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Improvement of performance efficiency of a hydrocyclone with design modification by suppressing air core

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Abstract−Hydrocyclones have been used for beneficiation of coal and mineral in coal washeries and mineral process industries. To enhance the efficiency of hydrocyclone, it is very essential to quantify the presence or absence of air core within the hydrocyclone. In the present study, for the first time, a new hydrocyclone design has been conceptualized and tested for its efficiency in separation of particles based on gravity. Experimental investigations have been carried out using design of experiments and the results have been analyzed statistically. The results have shown that suppressing the air core improves the separation efficiency of the hydrocyclone. Efforts have been made to explain the concept through fundamentals of fluid flow in hydrocyclone. The air core has a significant effect on particle separation as the relative density of the particles approach to the fluid density. The results will be used in the development of a new design of dense medium hydrocyclone at industrial scale that will improve the separation efficiency of the hydrocyclones by separating the near gravity particles more efficiently.

Key words: Hydrocyclone, Dense Medium Cyclone, Air Core, Separation Efficiency, Density Tracers, Particle Separation

INTRODUCTION

The hydrocyclone is a simple device that uses the centrifugal force for separation of materials in a fluid-particle stream. Unlike the slow settling within a settling tank, the pump and hydrocyclone separator system yields fast separation and utilizes less space. Separation occurs quickly because gravitation force “g” is replaced by many “g” components of centrifugal force. The materials may be particles of solid, bubbles of gas or immiscible liquids in the system. In the case of two solids suspended in the feed liquid they may separate according to size, shape or density. The cyclone utilizes the energy obtained from fluid pressure to create rotational fluid motion.

This rotational motion causes the materials suspended in the fluid to separate from one another or from the fluid quickly due to the centrifugal force. The rotation is produced by the tangential or involutes introduction of fluid into the vessel. A dense medium cyclone is a cyclone separator that uses fine magnetite suspended in water as the bulk fluid.

1. Dense Medium Hydrocyclone Washer

Dense medium (DSM) hydrocyclone separators are now widely used for the treatment of ores and coal. The DSM cyclone can treat ores and coal in the size range of 40 to 0.5 mm. The ore is suspended in a very fine medium of ferrosilicon/magnetite and is introduced into the cyclone under pressure, normally being gravity fed via a constant head. The lighter material leaves through the overflow outlet or the vortex finder and the heavier material collected through the underflow outlet or spigot

2. Flow Inside a Hydrocyclone

The flow pattern in the normal design of hydrocyclone is a spiral within a spiral [1]. Fluid on entry commences downward flow in the outer regions of the cyclone body. This is combined with the rotational motion to which it is constrained and creates the outer spiral. The existence of a top central outlet and the inability under normal feed pressure and flow rate conditions for all of the fluid to leave at the cone apex outlet assists the inward migration of some of the fluid from the external downward moving mass. The amount of inward migration increases as the cone apex is decreased and the fluid which flows in the migratory system. Rotation of the fluid creates a low pressure axial core, which normally results in a free liquid surface. The core in a cyclone which is directly connected with the atmosphere at both underflow and overflow becomes partially air filled. The surface of the air core will be found to be irregular due to the continuous disturbance from progressive waves.

3. The Air Core in a Hydrocyclone

Formation of the air core in any hydrocyclone is considered to be an indication of vortex stability. It is essential to maintain the feed rate and the pressure is sufficient to operate in stable operating range. It indicates that for any cyclone there is a minimum flow rate and consequently a minimum pressure drop or feed pressure for its operation. The size and stability of the air core is believed to affect the metallurgical performance of the separator. In addition, mathematical models have been developed using advanced fluid dynamics simulations which can predict the air core formation, its size and shape very accurately. Various researchers have studied the classification efficiency of hydrocyclones by blocking the air core. Xu et

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al. [2] and Liang-Yin Chu et al. [3] have reported improvement in the performance of the cyclone efficiency with suppression of the air core. However, in some cases the opposite trend has been reported in the literature. This paper describes the studies carried out to determine the separation efficiency of the dense medium cyclones with a suppressed air core. The study has shown encouraging results especially for the separation of near gravity materials/particles. This has led to the conceptualization of a new design of dense medium cyclones suitable for Indian coals. Steffens et al. [4] developed a mathematical model of the flow within a simplified hydrocyclone using the Navier Stokes equations and also investigated the behavior of the air core within a hydrocyclone and its effect on the flow splits to products ratio. Davidson [5] analyzed air core diameter in a hydrocyclone using the physics of uniform density, inviscid flow at each outlet, modified by an empirical factor to account for viscous effects. Dyakowski et al. [6] developed a new method to predict the size of the air-core within a hydrocyclone based on calculating the internal pressure distribution. Dwari et al. [7] reported performance characterization of fly-ash-FCC-sand particle separation in a novel hydrocyclone; however, understanding the physics of fluid flow within the cyclone was not discussed.

Recently, attention has been directed towards understanding the role of the air-core in particle separation in cyclones. Xu et al. [2] proposed a method for inserting a solid rod within the hydrocyclone, to replace the air core, which would result in an increase in tangential and a reduction in radial velocities. The separation efficiency would improve by increasing the magnitude of the tangential velocities within the body. This would increase the centrifugal force acting on the solid particles within the hydrocyclone, thus permitting the separation of finer solid particles. Liang-Yin Chu et al. [8] reported that the flow field characteristics inside the hydrocyclone with solid core became more suitable for the separation process, i.e., by replacing the air core with solid core, the hydrocyclone separation performance improved effectively. Shin et al. [9] reported the design and performance evaluation of a hydrocyclone to remove fine particles. Lee and Williams [10], on the other hand, in their study noted that when the air core was replaced by an axial steel rod, the sharpness of classification, fineness of cut-size and overall separation efficiency was inferior. Changlie et al. [11] suppressed the air core using a water seal at the spigot. Their results indicate that with the same structural parameters and operating conditions, the water-sealed cyclone had a greater tangential velocity than an ordinary cyclone. The water-sealed hydrocyclone had a wedge zone where the vertical velocity became zero unlike the ordinary cyclone, while the radial velocity in

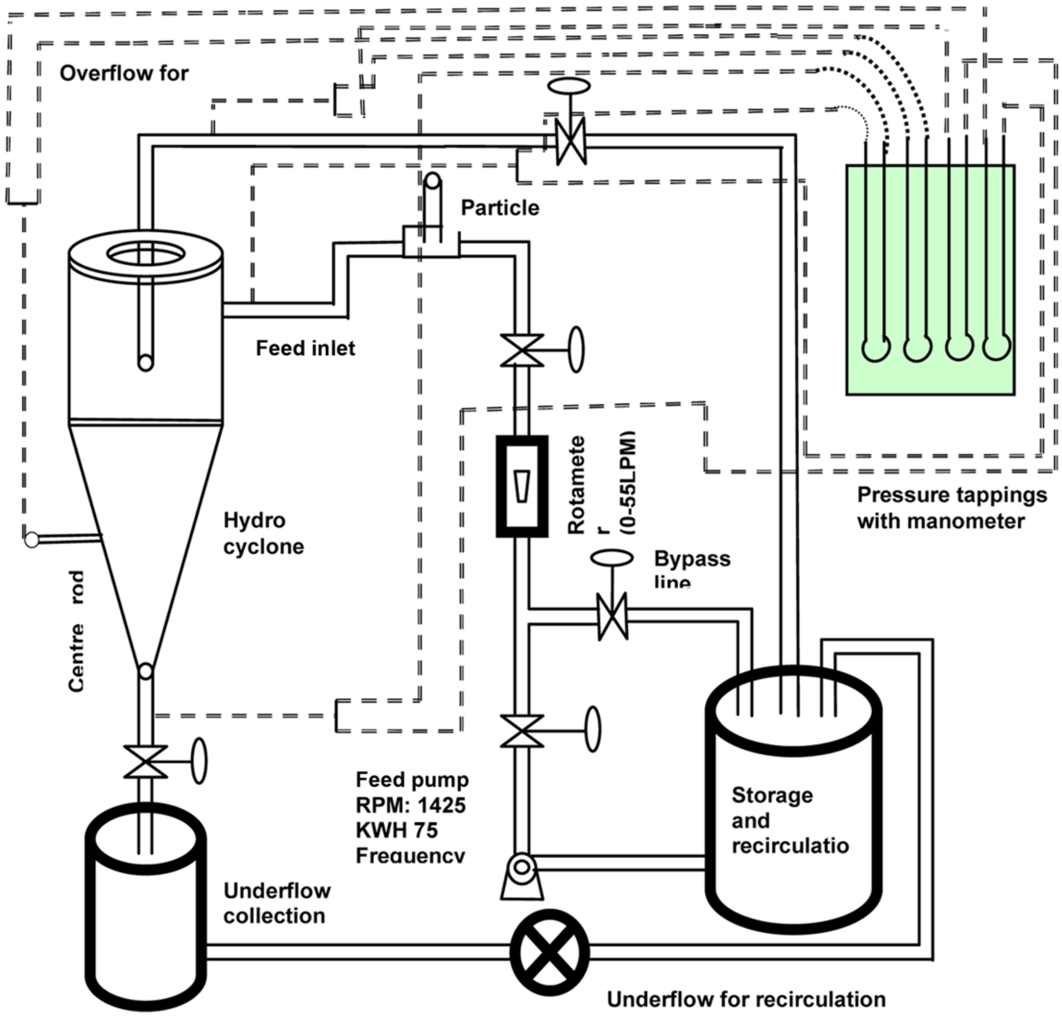

Fig. 1. Schematic diagram of the experimental setup of hydrocyclone.

Table 1. Design data of cyclone used for study

Diameter of cyclone	10 cm
Length of cylindrical portion of hydrocyclone	21.6 cm
Length of conical portion of hydrocyclone	36.5 cm
Apex angle	15.6°
Diameter of vortex finder pipe	2.5 cm
Diameter of apex pipe	1.8 cm
Diameter of feed inlet pipe	2.5 cm

the water sealed cyclone was similar to the ordinary cyclone. In this paper, an effort has been made to study and understand the effect of air core on particle separation in dense medium cyclones. Density tracers (both lighter and heavier than water) have been used in a Perspex made hydrocyclone and their separation efficiency is a step by step systematic manner. Since the present study indicates the removal efficiency by controlling the air core, this is a new type procedure to design a hydrocyclone.

4. Experimental Set-up and Technique

The experimental set-up made of Perspex column consisted of vertical straight column, conical bottom, vortex finder and bottom outlet as shown in Fig. 1. A 100-mm perspex cyclone was arranged in closed circuit with a water tank, a pump and a by-pass line as shown in Fig. 1. The by-pass valve in the line was used for adjusting the feed rate of water to the cyclone and the pressure at the feed inlet of the cyclone. The design details of the cyclone are shown in Table 1. A calibrated rotameter was fitted to the inlet line to measure the inlet flow rates. A provision was made in the center of the cyclone body which facilitated the insertion of a rod till the center of the cyclone to suppress the air core (Fig. 2). The variables affecting particle separation and air core formation in a cyclone have been used in the present study. The most important variables are the inlet design, cyclone design, inlet flow rate, vortex finder depth, spigot and vortex finder diameter. The diameter of the spigot and the vortex finder were kept constant. However, in the overflow and spigot were fitted with valves so that the flow split can be adjusted. The flow splits in turn determined the type of air core formed; and hence another variable called "the type of air core" was also defined. The design variables were converted into dimensionless numbers using the Buckingham's Pi theorem. In all, five variables, the cyclone design, the inlet design, the Reynolds number of the fluid at the inlet (N_{Rei}), the ratio of the depth to which the vortex finder was inserted inside the cyclone (Ho) to the height at which the inlet tube was fixed (Hi) and the type of air core were considered at different levels. The level of the variables maintained in the experiments is given in Table 2.

Since the setup was a transparent setup, it was decided to use density tracers for the tests. The tracers were of four different relative specific gravities (0.93, 1.3, 1.6 and 2) and were color coded for easy identification. The tracers were of a size 3 mm. The particles of relative density tracer of specific gravity 0.9, although lighter, had relative density very close to that of the fluid, which may be called as the near gravity lighter particle. Provisions were made so that tracer particles can be introduced into the cyclone just before the inlet.

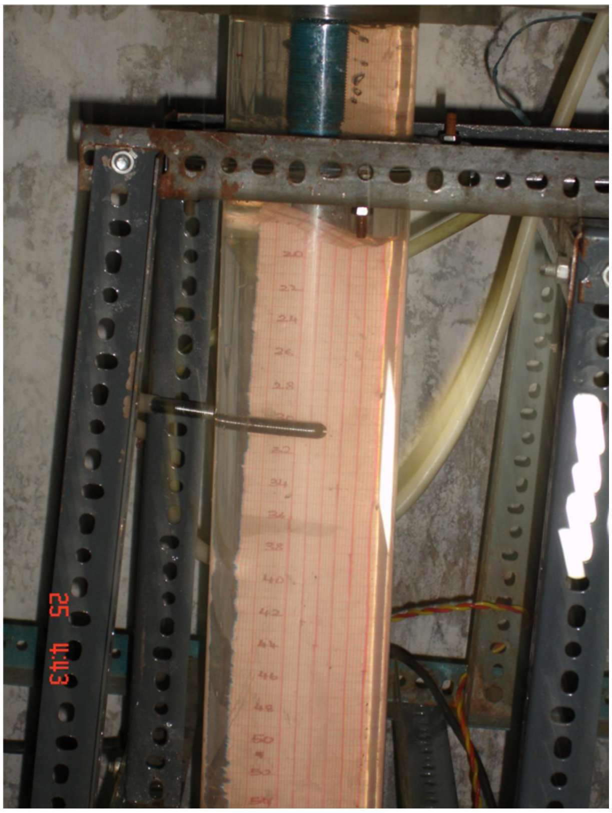

Fig. 2. Method of suppressing air core by insertion of solid rod from side wall.

Before the start of tests, the required inlet flow rate, Ho and Hi was fixed at desired value using the rotameter. In each test, the flow splits were adjusted to get four different types of air core. The conditions when no air core formed were called the "forms after this" type. With changes in the flow conditions, the air core would form and extend till the middle of the cyclone body. This was called the "forming air core type (Fig. 3). The conditions were further adjusted so that the air core became a thick rod extending from top to bottom. This was called the "good air core" (Fig. 4). The central rod

Table 2. Levels and variables used for study

Variables	Levels			
	1	2	3	4
Nre	<46000	>46000	-	-
Ho/Hi	<2.86	>2.86	-	-
Cyclone design	Cylidro-conical	Cylinder	-	-
Inlet design	tangential	Involute	Off- tangential	-
Type of air core	Forms after this	Forming	Good	Suppressed

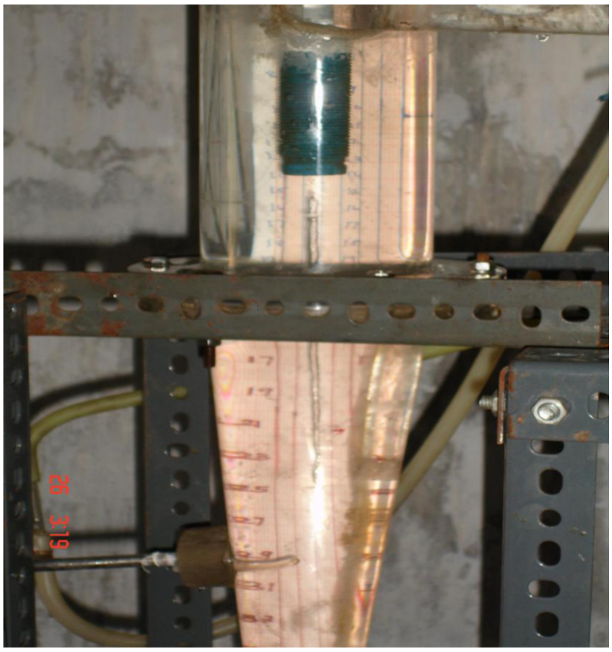

Fig. 3. A forming air core.

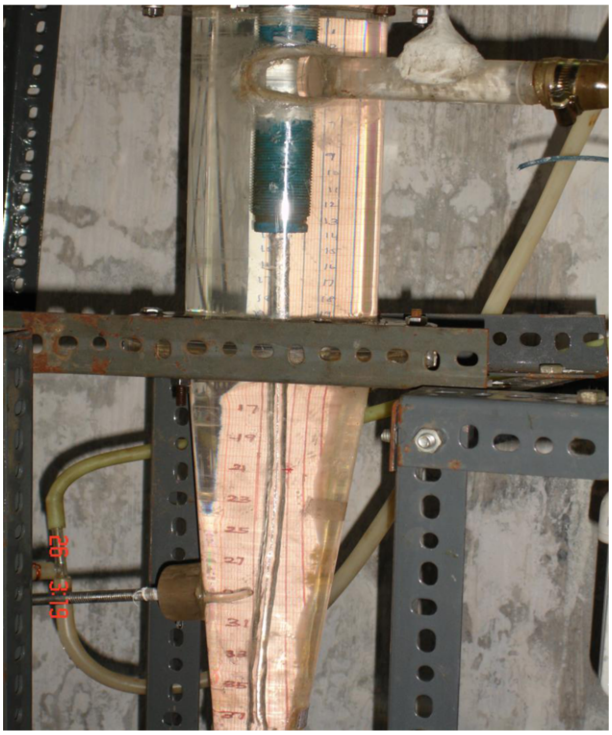

Fig. 4. Representation of a stable developed air core.

was then inserted to extend till the center of the air core so that the air core was suppressed. This condition was called the "suppressed air core" condition. At each condition, 54 numbers of lighter particles and 54 numbers of denser particles (compared to the fluid density) were introduced. The number of lighter and heavier particles reporting to the two streams was counted and the separation efficiency was calculated. The experiments were done as per the full factorial design and the results were analyzed using ANOVA soft computing system. A statistical package STATISTICA was used for the analysis of the data. In addition, tests for the significance of the effects of pertinent variables in the model were performed via the Wald statistic,which is computed as the generalized inner product of the parameter estimates with the respective variance-covariance matrix. It easily computes the efficient statistic for testing the significance of effects of various variables. The significant variables and interactions and their effect on separation efficiency were studied. This procedure was followed in all the experiments conducted at different levels of design and operating variables.

RESULTS AND DISCUSSIONS

Experiments were carried out at various flow rates of feed and pressure conditions. In all the tests, it was found that the heavier particles always reported in the underflow. The separation of lighter particles, however, varied with the various conditions. Since the separation efficiency of the heavier particles to the overflow was always zero, it was decided that the analysis would focus only on the separation efficiency of the lighter particles to the overflow. The ANOVA analysis of the tests is given in Table 3. Results indicate that out of the various variables studied, the effect of air core was found to be the most significant parameter. The interactions between the type of air core and Ho/Hi, cyclone design and inlet design were found to be the most significant. In all the cases, the effect of the variables and interactions on the % of particles reporting to the overflow was studied.

1. Effect of Air Core

The effect of air core on the separation of lighter particles to the overflow is shown in Fig. 5. The figure shows that the separation efficiency of the lighter particles was very good before the formation of air core. The separation efficiency dropped with the formation of the air core, reaching a minimum when good air core was formed. The separation efficiency again increased when the air core was suppressed.

Table 3. ANOVA results for the test work

Effect	Degrees of freedom	Sum of squares	P statistics
Inlet design	2	2.0977	0.350335
Cyclone design	1	1.6346	0.201073
Ho/Hi	1	0.0133	0.908125
Nrei	1	0.2292	0.632117
Type of air core	3	145.4273	00000
Cyclone design*inlet design	2	2.3191	0.313625
Inlet design*Ho/Hi	2	1.2916	0.524235
Cyclone design*Ho/Hi	1	0.1537	0.695059
Inlet design* Nrei	2	0.3928	0.821698
Cyclone design*Nrei	1	3.1682	0.075087
Ho/Hi* Nrei	1	0.3213	0.570862
Inlet design*type of air core	6	31.6386	0.000019
Cyclone design*type of air core	3	14.4974	0.002301
Ho/Hi*type of air core	3	8.73	0.033105
Nrei*type of air core	3	3.9836	0.263249

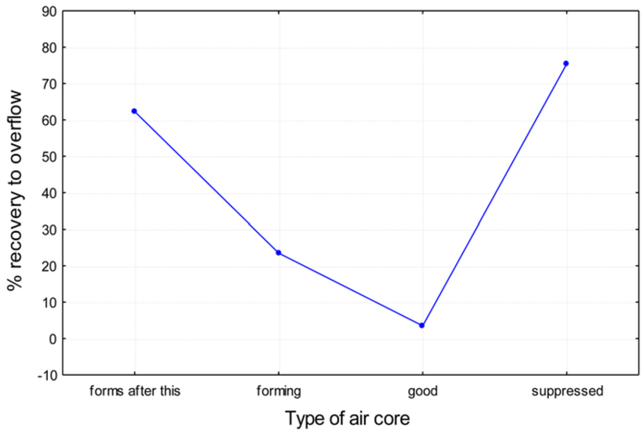

Fig. 5. Effect of the type of air core on % recovery to overflow.

2. Interaction Effects

Type of air core as a function of Ho/Hi greatly influences the separation efficiency. It was found that the ratio to be maximum when the air core was suppressed. Ho/Hi above 2 was found to give marginally better separation (Fig. 6), indicating that the vortex finder should be inserted to a depth well below the inlet of the feed stream.

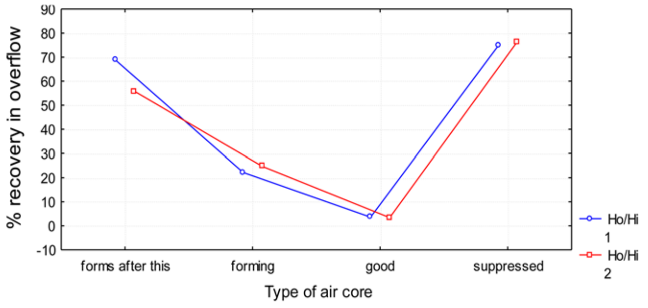

Fig. 6. Effect of Ho/Hi* type of air core on the % of near gravity lighter particles reporting to overflow.

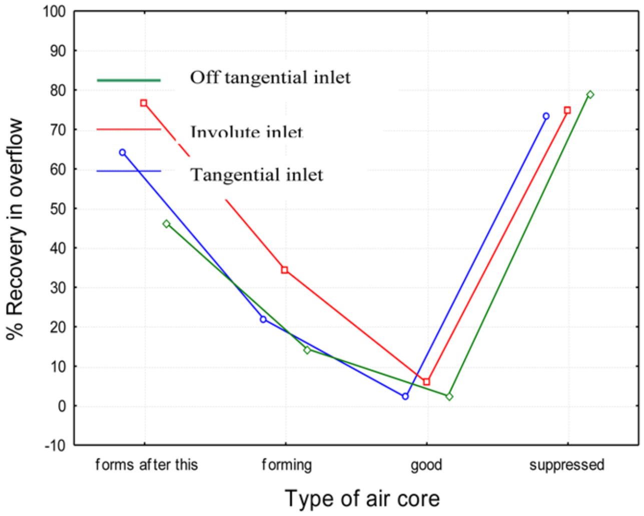

Fig. 7. Effect of inlet design type of air core on the % of near gravity lighter particles reporting to overflow.

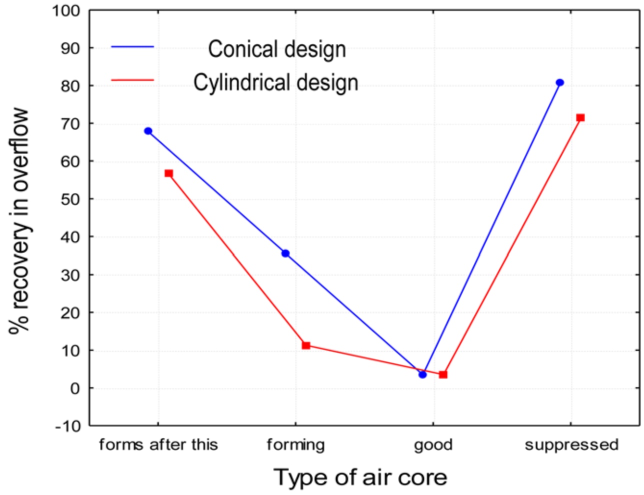

Fig. 8. Effect of cyclone design type of air core on the % of near gravity lighter particles reporting to overflow.

Type of air core on cyclone design: the cylindro-conical design was found to give the best separation efficiencies, again when the air core was suppressed (Fig. 7).

3. Type of Air Core Inlet Design

The difference in performance amongst the three inlets was marginal. The studies clearly showed that the separation of lighter particles was better when the air core was suppressed (Fig. 8). The air core zone basically represents useful area in the cyclone that could have been effectively used for separation. Interestingly, as the space is occupied by the air core the zone remains a dead zone, not contributing to particle separation in any useful manner. By suppressing the air core, the radial and the tangential velocities of the region change completely, facilitating the faster removal of lighter particles. This effect may be due to the fact that the change in flow split and pressure drop occurs, which results in faster separation and is discussed elsewhere [12].

The effect of air core on particle separation can also be explained by using a simple force balance equation on the particle separating in a cyclone with air core. In addition to the centripetal force, the buoyant force, and the drag force, the particles are also acted upon by another extra force, which is the pressure force due to air core, that pulls the particles down irrespective of their relative density. The pressure force can be calculated by multiplying the pressure drop occurring at the air fluid interface of the air core with the area of the air core.

Hence, force balance for particle separation in cyclone with air core:

- Net acceleration in positive ‘x’ direction+centripetal force–buoyant force–drag force+pressure force due to air core=0
- $m_p*Ur^2/r+m_p*v_t^2/r-m'v_t^2/r-.055\Pi Dp^2\rho_f$+pressure force due to air core=0

Solving for Ur

$$U_r=\sqrt{\frac{((\rho_f-\rho_p)*4/3*\Pi*r_p^3*v_t^2/r-\text{pressureforce})}{4/3*\Pi*r_p^3*\rho_p/r-.055\Pi D_p^2\rho_f}}$$

Assuming constant r, V_t and r_p

$$U_r = \sqrt{\frac{((\rho_f - \rho_p)*\mathrm{k1} - \text{pressure force})}{\mathrm{k2}*\rho_p - \mathrm{k3}\rho_f}}$$

It can be seen that the forces that determine the separation are the relative densities of the particles, the fluid and the pressure force. Three situations can be considered:

For a constant pressure force,

when ρ_p is very small, $\rho_f - \rho_p$ is bigger and the pressure force is relatively insignificant.

As ρ_p increases and becomes equal to ρ_f, pressure force becomes more and more significant

If the ρ_p is very big, then

$\rho_f - \rho_p$ is bigger (though negative) and pressure force is relatively insignificant.

It can thus be concluded that

- For particles that are very light and very dense compared to the relative density of fluid, the effect of air core becomes negligible.
- As particle density increases, the effect of air core becomes significant.

To confirm the findings, the tests were extended to include different combinations of different density particles. The basket of particles contained lighter particles (R.D 0.28), near gravity lighter particles (R.D 0.93), near gravity heavier particles (R.D 1.03), and heavier particles (R.D 1.56). The tests were carried out as discussed in the previous section.

An index called separation efficiency was defined:

$$\text{Index} = \frac{\text{Number of particles of a particular relative density reporting to the overflow}}{\text{Total number of that relative density particles in feed}}$$

The results of the tests are summarized in Table 4. The effect of air core reduced when the density differential increased, and it became significant as the relative density of the particles approached that of the fluid. In all cases the separation efficiency improved with suppression of the air core.

It is interesting to note that a 45% removal efficiency was reported by Sripriya et al. [12], whereas with eliminating air core an improved removal efficiency of 75% was achieved in the present case.

4. The New Design

The research findings and the concept have been used for designing a new dense medium cyclone with suppressed air core. The study assumes significance for the washing of high ash Indian coals which have higher quantities of near gravity material.

CONCLUSIONS

For the first time, a new cyclone design has been conceptualized, designed and fabricated. The performance on efficiency for particle separation based on gravity has been investigated. Test work has been carried out using design of experiments and the results have been analyzed statistically. The results have shown that suppressing the air core improves the separation efficiency of the hydrocyclone. Efforts have been made to explain the mechanism through a simple force balance equation. It has been concluded that the air core has a significant effect on particle separation as the relative density of the particles approaches to that of the fluid. As the density differential becomes larger, the effect of air core becomes negligible. This has again been validated through tests using tracers. The study has led to the development of a new design of dense medium hydrocyclone that will improve the separation efficiency of the hydrocyclone by separating the near gravity particles more efficiently.

NOMENCLATURE

m_p : mass of the particle

Table 4. Results of test work with different combinations of density tracers

Test 1	Relative density of particles	Separation efficiency with air core	Separation efficiency without air core
	0.97	1.86	16.7
	1.03	1.85	1.85
	1.57	0	0
Test 2	Relative density of particles	Separation efficiency with air core	Separation efficiency without air core
	0.97	1.86	20.4
	1.03	3.7	0
Test 3	Relative density of particles	Separation efficiency with air core	Separation efficiency without air core
	0.97	5.6	18.5
	1.57	0	0
Test 4	Relative density of particles	Separation efficiency with air core	Separation efficiency without air core
	0.28	39	100
	1.03	1.85	1.85
Test 5	Relative density of particles	Separation efficiency with air core	Separation efficiency without air core
	0.28	50	100
	1.57	3.7	1.9
Test 6	Relative density of particles	Separation efficiency with air core	Separation efficiency without air core
	0.28	13	48.1
	0.97	5.6	9.3
	1.03	3.7	0
	1.57	0	0

U_r : radial velocity of the particle
r : radius/position occupied by the particle at any point
r_p/D_p : radius/diameter of the particle
v_t : tangential velocity of the particle
ρ_f : density of fluid
ρ_p : density of particle

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