Experimental and CFD study of influence of sediment size on efficiency of hydrocyclone for use as sediment separation device

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Abstract. Hydrocyclones are separation devices used in several industrial applications for separation of particles even smaller than 5 µm. However, this paper presents the feasibility of using hydrocyclone as a sediment separation system in hydropower plants, as well as in the development of a non-recirculating type of an erosion test rig. The design of the experimental set up is a part of the erosion test rig that consists of a discrete sediment feed and separation system to conduct erosion related research. Experimental as well as numerical investigation of effect of sediment particles sizes on overall separation efficiency of hydrocyclone geometry is conducted. Hydrocyclone’s overall efficiency is depicted by measuring the particle separation and its variation with sediment particle’s size. The results indicated that under appropriate flow conditions, particles below 200 µm that are responsible for turbine wear can be separated and prevented from entering into the system. Also, it can be concluded that this system can be used to develop non-recirculating type of erosion test rig.

Keyword: Hydrocyclone, Separation, Sediment sizes, Erosion, Efficiency

1. Introduction

Hydropower plants suffer serious sediment erosion problems from the rivers originating directly or indirectly from Himalayan region, European Alps, Andes and Pacific Coast Ranges [1]. Physical and topographical condition is highly favorable for presence of sediment particles in the river. High content of sediment particles that have higher hardness value than that of turbine materials can easily be eroded, thereby causing significant reduction of efficiency and loss of economy each year. Thus, it is a major and challenging task in the hydro power plants to remove sediment particles from entering into turbines in order to prevent it from erosive wear. This requires proper design and use of a sediment separation system to eliminate the entry of sediment particles into the runner, thereby causing less effect on erosion rate of turbine blades. There are several ways being in use in hydropower plants to reduce the sediment concentration and particle size in the turbine water. However, effective and efficient design of sediment removal basin for trapping sediment particles is costly [2].

Wide varieties of past researches have been carried out to study design analysis and sediment removal efficiency comparison of different separation systems. Pandit et al. [3] presented the detailed comparison of sediment removal efficiency of hydrocyclone and gravity settling basin; and reported highest efficiency of 96.8 % for hydrocyclone as compared to two large settling basins with trapping efficiency of 32.5% . Likewise, Kayastha et al. [4] developed and conducted an open loop experiment on pico hydro Francis turbine to investigate the effectiveness of hydrocyclone for operation during high sediment season and its subsequent effect on turbine efficiency. Study concluded that hydrocyclone separator is efficient in separating sediment particles of sizes as low as 45 µm.
1.1. Sediment characteristics
Sediments are inorganic particles found in water in the form of clay, silt, sand and gravel. They are formed as a result of fragmentation of rock due to chemical and mechanical weathering. The characteristics of sediment particles influence the rate and mechanism of erosion. Therefore, it is very important to study particles’ characteristics such as size, shape, density and hardness for estimation, reduction and prevention of sediment erosion [5]. These sediment particles are categorized on the basis of particle size as seen in Table 1.

Table 1: Classification of sediment on the basis of size [6]

| Class | Clay | Silt | Sand | Gravels | Cobbles | Boulders |
|-------|------|------|------|---------|---------|----------|
| Size (µm) | 0.24-4 | 4-62 | 62-2000 | 2000-64000 | 64000-250000 | 250000-400000 |

Furthermore, particle size can be categorized in terms of mass and length. Usually, sediment particles having high mass value have higher terminal velocity and tend to settle at higher rate while flowing from upstream to downstream. This is because weight is proportional to cube of the linear dimension. It has been found that sediment particles <200 µm can easily pass through the runner and cause damage, especially in medium and high head power plants. Three Francis turbine and components, each unit capacity of 48 MW installed in Kali Gandaki ‘A’ Hydroelectric project (144 MW) at Nepal observed rapid erosion on vane thickness of 5.37 mm (17.3 mm is reduced to 11.93 mm) at runner outlet after three flood seasons despite the settling basin are designed to trap 100% of sediments with particle size larger than 200 microns, 95% of sediments with particle size larger than 150 microns and 70% (Approx.) of sediments with particle size larger than 100 microns [7].

1.2. Laboratory erosion test rigs
Erosion is a complex process to predict and study in laboratory conditions as there are numbers of interdependent erosion influencing factors that act at the same time. Still, there have been development of numerous test rigs and test procedures for study of erosion and testing of erosion resistivity of material in lab environments where erosion influencing parameters variation can be controlled according to study requirement. These rigs are designed to replicate the actual operating conditions of hydropower plants as closely as possible. Test rigs so far developed have been categorized into recirculating (RC) and non-recirculating types (NRC). In recirculating type, the slurry is mixed into a tank by a stirrer motor and forced to strike specimen material in a closed loop, whereas in the case of non-recirculating type of test rigs, fresh sediment particles are injected through injecting mechanisms to erode the test specimen every time. The two types of the test rigs are shown in Figure 1. In RC types of rigs, the erosion rate decreases with time due to a reduction of the particle shape ‘angularity’ unless efficient sediment separation system is employed. NRC types of rigs are provided with a discrete sediment injection system as well as a sediment removal system to remove sediment that has once passed through the test specimen.

![Figure 1: Schematic of erosion test rig: (a) Circulating type [8] (b) Non-recirculating type (Right) [9]](image-url)
1.3. Solid-Liquid Separation system

Hydrocyclone is a simple mechanical device to classify, separate or sort solid particles in a liquid suspension based on the ratio of their centripetal force to fluid resistance \[10\]. The selection of this device is based on the separation efficiency by particle size (diameter) and concentration. This mechanical device is well suited for separating sediment particles from sediment laden rivers with concentration lower than 20% \[11\]. Two geometries of hydrocyclone proposed by Rietema \[12\] and Bradley \[13\] are mostly adopted for design of the device for solid-liquid separation. Study shows Rietema’s geometry works efficiently for coarser particles whereas Bradley’s geometry has higher separation efficiency for finer particles.

Figure 2 shows the solid liquid separation technique according to particle size and feed concentration; and typical hydrocyclone set up for solid liquid separation respectively.

![Figure 2](image-url)

**Figure 2:** (a) Solid-liquid separation techniques according to particle size and feed concentration \[14\] and (b) schematic of hydrocyclone \[15\]

2. Hydrocyclone Design

For performance testing of hydrocyclone to observe the influence of sediment particle sizes (0-400 microns), hydrocyclone model was designed with operating conditions of inlet flow rate of 16 l/s. Hydrocyclone models were simulated and dimensions were modified to obtain the best separation efficiency. Table 2 shows the empirical relationships for obtaining the initial geometry of hydrocyclone.

| Ratio            | Rietema | Bradley |
|------------------|---------|---------|
| D₀/D₂            | 0.28    | 1/7     |
| D₂/D₂            | 0.34    | 0.20    |
| L₁/D₂            | 5       | -       |
| L₂/D₂            | -       | 1/2     |
| λ/D₂             | 0.40    | 1/3     |
| θ                 | 20°     | 9°      |
2.1 Calculation of Reduced cut diameter ($d_{50}$) and Characteristic Diameter ($D_c$)

Bradley geometric ratios were used to calculate the initial geometry of hydrocyclone. The values of particle size (d) of 30 microns and separation efficiency of 95% were taken into study for determination of reduced cut diameter ($d_{50}$) and characteristic diameter ($D_c$) of cyclone chamber. The $d_{50}$ particle diameter is the diameter of the particle, 50% of which will pass through the overflow and 50% in the underflow.

Figure 3 (a) and (b) represent the values of cut size ($d_{50}$), particle size (d) and separation efficiency ($\eta$) on respective scales. The value of $"d_{50}"$ can be obtained from the figure by drawing and extending a line connecting values of "d" and "$\eta$" to the "$d_{50}$" scale. The values of "d" and "$\eta$" taken in this study are 30 $\mu$m and 95% respectively, for which the corresponding value of "$d_{50}$" is 19 $\mu$m.

The value of characteristic diameter of the hydrocyclone separator obtained by referring to the values of different parameters mentioned in Table 3 and from the nomogram as shown in Figure 3 (b) is 45 cm which exhibits 50% separation efficiency for particle size of 19 $\mu$m.

| Properties          | Notation | Value | Unit       |
|---------------------|----------|-------|------------|
| Dynamic viscosity   | $\mu$    | 1     | mNs/m²     |
| of liquid           |          |       |            |
| Density of liquid   | $\rho_L$ | 1     | gm/cm³     |
| Density of solid    | $\rho_S$ | 2.65  | gm/cm³     |
| Flow rate           | L        | 960   | l/min      |
| Diameter of particle| d        | 30    | $\mu$m     |
| Separation efficiency| $\eta$  | 95    | %          |

The theoretical efficiency of the sediment particle of different sizes passing through the hydrocyclone can be calculated using Eq. (1) as developed by Bennett [18].
\[ \eta = 100 \left( 1 - e^{-\left( \frac{d}{d_{50}} - 0.115 \right)^3} \right) \]  

(1)

Where \( \eta \) is the efficiency of the cyclone in separating any particle of diameter ‘d’ in percentage and \( d \) is the selected particle diameter in \( \mu \text{m} \).

Experimentally, the overall efficiency of the hydrocyclone is calculated using Eq. (2).

\[ \eta = \frac{M_c}{M_f} = \frac{M_c}{M_c + M_u} \]  

(2)

Where \( \eta \) is the overall separation efficiency, \( M_f \), \( M_c \) and \( M_u \) are the mass flow rate of the feed, mass flow rate of the particle collected from the overflow pipe and underflow pipe respectively.

Using the Bradley model as reference, the model of hydrocyclone was modified to obtain the best separation efficiency. Table 4 shows the comparative change between the values obtained from Bradley model and results from CFD.

| Parameters                     | Reduced cut size diameter (d_{50}) | Dia. of cyclone chamber(D_c) | Inlet Dia. (D_i) | Over flow Dia. (D_o) | Under flow Dia. (D_u) | Vertex finder length (S_v) | Cylindrical section length (L_1) | Cone angle (\gamma) | Length of cone (L_c) | Cross section of Inlet (H) |
|--------------------------------|-----------------------------------|------------------------------|-----------------|---------------------|----------------------|---------------------------|-------------------------------|-------------------|---------------------|------------------------|
|                                | 30                                | D_i/7                        | D_i/3           | D_i/10              | D_i/3                | D_i/2                      | 2D_c                         | 9                 | 90                  | 8*6.2                  |
| Nomogram                       | 45                                | 6.43                        | 15             | 4.5                | 15                   | 23                        | 9                            | 90                |                     |                        |
| Modified                       | 45                                | 8                           | 12.5           | 4                  | 15                   | 22.5                      | 13                           | 90                | 8                   |                        |

3. Numerical Analysis

3.1 CFD model description

For numerical analysis of hydrocyclone, ANSYS 18.1 was used. The generation of the domain of hydrocyclone was done in CREO Parametric 4.0 (Student version) and mesh in ANSYS workbench for numerical analysis as shown in Figure 4. The patch conforming method is used for mesh generation with tetrahedron elements and proportional refinement ratio of 0.77 for smooth transition between the large and small control volumes. The near wall condition was captured by applying the first inflation layer thickness of 0.5 mm, maximum layer of 10 and growth of 1.2. Mesh independence analysis was carried out for the full domain of hydrocyclone as presented in Figure 5.
3.2 Mathematical model
Among the various available turbulence models in ANSYS CFX, Reynolds Stress Model (RSM) was used as this model is based on model transport equations for Reynolds stress tensor and its dissipation rate. This model assumes that the rate at which energy declines the turbulent energy form large to dissipative eddies is constant over all the energy sizes; and solves Reynolds stress transport equation for individual stress components. Therefore, this RSM turbulence model has greater potential to accurately predict complex flows that occur in hydrocyclone [19].

\[
\frac{Du_{i}u_{j}}{Dt} = \left[ \frac{\partial u_{i}u_{j}}{\partial x_{k}} + \frac{\partial u_{j}u_{i}}{\partial x_{k}} \right] - 2\nu \frac{\partial u_{i}u_{j}}{\partial x_{k}} + \frac{\rho}{\rho^{2}} \left[ \frac{\partial u_{i}u_{j}}{\partial x_{i}} + \frac{\partial u_{i}u_{j}}{\partial x_{j}} \right] - \frac{\rho}{\rho^{2}} \left[ \frac{\partial u_{i}u_{j}}{\partial x_{k}} + \frac{\partial u_{i}u_{j}}{\partial x_{k}} \right]
\]

\[
\frac{\partial}{\partial x_{k}} \left[ \frac{\partial u_{i}u_{j}}{\partial x_{k}} - \nu \frac{\partial u_{i}u_{j}}{\partial x_{k}} + \frac{\rho}{\rho^{2}} \left[ \frac{\partial u_{i}u_{j}}{\partial x_{i}} + \frac{\partial u_{i}u_{j}}{\partial x_{j}} \right] \right]
\]

Where, the first term represents the rate of change of Reynolds stresses, second term represents stress generation, third term represents energy dissipation, fourth term represents pressure strain effects and fifth term represents diffusion of Reynolds stresses.

3.3 Initial and Boundary Conditions
Constant mass flow rate boundary condition of 16 l/s was specified at the inlet of the hydro cyclone. Sediment concentration was input to a value range of 1000 ppm with particle size varying from 0-400 microns. Pressure outlet boundary condition types were specified at both pipes (overflow and underflow), at which average static pressure of 0 Pa was prescribed. The boundary condition of the wall was set as no slip wall whose velocity components (u, v, w) are zero. The interaction of solid particles with the wall was set to equation dependent. Standard wall functions were used to approximate flow variables in the near wall region.

4. Experiment materials and methods
4.1 Experimental Setup
The overall experimental setup for this study is shown in Figure 6. Flow rate of 16 l/s was admitted tangentially under pressure through a circular inlet pipe of 80 mm diameter, accelerated by a centrifugal pump. Discharge rate can be varied by adjusting the valve installed in the discharge outlet of the pump. The overflow was discharged to a reservoir tank without any flow hindrance in between while the underflow was provided with a valve to control the flow and maintain the desired pressure in the system.
During the test run, timed samples of discharge from underflow and overflow pipeline were taken to determine the sediment removal efficiency of the hydrocyclone operating under designed flow conditions. The sediment concentration was kept 1000 ppm while the particle of diameter ranging from 0 to 400 microns was varied as feed sediment. Sediment particles for testing were screened using sieves sizes of 0-125, 125-212, 212-300 and 300-400 µm to co-relate the particle size in numerical simulation to an average value of 63 µm, 168 µm, 255 µm and 350 µm respectively. The pressure drop across the hydrocyclone was recorded using pressure transducer flush mounted at two circumferential location of the inlet and outlet pipe at 180°. The mixing of the sediment particles and water was achieved by mechanical agitating device manually.

![Figure 6. Schematic of the experimental setup with 1. Pump, 2. Mixing tank, 3. Hydrocyclone, 4. Underflow control valve, 5. Pressure transducer, 6. Data logger, 7. Computer, 8. Overflow pipe, 9. Outlet tank, 10. Air release pipe and sediment monitoring port.](image)

### 4.2 Experimental Procedure

A series of experiments were conducted with varying particle sizes. Samples from the inlet, under flow and overflow were taken for particle analysis. Filtration of the sampled mixture was carried out to remove water from mixture. For removal of the moisture, hot air oven was used and samples were dried for 2 hour at 80ºC. Solid particles were weighed for calculations of the solid concentration as mass per unit volume of the sample. Particle size distribution (PSD) from underflow and overflow dried samples was carried out using sieve analysis. The temperature of the feed was maintained at a temperature range of 15-25 degrees during the experimental tests. Mechanical agitator was used continuously throughout the experiment to achieve the homogenous mixture in the mixing tank. Sample was taken after 3 minutes to ensure that equilibrium state of mixture has reached. For sediment monitoring, the samples were collected every 30 seconds from the port provided at the inlet of the hydrocyclone. The test was allowed to run for a short duration of 1 minute keeping all the operating parameters constant at a time. Samples from underflow and overflow were taken twice at every interval of 30 seconds to check uniformity. Flow rates of the overflow and underflow were measured using measuring cylinders and a stopwatch.

| Parameters          | Range                          |
|---------------------|--------------------------------|
| Concentration       | 1000 ppm                       |
| Sediment Size       | 0-125 µm, 125-212 µm, 212-300 µm, 300-400 µm |
| Operating time      | 1 minute                       |
5. Results and Discussion
This study has been attempted to investigate the effect of sediment size on overall separation efficiency for constant flow rate and constant inlet concentration of 1000 ppm.

As presented in Figure 7, simulated results for pressure and velocity distribution in hydrocyclone agrees with the paper from the literature [20]. Pressure distribution chart showed that pressure has decreased radially from the wall towards the center. The inner cavity of the hydrocyclone has gradual pressure change with formation of a negative pressure zone in the core outlet regions. This negative pressure zone is responsible for flow of the mixture through overflow and underflow pipes. Likewise, velocity streamlines are maximum toward the inlet due to the accelerated fluid flow and then gradually decreased towards the bottom of the hydrocyclone. High speed fluid is forced by the centrifugal pump at the inlet and it is found to be accelerated by 0.75 times the inlet velocity. Past study showed that this velocity can reach up to 1.5-2 times the inlet velocity [21]. The value of tangential velocity is zero on the wall followed by rapid increment towards the center and again reduces to zero in the core of the cyclone. This state of almost zero velocity close to the wall along the z-direction is responsible for driving sediment particles out from the downstream.

**Figure 7:** (a) Pressure distribution inside hydrocyclone at Q=16 lt/s, Sediment size=19 µm (b) Velocity Streamline in hydrocyclone at Q=16 lt/s, Sediment size=19 µm

Figure 8 depicts the particles velocity distribution obtained from simulation at the sectional plane 0.1 m from the top surface of the cylindrical portion in the hydrocyclone for different particle sizes. From simulation results, it can be clearly observed that the smaller size particles were seen to escape through the overflow pipe with decreasing particle size, thereby decreasing separation efficiency. This is because smaller particles are forced into the inner core of the hydrocyclone by the effect of radial fluid drag force which increases exponentially with decreasing particle size [22]. Also, the flow is turbulent in nature causing re-entrainment and loss of particles from the overflow.

Experimental results also showed that faster deposition of the large sized particle out of the hydrocyclone is due to high deposition velocity which is proportional to the particle diameter. Also, the concentration of the particles escaping through the overflow pipe is found to be decreasing with the particle size becoming bigger, resulting in better separation efficiency. Some of the coarser particles were traced at the outlet of overflow pipe due to short circuiting of the flow near the inlet as evident by Bradley [13].
For determination of sediment removal efficiency, PSD samples and mass flow rate of mixture from overflow, underflow and inlet of the hydrocyclone were measured for different particle sizes at same flow conditions. Eq. (1) developed by Bennett is used to calculate the theoretical separation efficiency whereas Eq. (2) is used for determining numerical and experimental efficiency. Table 6 clearly tabulated the separation efficiency data obtained from theoretical, numerical simulation and experimental calculation. Experimental results showed lower separation efficiency than obtained from numerical simulation and theoretical calculation.

### Table 6: Calculated separation efficiency for different particle sizes

| Particle size (µm) | Theoretical η % | CFD η % | Experiment η % |
|--------------------|-----------------|---------|----------------|
| 63                 | 99.3            | 81.3    | 78             |
| 168                | 99.9            | 96      | 88.8           |
| 255                | 99.9            | 98.3    | 91.6           |
| 350                | 99.9            | 99      | 94.6           |

However, the separation efficiency trend is similar for three cases as shown in Figure 9. Deviation of the result from numerical simulation and experiment can be explained as: (a) shape factor of the particles injected is assumed to be 1 which implies spherical. These particles have a lesser projected area than that of irregular particles and the effect of drag force experienced by these spherical particles is less. So, these spherical particles are moved to the walls and collected at the underflow. Thus, concentration of spherical particles is found to be increasing towards the wall of the hydro cyclone, expelling it out from the underflow as revealed by literature paper [23]. (b) Injected sediment particles in CFD do not interact with each other. However, during experimentation, high sediment loading may hinder the particle path, collide with each other and re-circulation of the particle takes place before finally escaping out of the system [24].
6. Conclusion
In this present study, it has been demonstrated numerically and experimentally that the performance of hydrocyclone is significantly influenced by different sized particles. As of the simulation analysis, increasing the particle size has increased the separation efficiency from 27% to 99.2% for cut size diameter $d_{50} (19\mu m)$ up to particle size of 400 $\mu m$ respectively. However, the experimental result showed slightly lower separation efficiency for average value of particles’ size range. The separation efficiency is 78% for average value of particle size i.e. 63 $\mu m$, screened using a 0-125 $\mu m$ mesh screen and 88.8% for average value of particle size i.e. 168 $\mu m$, screened using a 125-212 $\mu m$ mesh screen.

Results revealed that hydrocyclone is efficient in separating particles < 200 microns that are responsible for maximum erosion of turbines in hydropower plants. The use of hydrocyclone as a separation device is best suited during peak monsoon season to reduce the sediment load and ultimately sediment erosion problem in hydro turbines. Likewise, this device is effective in eliminating the injected sediment particles from the system once it has passed through the test specimen. Thus, it can also be used to develop re-circulating type of erosion test rig to minimize the slurry ageing problems to greater extent.

7. Recommendation and future scope
Based on the observation and conclusion made from the study, following recommendations and future works are suggested:

(a) This study takes only the influence of sediment size on efficiency of the hydrocyclone into account. This study can be extended to different sediment concentrations to get more realistic results.

(b) It is recommended to use sieve size close to each other in order to segregate individual size groups to eliminate the influence of presence of other size groups.

(c) There is further scope to investigate the effect of sediment shape on separation efficiency of hydrocyclone. It may be beneficial to compare and analyze CFD with experimental results.
References

[1] Winkler K, 2014, *Hydro-abrasive erosion: Problems and solutions*, IOP Conference Series: Earth and Environmental Science, 22:5202

[2] Padhy M.K, Saini R.P, 2008, *A review of silt erosion in hydro turbines*, Renewable and sustainable Energy reviews, 12:1974-87

[3] Pandit H.P, 2007, *Hydrocyclones: Alternative Devices for Sediment Handling in ROR Projects*, International Conference on Small Hydropower, Hydro Sri Lanka

[4] Kayastha A, Thapa B.S, Thapa B, Lee Y.H, 2020, *Experimental investigation for R&D in sediment laden pico hydraulic Francis Turbine*, Elsevier, Renewable Energy, 155:889-898

[5] Thapa B, 2004, *Sand erosion in hydraulic machinery*, PhD Thesis, NTNU, Norway

[6] Lysne D.K, Glover B, Støle H, Tesaker E, 2003, *Hydropower development book series number 8 - Hydraulic design*, NTNU, Norway

[7] Chhetry B, Rana K, 2015, *Effect of sand erosion on turbine components: A case study of Kali Gandaki ‘A’ Hydroelectric project (144MW)*, Hydro Nepal, Issue no:17, Nepal

[8] Rai A.K, Kumar A, Staubli T,2015, *Developing a Test Rig To Measure Hydro-Abrasive Erosion in Pelton Turbine*, International Conference in Hydropower Sustainable Development, 05-07, pp. 535–547

[9] Grewal H.S, Agrawal A, Singh H, 2013, *Slurry erosion mechanism of hydroturbine steel: Effect of operating parameters*, Tribology Letters

[10] Castilho L.R, Medronho R.A, 2000, *A simple procedure for design and performance prediction of Bradley and Rietema hydrocyclones*, Minerals Engineering, 13:183-191

[11] Sinnott R.K, 2005, *Chemical Engineering Design*, 6(4)

[12] Rietema K,1961, *Performance and design of hydro cyclones*, Chemical Engineering Science, Vol.15, pp. 298-325

[13] Bradley D, 1965, *The Hydro cyclone*, Pergamon Press, London

[14] Svarovsky L,1990, *Efficiency of separation of particles from fluids in solid-liquid separation*, 3:43-73

[15] Oliveira D.C, Almeida A.K, Vieira L.G.M, Damasceno J.R, Barrozo M.A.S, 2009, *Influence of geometric dimensions on the performance of a filtering hydrocyclone: An experimental and CFD study*, Brazilian journal of Chemical Engineering, Vol. 26, pp. 575-582

[16] Lenzi M.K, Lenzi E.K, 2006, *Spreadsheet for cyclone and hydro cyclone design considering non spherical particle geometry*, Wiley periodicals Inc., Brazil

[17] Zanker A, 1977, *Hydrocyclones: dimensions and performance*, Chemical Engineering

[18] Bennett J. G, 1936, *Broken Coal*, Journal of Institute of Fuel, 10:22-39

[19] Dlamini M.F, Powell M.S, Meyer C.J, 2005, *A CFD simulation of a single phase hydrocyclone flow field*, Journal of the South African Institute of Mining and Metallurgy, Vol.5

[20] Cuijong Z, Shihan W, Changshun Y, Ling X, 2018, *Study of Particle-Size Control of
Hydrocyclone for Slurry Recycles, IOP Conf. Series: Environmental Science and Development

[21] Wang B, Xu D.L, Chu K.W, Yu A.B, 2006, Numerical study of gas–solid flow in a cyclone separator, Applied Mathematical Modelling, 30:1326-1342

[22] Zhang J, Fan L.S, 2002, A semi analytical expression for the drag force of an interactive particle due to wake effect, Industrial and Engineering Chemistry Research, 41:5094–5097

[23] Papoulias D, Lo S, 2015, Advances in CFD modelling of multiphase flows in cyclone separators, Chemical Engineering Transactions, 43:1603-1608

[24] Cullivan J. C, Williams R. A, Dyakowski T, Cross C. R, 2004, New understanding of a hydrocyclone flow field and separation mechanism from computational fluid dynamics, Minerals Engineering, 17:651–660

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