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Numerical modelling of axial outlet hydrocyclone

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Abstract

Nepal possesses huge networks of perennial rivers and together with the steep topography, the rivers of Nepal prospects enormous hydroelectric potential. However, due to significant amount of sediments in the rivers, the hydropower plants suffers considerable losses due to damages in turbines and other hydromechanical equipment's. Since the gravity-based settling basins, designed for handling suspended sediments has been found inefficient, this study focuses on use of centrifugal separation method for better handling of suspended sediments. This paper presents the simulation of axial outlet hydrocyclone using ANSYS Fluent software. The simulation is first validated with the physical model in terms of both water distribution and sediment throughput. Subsequently, the hydraulic performance of the device is analysed by studying various velocity profiles and headloss in the device. Finaly, the device performance is assessed at various angle of inclination of its axis at 90^{o}, 60^{o}, 53^{o}, 45^{o} and 30^{o} to horizontal with an intent to reduce the overall height of device considering difficulties in excavation in rugged topography of Nepal. It was observed that the sediment separation efficiency decreased, particularly for very fine sediments with reduced headloss by 0.071 m as the axis of device was changed from 90^{o} to 30^{o} to horizontal.

Keywords: 3D Model, ANSYS Fluent, CFD, Headloss, Hydrocyclone, Hydropower

Introduction

Sediment is a mixture of various organic and inorganic materials that is carried by the rivers along with the water from one place to another. And Nepal's river system are the ones that are responsible for transporting highest sediment loads to the ocean. The estimated total specific yield of the country is about 4240 tons/km^2/year (Bajracharya et al. 2008) [1]. Major rivers like the Narayani often record sediment loads as high as 25,000 ppm (Carson 1985) [5]. Similarly, sediment load as high as 50,000 ppm has been found in smaller river like Jhimruk (Basnyat 1997) [3]. The reason behind high sediment yield is due to fragile geology of Nepal as Nepal is situated in seismically active area at convergence of Indian and Eurasian plates, the steep topography of Nepal together with the combination of heavy monsoon rainfall spanning between June and September during which the country receives 55-80% of its annual rainfall (Basnet et al. 2020) [2], and the influence of South Tibetan Detachment Surface (STDS) which marks the boundary between Indian and Eurasian Plates is considered as most active tectonic features in the world that is responsible for erosion and transport of large volume of sediment to the rivers (Pandit et al. 2008) [9].

Because of the sedimentation problem, many hydropower turbines in Nepal suffers severely causing reduced plant efficiency, unplanned outage and requires frequent repair and maintenance. For instance, the Jhimruk Power Plant is one of the severely affected power plants by river sedimentation and the study shows that the turbine efficiency drops by 8% within just 2 months (Chitrakar and Neopane 2019) [7]. Similarly, the turbine of Kaligandaki 'A' HEP has undergone five major maintenances in between year 2002 and 2014 including replacement of runner (Chhetry et al. 2014) [6]. Generally, Settling Basins are designed for excluding the suspended sediments coarser than 200 microns in hydropower plants has been found inadequate in Himalayan regions like Nepal (Pandit et al. 2008) [9]. Khimti Hydroelectric Project experiences significant turbine wear and tear despite effectively trapping 97% of particles larger than 200 microns and 85% of particles exceeding 130 microns (Deshar 2007) [8]. A Pelton turbine operating at high head of 920 m showed severe erosion and cavitation after just 600 hours of operation because of abundance of 77% particles finer than 63 microns and 99% particles finer than 125 microns (Brekke et al. 2003) [4].

An attempt to trap such fine sediments would require large settling basin, which will increase the capital cost and also the space required to house such large settling basin is generally not available in mountainous topography of Nepal. Since centrifugal separation methods has been successfully employed in industries like oil and gas refineries as well as food and beverages industries, this research focuses on studying application of hydrocyclone for improved exclusion of suspended sediments in hydropower projects.

Hydrocyclone is a device that separates fluid from solid particles or separate one fluid from another based on their difference in density by the action of centrifugal force. The schematic diagram of a typical hydrocyclone device is presented in Figure 1.

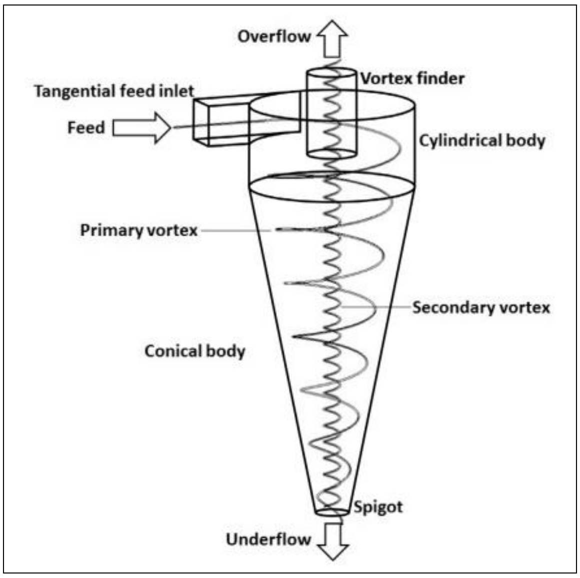


Fig 1: Schematic diagram of hydrocyclone (Vega-Garcia et al. 2018)

As the fluid with suspended particles enters the hydrocyclone rapidly through a tangential inlet, it initiates a spiral motion. The particles undergo centrifugal force pushing them towards the wall and drag force pulling them inward due to the fluid. Heavier particles, experiencing stronger centrifugal force, hit the wall early and exit through the underflow outlet after losing momentum. The conical section's decreasing radius raises pressure, pulling in air from underflow. Swirling air exits through overflow, carrying finer particles and fluid, enabling their escape due to local drag.

Methodology

The flow inside the hydrocyclone is very complex and turbulent. Therefore, the study of the device is carried out using numerical modeling approach by using ANSYS Fluent (Version 2019 R1), a commercial CFD program. The numerical model is performed to study the behavior of axial outlet hydrocyclone. Initially, the numerical model is validated with the physical model conducted by H.P. Pandit (Pandit et al. 2008) [9], considering both hydraulic and sediment trapping aspects. The hydraulic behavior of device is assessed by studying different velocity profiles and headloss within the device. Lastly, the device's performance at various angles of inclination of its axis (90°, 60°, 53°, 45° and 30° with horizontal) is studied thereby reducing the overall height of device considering the difficulties in excavation in rugged geography of Nepal.

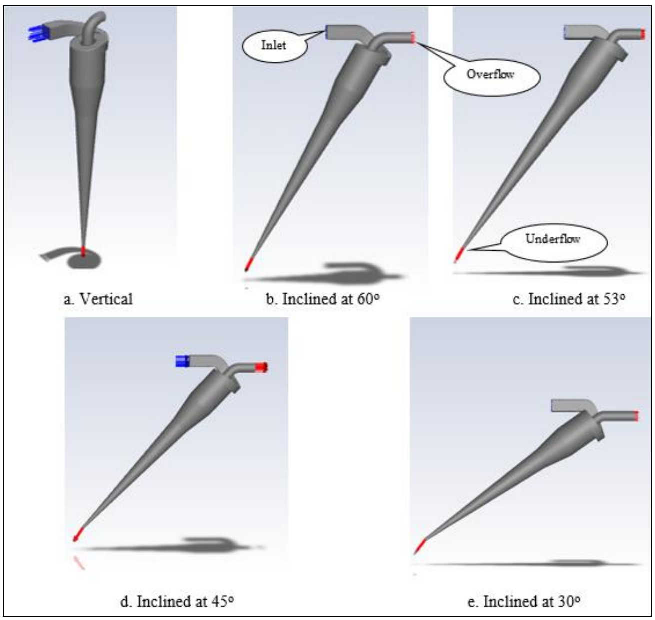
The model setup in ANSYS Fluent includes following steps:

Geometry

The 3D geometry resembling the test rig of physical model serves as the foundational step in the research process. The dimensions of the test rig are presented in Table 1 and the 3D model of test rig is illustrated in Figure 2.

Table 1: Dimensions of test rig of Physical Model (Pandit et al. 2008) [9]

S.N.	Parameter	Unit	Measurement
1	Diameter of hydrocyclone	m	0.38
2	Height of cylindrical part	m	0.50
3	First cone angle	deg	18
4	Second cone angle	deg	6
5	Height of first conical part	m	0.40
6	Height of second conical part	m	1.35
7	Dimension of inlet	m	0.055 x 0.11 (B x H)
8	Diameter of overflow	m	0.035
9	Diameter of underflow	mm	15 - 60
10	Length of vortex finder	m	0.19



a. Vertical b. Inclined at 60° c. Inclined at 53°

d. Inclined at 45° e. Inclined at 30°

Fig 2: 3D model of test rig

Meshing

The generation of mesh for fluid domain is performed in ANSYS workbench for numerical analysis. Tetrahedral elements are used with a global element size of 20 mm. Three layers of inflation are added with the first layer thickness of 2×10^{-3} m at a growth rate of 1.2 to capture the near wall behavior more accurately. The mesh quality analysis is performed as per ERCOFTAC 2018 guidelines. The number of elements in different configuration of device is tabulated in Table 2.

Table 2: Mesh element numbers for different configuration of device

Angle of inclination with horizontal	90°	60°	53°	45°	30°
Number of elements	220,912	284,626	259,466	239,314	243,135

Boundary Conditions

The hydrocyclone simulation involved setting the inlet boundary as "mass flow inlet." Both outlets were defined with the boundary condition of "pressure outlet" at atmospheric pressure. For the walls, non-slip conditions were assigned and partial slip condition was assumed for the sand, with a specularity coefficient of 0.5. The summary of boundary conditions set is shown in below.

Table 3: Summary of Boundary Conditions

Boundary Conditions	Settings
Inlet: mass flow rate of water	16.60 l/s
Inlet: mass flow rate of sand	0.028 kg/s
Overflow and Underflow Outlets	Pressure Outlet at atmospheric pressure
Walls	No slip for water and partial slip for sediments

Numerical Simulation

For numerical modeling of device, multiphase model was used in which water is considered primary phase and sediment as secondary phase. The density of water and viscosity is set as 998.2 kg/m^3 and 0.001 kg/m/s. Sediment size ranging from 1 micron to 400 microns with a density ranging from 2500 kg/m^3 for finer particles to 2680 kg/m^3 for coarser particles were used.

For the numerical simulation hydrocyclone, the swirl modification RNG (k-epsilon) model is selected as this model is an improvement over traditional RANS models such as ƙ-ε (k-epsilon) model. Although this model requires high computational resources, it provides more accurate results in complex flows or near walls (Yakhot and Orszag 1986) [11].

The convection term was treated using an upwind scheme, and the pressure term was solved using the SIMPLE algorithm. A total of 20,000 iterations were set to capture the turbulent behavior of flow and to ensure convergence criteria of 5 x 10^{-4} to reach a stable and accurate solution.

Results and Discussion

Validation of Numerical Model

The results of numerical modeling of axial outlet hydrocyclone is compared with the results of physical model (Pandit et al. 2008) [9]. The primary focus was to verify the hydraulic performance for which the continuity of flow was compared with the results of physical model. The results depicting the comparison of flow rate from different outlets for different inlet discharge is presented in Table 4.

Table 4: Comparison of flow rates between physical and numerical model

S.N.	Discharge passing through	Physical Model (l/s)	Numerical Model (l/s)
Test No. S2-1	Inlet	17.20	17.20
	Overflow Outlet	14.68	15.35
	Underflow Outlet	2.52	1.84
Test No. S2-3	Inlet	19.40	19.40
	Overflow Outlet	17.30	17.33
	Underflow Outlet	2.10	2.06
Test No. S2-5	Inlet	17.85	17.850
	Overflow Outlet	15.45	15.972
	Underflow Outlet	2.4	1.874
Test No. S2-8	Inlet	16.60	16.60
	Overflow Outlet	14.33	14.52
	Underflow Outlet	2.27	2.07

After achieving the similar continuity of flow, a detailed numerical simulation was carried out involving the mixture of sediments and water. The sediment trapping efficiencies is calculated using the following formula:

$$E = \frac{q_{su}}{q_{su} + q_{so}} \quad (1)$$

Where

q_{su} = Rate of sediment received from underflow outlet in kg /s,

q_{so} = Rate of sediment received from overflow outlet in kg/s.

The comparison of sediment trapping efficiencies for various sizes of sediments is illustrated in Figure 3.

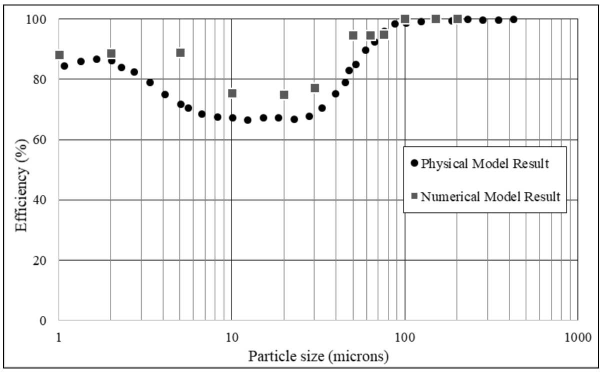


Fig 3: Comparison of sediment trapping efficiencies for various sizes of sediments

To quantitatively assess the numerical model's performance against the physical model, statistical parameters were checked. The R^2 value was calculated as 0.96 while the RMSE and PBIAS values were computed as 4.407 and -3.40 respectively.

Hydraulic Performance of Device

Velocity Profile

The post processed result of simulation depicting the velocity vector of water is presented in Figure 4. The velocity streamlines illustrate that the maximum velocity is observed near the inlet, where the fluid flow is accelerated due to the reduction in cross-sectional area. The velocity gradually decreases towards the bottom of the hydrocyclone. Additionally, there is an upward flow in the opposite direction, causing the fluid to exit the hydrocyclone through the overflow outlet.

Different velocity profiles were assessed to better understand the hydraulic behavior of device. The flow velocity inside the hydrocyclone can be split into three components as shown in Figure 5.

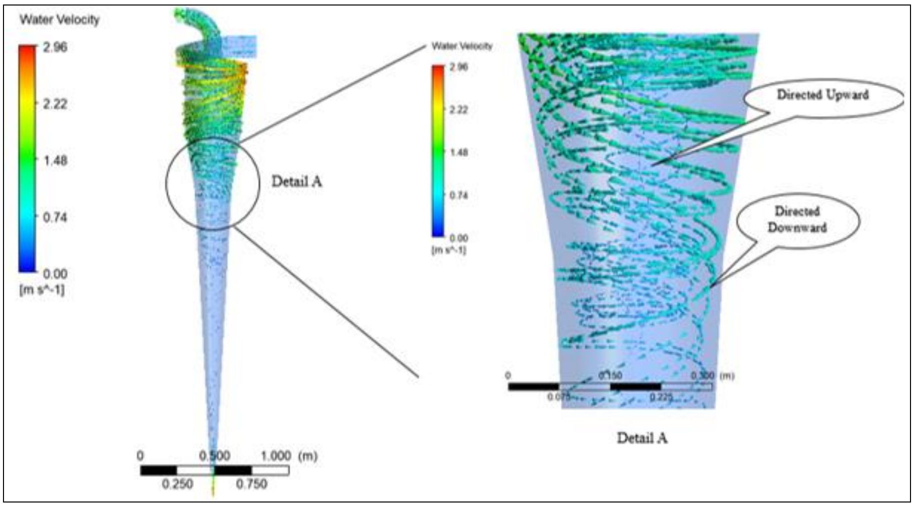


Fig 4: Velocity vector showing magnitude and direction of flow inside device for discharge of 16.60 l/s

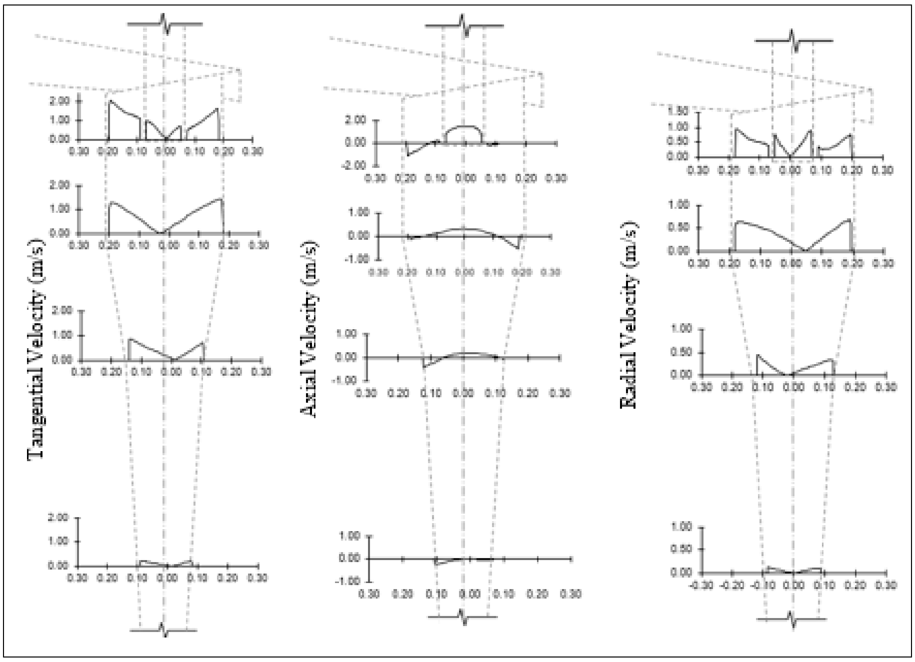


Fig 5: Tangential, Axial and Radial velocity profiles inside hydrocyclone for discharge of 16.60 l/s

1. Tangential velocity

Tangential velocity is the most crucial and important velocity component in the hydrocyclone. From Figure 5 it can be observed that the tangential velocity is higher near the walls at the greater radial distance and minimum at core. Because of this, the particles near the walls are exposed to higher centrifugal force which causes them to accelerate while the middle core area with low velocity allows the water (lighter media than sediments) to be carried away from the overflow outlet.

2. Axial velocity

Axial velocity refers to the velocity in the direction of cyclone axis. In Figure 5, the outer walls of the cylindrical and conical sections exhibit higher velocity, indicated by negative axial velocity, directing flow downward. Whereas in the middle core the velocity decreases and it is directed upward with positive axial velocity. This downward flow from the outer circumferential region is crucial for guiding sediment particles to the underflow outlet while the upward flow near the central axis facilitates the recirculation of clear water towards the overflow outlet.

3. Radial velocity

The radial velocity distribution in a hydrocyclone typically follows a pattern in which the velocity is highest near the outer wall and decreases as you move towards the center of axis.

Headloss in the device

The headloss in the device was assessed by measuring the difference in total pressure between inlet and overflow outlet and the headloss of 0.758 m was estimated for the discharge of just 16.60 l/s. Considering the short conveyance and small discharge, the headloss in the device is very high which is due to turbulent flow induced by the centrifugal force and longer spiral flow path.

Performance of Device at Different Inclination

The study is carried out to check the sediment trapping efficiency for different sizes of sediments at different inclination of device axis. The figure comparing the trapping efficiency of sediment for different orientation of device is shown in Figure 6.

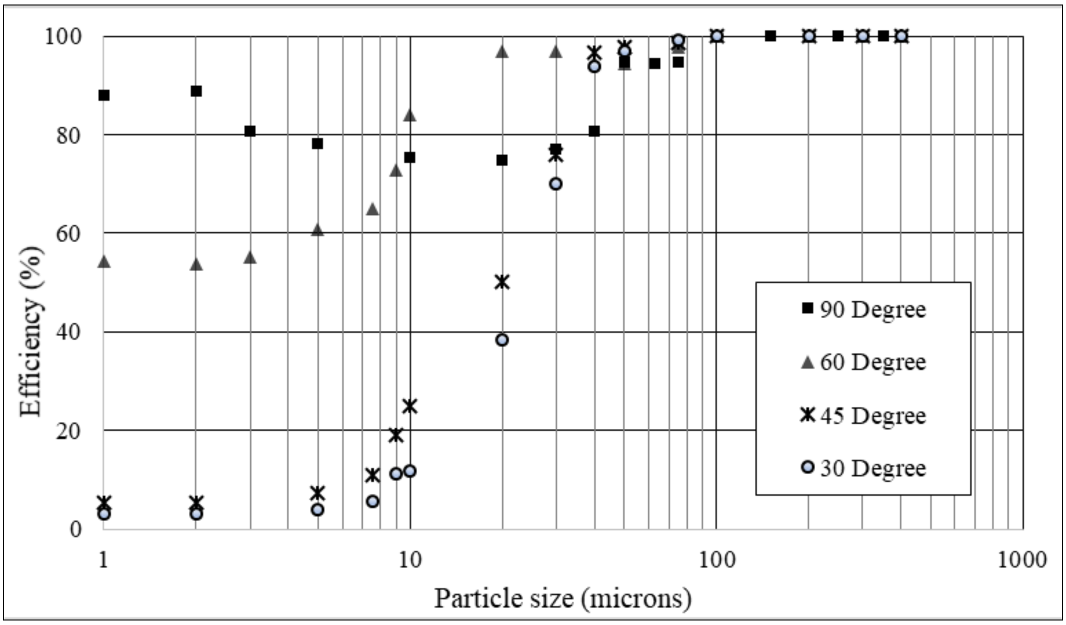


Fig 6: Trapping efficiencies for different sizes of sediments at different orientation of device

It is observed that as the inclination of device is more towards horizontal, the trapping efficiency of device is reduced, particularly in case of very fine sediments. The same can be observed in the velocity streamline of sediments as shown in Figure 7. It is observed that more sand particles escaped from overflow outlet while tilting the device axis from vertical to 30° with respect to horizontal.

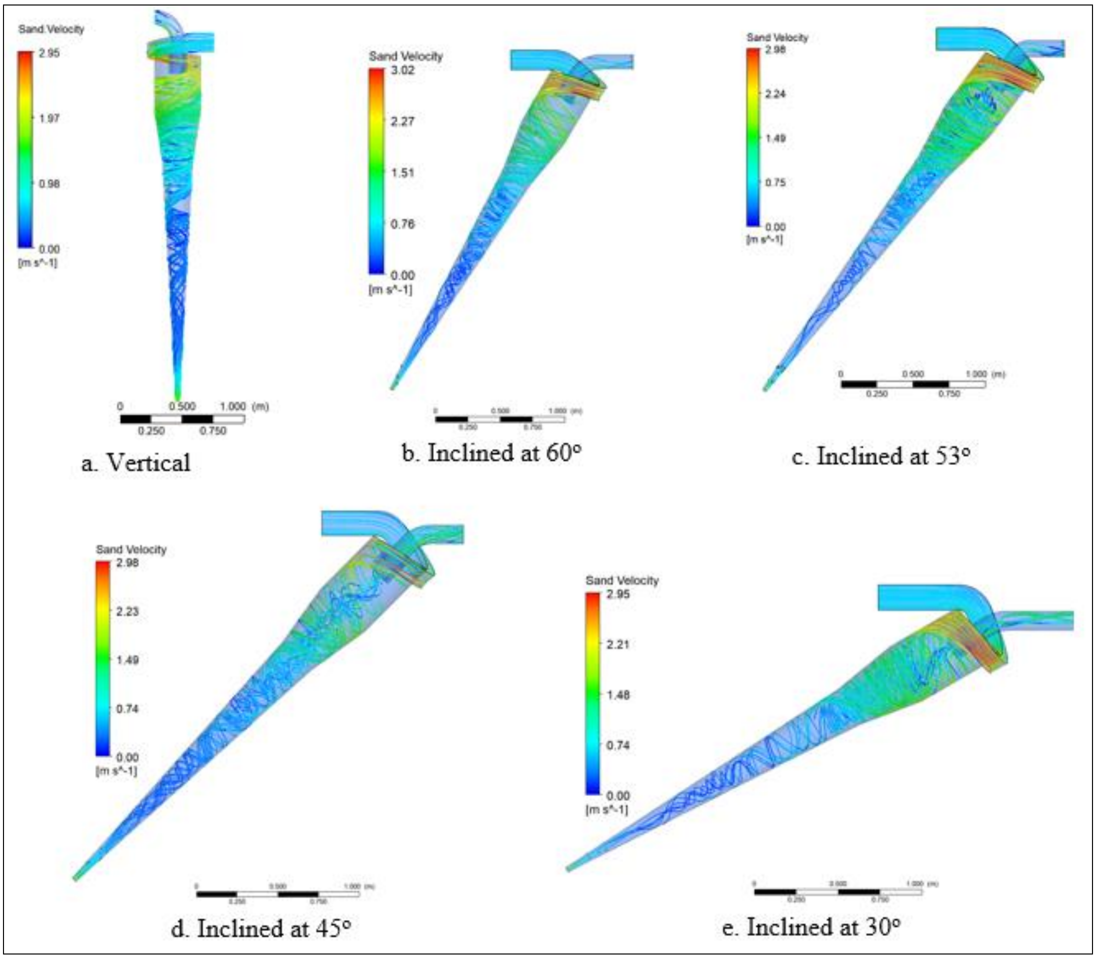


Fig 7: Velocity streamline of sediment for different inclination of device

The headloss in the device at different orientation of its axis is shown in Table 5. It is observed that as the device is inclined from 90° to 30° towards horizontal, the headloss in the device is reduced by around 0.071 m. This decrease in headloss is desirable, however it comes with the cost of reduced trapping efficiency, particularly for very fine sediments.

Table 5: Headloss in device at different inclination of device for discharge of 16.60 l/s

Angle of inclination with horizontal	**90º**	**60º**	**53º**	**45º**	**30º**
Headloss (m)	0.758	0.709	0.702	0.695	0.687

Conclusion

In this study, the comprehensive study and analysis of axial outlet hydrocyclone has been carried out. The numerical model was first validated with the physical model. The output of numerical model closely matched with the physical model exhibiting similar water distribution and sediment throughput. The model results were compared both visually and quantitatively. The quantitative assessment involved the utilization of various statistical tools such as Coefficient of Determination (R^2), Root Mean Square Error (RMSE) and Percentage Bias (PBIAS), and whose values were determined to be 0.96, 4.407 and -3.40 respectively. Furthermore, a fish hook effect can be observed in Figure 3, which further validates the capability of model to accurately capture the distinct behavior of hydrocyclone device.

Further the device's hydraulic performance was studied by analyzing various velocity profiles and headloss within the device. The tangential velocity, vital for sediment separation, increases from the central axis to the walls due to centrifugal force. Axial velocity moves downward near the outer wall and upward near the core, while radial velocity peaks at the outer wall and decreases towards the center. The observed velocity profiles matched with the typical velocity profiles inside the hydrocyclone device. A headloss of approximately 0.76 m was observed for a discharge of just 16.60 l/s.

Lastly the device's performance was assessed under different angle of inclination of its axis at 60º, 53º, 45º, and 30º with horizontal. The results showed that while adjusting the device's axis from vertical to 30º to horizontal, a reduction in headloss was observed by 0.071 m. This decline in headloss is desirable, however it comes at the cost of lowered sediment separation efficiency, especially for very fine sediments.

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