst addition and downstream cleaning which will lead to better cyclone performance [9].

The prediction of erosion by particles in oil and gas industry was done with an elbow pipe of 90-degree curvature angle by numerical models. By using CFD models for gas-particle flow, the pattern, magnitude, location of erosion and model parameters such as the coefficients of restitution, wall roughness and coefficients of friction can be predicted [10].

Investigation has been done to predict the turbulent flow of particle trajectories around the tube and erosion due to the particle impaction on the tube. [11].

Tube failures occurs in boilers are caused due to the erosion of ash particles. Many investigations and enquiries were done on heat exchange tube erosion. A number of boilers were examined to find the sections where the erosion occurs. Frequently, one-third of the tubes got fault due to erosion. [13].

CFD based analysis was performed along with experimental work of conventional cyclone @ three different velocities with two different flow rates. Two erosion models were used for numerical simulation, and they are OKA and DNV model. The comparison of pressure drop values and global erosion rate were done between the experiment results and the computational results [14].

2.0 Methodology for Computational fluid dynamics models for cyclone separators

The flow inside a cyclone separator is very complex. It consists of many practical difficulties for numerical simulations. The primary difficulty arises from the fact that the turbulence observed in cyclones is highly anisotropic. This renders most of the first order turbulence closures, like the popular k-e model, unusable for reliable prediction of the flow characteristics. Several attempts were made to overcome this limitation. Boysan et al. (1982, 1983) were one among the first to report CFD studies on cyclone flows. These early studies indicated that the standard k-e turbulence model is not able to accurately simulate this kind of flow and hence a second-order closure is attempted. Software used for the present analysis is FloEFD..

2.1 Momentum and Energy Conservation Equation

FloEFD solves the Navier-Stokes equations, which are formulated through the application of mass, momentum and energy conservation laws for fluid flow. These equations are supplemented by fluid state equations defining the nature of the fluid, and by empirical dependencies of fluid density, viscosity and thermal conductivity as a function of temperature. Inelastic non-Newtonian fluids are considered by introducing dependency of their dynamic viscosity on flow shear rate and temperature, while in the case of compressible liquids. the density is expressed as a function of pressure. Finally, the geometry, boundary and initial conditions are specified. The most important feature of FloEFD is , its capability to predict both laminar and turbulent flows. Laminar flows occur at low values of the Reynolds number, which is defined as the product of representative scales of velocity and length divided by the kinematic viscosity. However, when the Reynolds number exceeds a critical value, the flow becomes turbulent, i.e. flow parameters start to fluctuate randomly. Most of the fluid flows encountered in engineering practice are turbulent, and so Flow Simulation was mainly developed to simulate and study turbulent flows. To predict turbulent flows, the Favre-averaged Navier-Stokes equations are used, where the time-averaged effects of the flow turbulence on the flow parameters are considered, whereas in the other, i.e. large-scale, time-dependent phenomena is taken into account directly. In this approach, extra terms known as the Reynolds stress appears in the equations for which additional information has to be provided. To close the system of equations, FloEFD employs transport equations for the turbulent kinetic energy and its dissipation rate, which is the so-called k-ε model. FloEFD employs one system of equations to describe both laminar and turbulent flows. Moreover, transition from a laminar to turbulent state and/or vice versa is possible.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho u_i\right) = 0 \qquad (2.1)$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) + \frac{\partial \rho}{\partial x_i} = \frac{\partial}{\partial x_j}\left(\tau_{ij} + \tau_{ij}^{R}\right) + S_i \; i = 1,2,3 \qquad (2.2)$$

$$\frac{\partial \rho H}{\partial t} + \frac{\partial \rho u_i H}{\partial x_i} = \frac{\partial}{\partial x_i} = \left(u_j\left(\tau_{ij} + \tau_{ij}^{R}\right) + q_i\right) - \tau_{ij}^{R}\frac{\partial u_i}{\partial x_j} + \rho\varepsilon + S_i u_i + Q_H \,, \qquad (2.3)$$

$$H = h + \frac{u^2}{2} + \frac{5}{3}k - \frac{\Omega^2 r^2}{2} - \sum_m h_m^0 y_m \qquad (2.4)$$

where u is the fluid velocity, ρ is the fluid density, Si is mass-distributed external force per unit mass , Si porous is mass distributed external force per unit mass due to porous media resistance, Si gravity is buoyancy (Si gravity = - ρgi, where gi is the gravitational acceleration component along the i-th coordinate direction), and Si Rotation is the coordinate system's rotational force (Si Rotation), i.e., Si = Si porous + Si Gravity + Si Rotation , h is the thermal enthalpy, QH is a heat source or sink per unit volume, τik is the viscous shear stress tensor, qi is the diffusive heat flux, Ω is an angular velocity of the rotating coordinate system, r is the distance from a point to rotation axis in rotation reference frame, k is the kinetic energy of turbulence, hm0 is an individual thermal enthalpy of the m-th component in the mixture, ym is a concentration of the m-th component in the mixture. The subscripts are used to denote summation over the three coordinate directions.

2.5 Mesh Independency

For the Mesh independency evaluated for the Conventional cyclone with the cells given in Table 2.2, there are not many deviations between the values of higher cell size, and hence 84983 (Sl.No. 4) cells mesh size chosen for the analysis of cyclones.

Table 2.2: Conventional cyclone cell details

Sl.No	Total No. of Cells	Inlet Pressure (Pa)	Outlet Pressure (Pa)	Pressure Drop (Pa)
1	6762	102329	101351	978
2	13000	102569	101385	1184
3	35893	102377	101375	1002
4	84983	102392	101365	1027

2.6 Boundary conditions:

Working fluid in the present study is taken as air, with Velocities as 25, 30 and 35 m/s. The mass flow rate of solid particles for both conventional and Novel design cyclones taken as 1.2 kg/s. FloEFD software used for analysis. A computer was having a Xeon 32 logical core processor with 64 GB ram used for analysis.

3.0 Results and Discussion

Two cyclones one a conventional standard cyclone and the other a novel cyclone which is having a slot in the body of the cyclone to store the particles is used. Fig 1 shows 3D view of the conventional standard and novel cyclones. Analysis is done for various velocities and the contour plots are shown only for 30 m/s velocity as this is the prominent velocity.

Figs 2a and 2b show the Pressure, Velocity, Turbulence Intensity and Vorticity for Novel Cyclone. The Pressure Drop for a Conventional Cyclone is higher than that of the Novel Cyclone by 29.17 %.

Turbulence Intensity is less in the area of cone for novel cyclone. Vorticity is less on cone as well as body of the cyclone in novel cyclone.

Figs 3a and 3b show Tangential Velocity of Conventional standard cyclone and Novel Cyclone. A fully developed tangential velocity is found in section A-A for Conventional standard cyclone, whereas, it is not fully developed in Novel cyclone. At Section B-B, C-C and D-D there is a vertical flip in velocities between Conventional standard cyclone and Novel Cyclones.

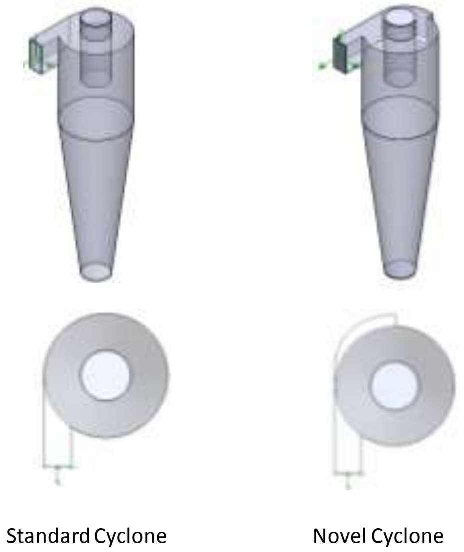

Figure. 1. 3D View of Standard and Novel Cyclone.

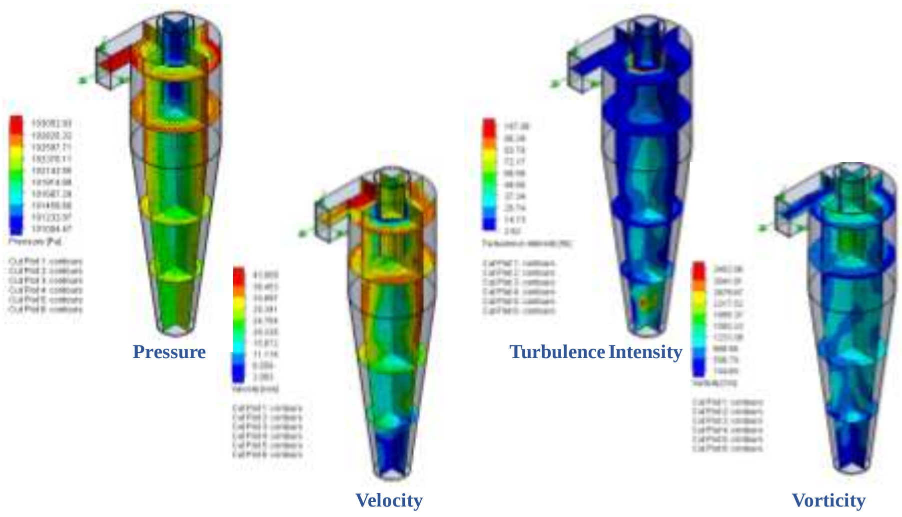

Figure. 2a. Conventional Cyclone @ 30 m/s

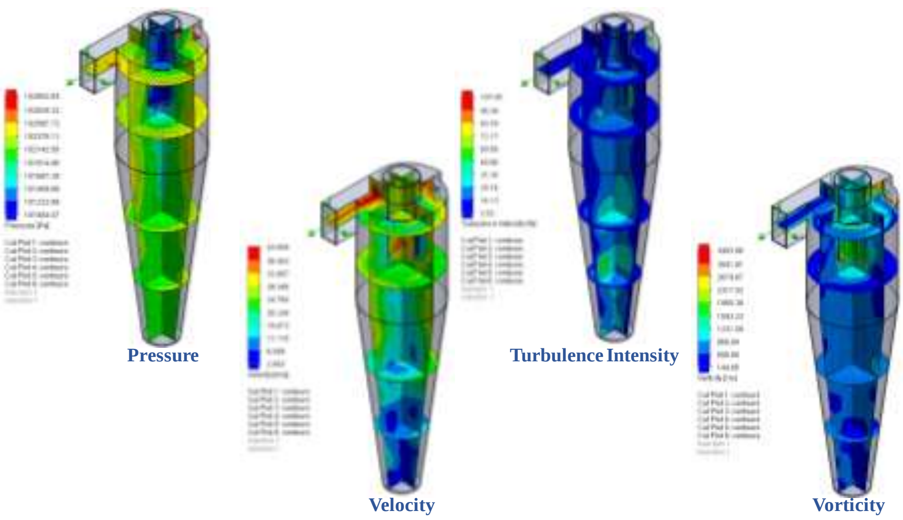

Figure. 2b. Novel Cyclone @ 30 m/s

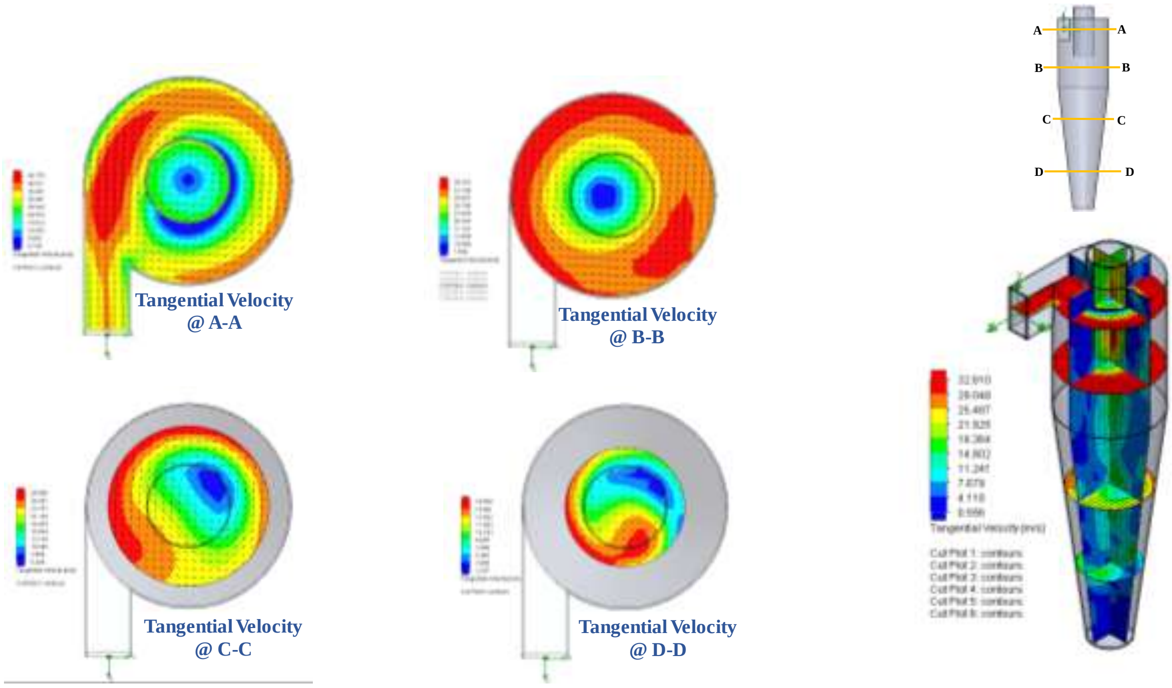

Figure. 3a. Tangential Velocity - Conventional Cyclone @ 30 m/s

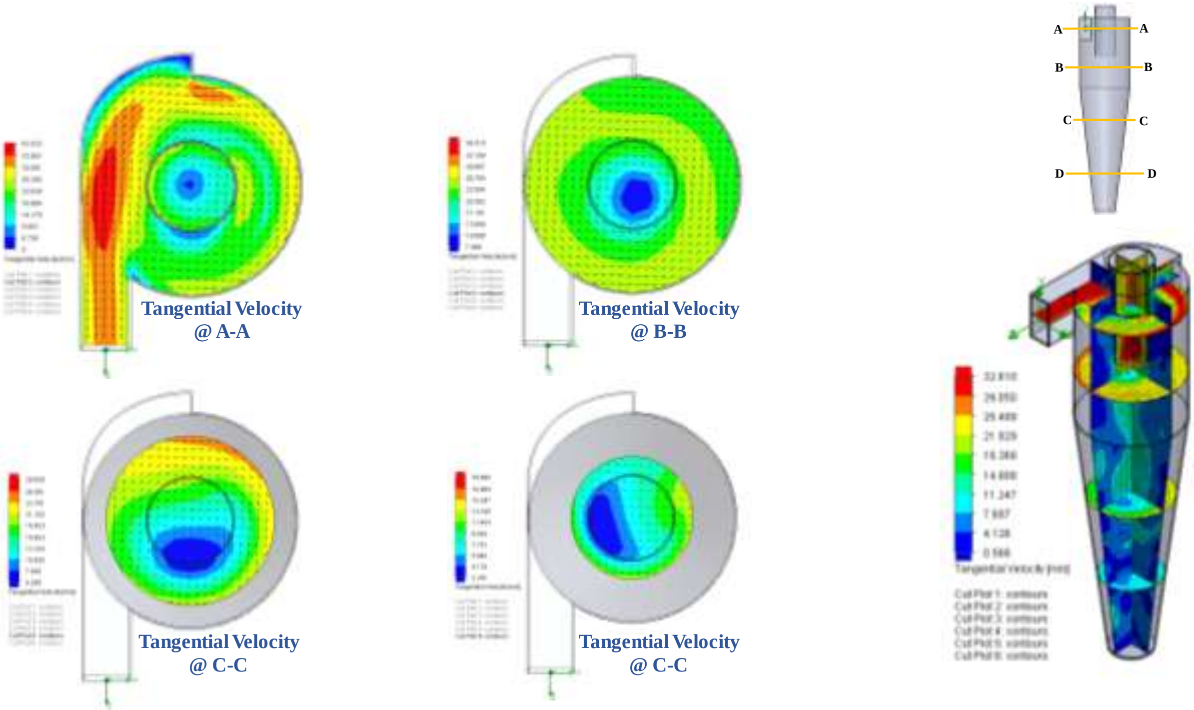

Figure. 3b. Tangential Velocity - Novel Cyclone @ 30 m/s

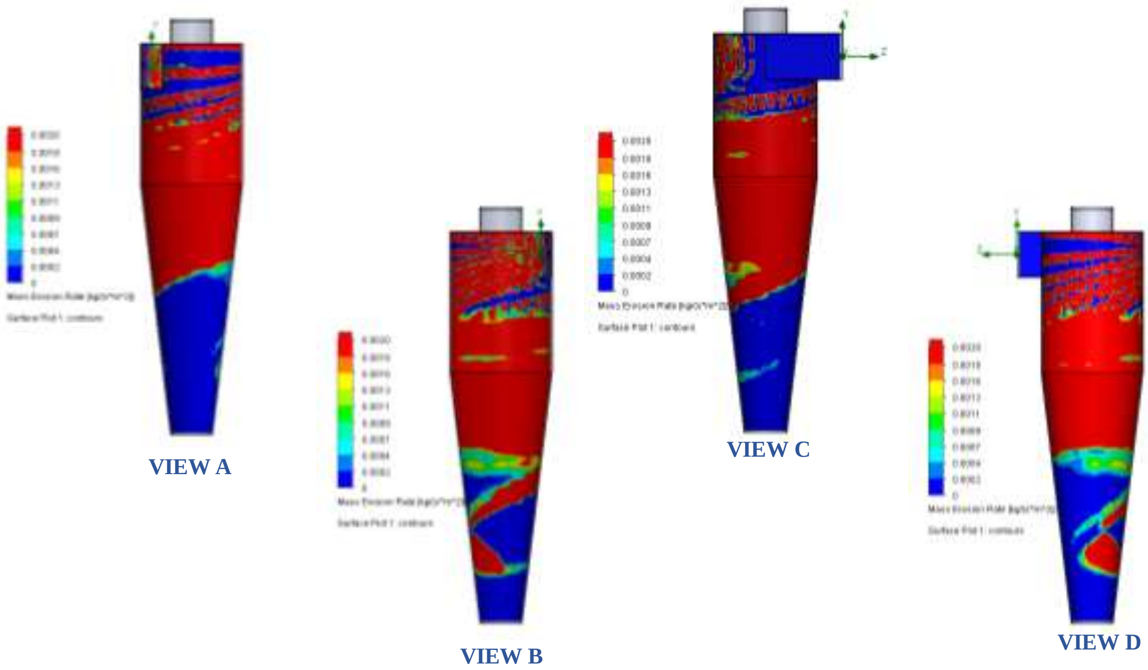

Figure. 4a. Mass Erosion Rate - Conventional Cyclone @ 30 m/s

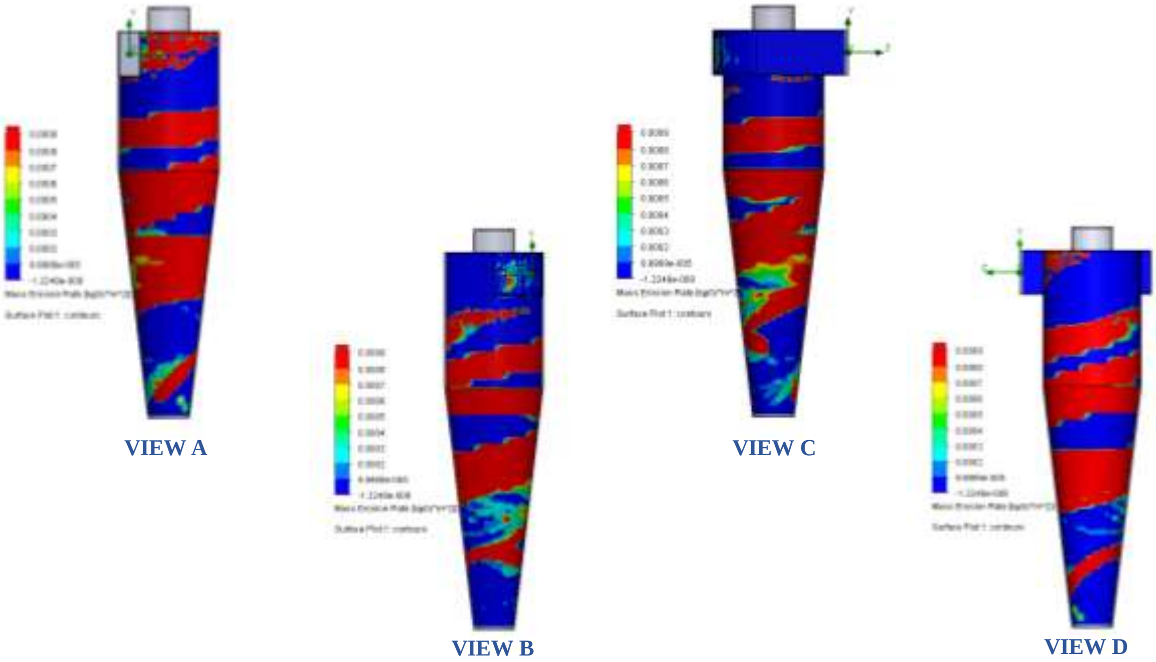

Figure. 4b. Mass Erosion Rate - Novel Cyclone @ 30 m/s

Figs. 4a and 4b show Mass Erosion rates of Conventional standard cyclone and Novel Cyclone. At View A (normal to the inlet), the Novel cyclone has is less erosion in comparison to the conventional standard cyclone. At View B (back side of inlet) where higher erosion rate found in the body of the conventional standard cyclone. However, in Novel Cyclone particles stored in the slot of the cell body are impinging against each other, and hence the erosion rate is very less. At View C and View D, the mass erosion rates are lesser in the novel cyclone.

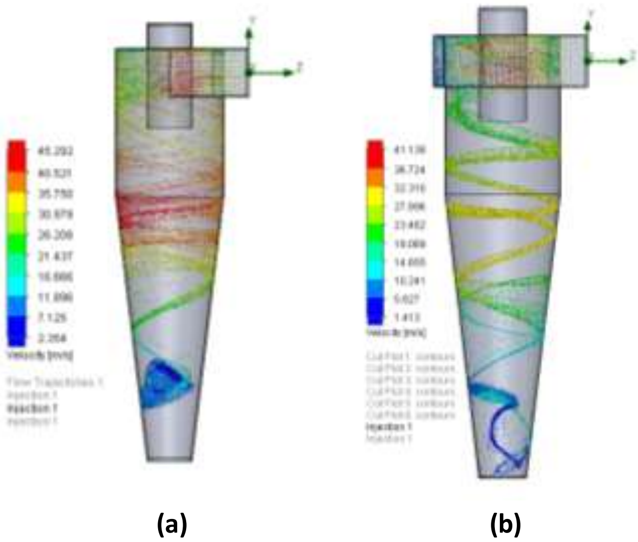

Figure. 5. Particle trajectories for Conventional Standard Cyclone (a) and Novel Cyclone (b)

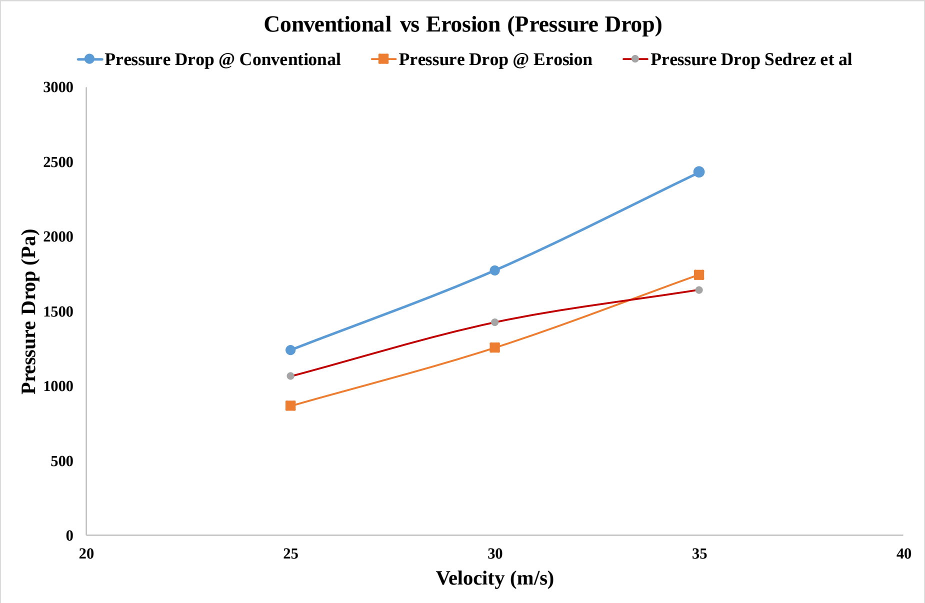

Figure. 6. Pressure Drop Comparison between the Conventional & Novel cyclone at different velocities

Fig 6 shows the Pressure Drop Comparison between the Conventional standard cyclone and Novel cyclone based on the data from sedrez et al [14] for different velocities. Pressure drop for novel cyclone is lesser in comparison to the conventional cyclone by 29.15 %. Pressure drop computed is also in good agreement with the published data from sedrez et al.[14]

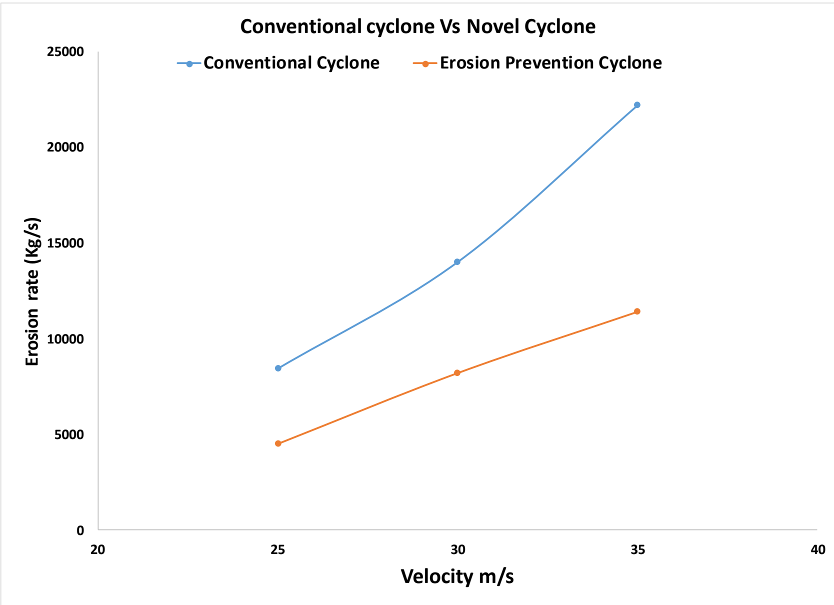

Figure. 7. Mass erosion rate Comparison between the Conventional cyclone & Novel cyclone at different velocities

Fig 7 shows the Comparison of Mass erosion rate between the Conventional standard cyclone and Novel cyclone for different velocities. Mass erosion rate for novel cyclone is lesser in comparison to the conventional standard cyclone by 45.5 %. It is also observed that as Velocity increases Mass erosion rate also increases.

4.0 Conclusion

Based on the CFD Analysis of erosion of conventional standard cyclone and novel cyclone the following conclusions are arrived.

- The novel cyclone has a slot on the body of the cyclone, which stores the particles at in the slot and particles entering the cyclone will impinge on the particles stored in the slot. This avoids erosion at the cyclone body.
- Pressure drop for the novel cyclone is lesser by 29.15% compared to the conventional standard cyclone
- Mass erosion rate for the novel cyclone is lesser in comparison to the conventional standard cyclone by 45.5 %.
- Axial velocities remain the same for both the cyclones.
- There is a flip in tangential velocity for novel cyclone and conventional standard cyclone
- No of swirl path taken by the particle inside of the Conventional standard cyclone is 6
- No of swirl path taken by the particle inside of the Novel cyclone is 7

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