Investigation on the effects of major design and operating variables on water partitioning behaviour in hydrocyclone

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Abstract

It is well known that particle separation characteristics in a hydrocyclone is strongly influenced by the water partitioning behavior. Therefore, an attempt has been made to quantify the effects of four major variables - spigot diameter, vortex finder diameter, feed inlet pressure and vortex finder length on water partitioning in hydrocyclone. For this purpose systematic experiments were carried out with a 76 mm hydrocyclone at various operating conditions. The study reveals that out of those four variables only spigot diameter and vortex finder diameter play significant role whereas, in contrary to the literature, feed inlet pressure and vortex finder length have marginal effect on water split. Regression analyses of the data reveal that both spigot diameter and vortex finder diameter have equal impact on the water split in hydrocyclone. Mechanistic arguments have also been provided in support of the trend of the data observed.

Keywords: Water split; Spigot diameter; Vortex finder diameter; Hydrocyclone; Modeling

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Introduction

Hydrocyclones are used as a classifier in mineral processing industries. This device has a lot of advantage like continuous operation, less floor space requirement, low maintenance cost, no moving part, ease of operation etc. The hydrocyclone consists of a conical shaped vessel, joined to a cylindrical section, which has a tangential feed inlet. There are two axial product outlets, the spigot is situated at the apex of the conical part and the vortex finder is located at the upper end of the cylindrical section and contains a tube extending into the hydrocyclone, known as vortex finder length. This is a dynamic particle separation unit, which utilizes centrifugal force to enhance the relative settling velocity differentials between the particles.

The performance of a hydrocyclone is evaluated based on a partition curve. This curve is drawn based on the calculation of recovery of different particle sizes in a particular product stream in relation to their relative percent availability in the feed. The cut size or separation size is defined as the size for which 50 percent of the particles in the feed will report to the underflow and usually referred to as d_{50} size.

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Despite of several advantages associated with hydrocyclones, the inability to classify particles at a given cut size consistently is the major disadvantage with them. The inefficiency is mainly due to the misplacement of significant amount of fine particles through underflow. Lynch and Rao (1975) have concluded that the recovery of relatively finer particles in the cyclone underflow is directly proportional to the water recovery through underflow. This suggests that water split behavior in a hydrocyclone influences its classification efficiency.

Therefore, many correlations (Abbot, 1962; Lindner, 1956; Moder and Dahlstrom, 1952; Plitt, 1976; Stass, 1957; Yoshioka and Hotta, 1955) have been developed to predict the water split in hydrocyclone. All these models are empirical in nature and therefore, the actual mechanism of water partitioning behavior in a hydrocyclone is yet to be understood properly. It may also be observed that majority of the models developed so far use cone ratio (ratio of spigot diameter and vortex finder diameter) as one of the model parameters. Use of cone ratio as a variable may be misleading (Shah et al, 2006) because the ratio may be kept constant by changing appropriate dimensions of spigot and vortex finder diameter but their effects are bound to be different.

Castro (1990) found that the water split is mainly controlled by the air core size and, therefore, the water split is governed by those operating conditions and variables which affect the air core. In literature, it is found that the vortex finder diameter (VFD), spigot diameter (SPD) and feed inlet pressure (P) are the three major variables, which affect the water split behavior in cyclones (Verghese et al, 1994; Banerjee et al, 2003). As the effect of vortex finder length (VFL) has not yet been studied extensively on the water split behavior, an attempt has been made to do so. Therefore, systematic data was generated using a hydrocyclone test rig to understand the effects of these four variables on the water split behavior following one variable at a time procedure.

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Experimentation

A laboratory scale 76 mm diameter Mozley hydrocyclone made of polyurethane fitted in a closed circuit test rig used for experimental purpose. The schematic diagram of the test rig is shown in Figure 1. The rig consists of a feed water tank of a 200-liter capacity mounted on a stable platform. The bottom of the tank was connected to a centrifugal pump. The outlet of

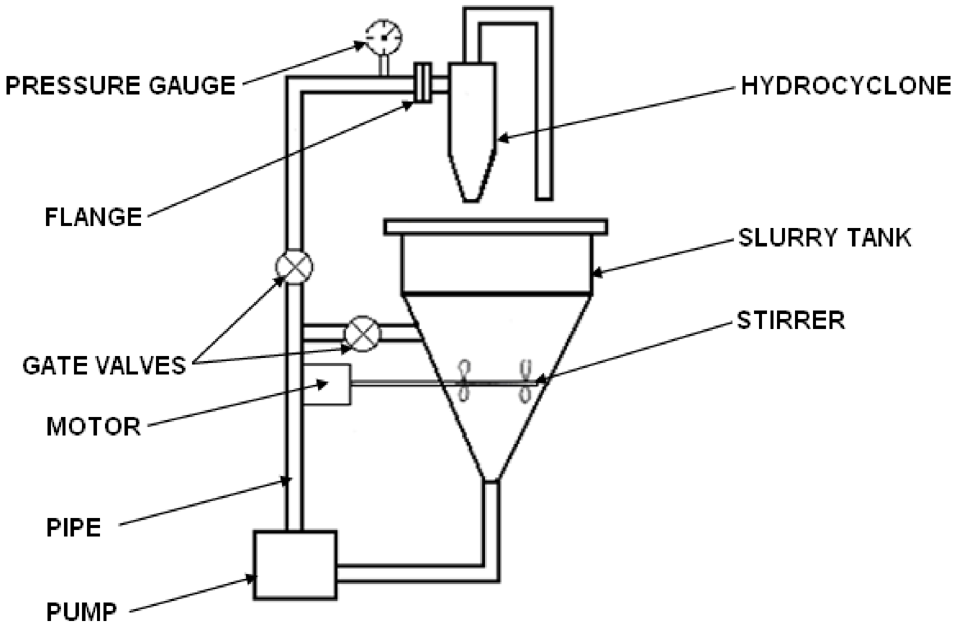

Figure 1. Schematic diagram of the test rig

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the pump was connected to the feed inlet of the cyclone. A by-pass pipe with a control valve was connected to the pump outlet line to maintain the required feed inlet pressure. A diaphragm type pressure gauge was fitted near the feed inlet of the cyclone to record feed inlet pressure. Flexible arrangements, using flange, were made to position the cyclone directly above the water tank.

During the experimental work with hydrocyclone, the overflow and underflow products were allowed to continuously discharge in to the feed water tank and thus were re-circulated. A product splitting arrangement fitted on the top of the feed tank enabled the collection of overflow and underflow water simultaneously.

The hydrocyclone used for the water split experiments is a locally fabricated one to have much more wider range of the variables to be studied than any commercially available hydrocyclone. The ranges of these variables used are presented in Table 1.

Table 1. Ranges of variables used for experiments with water

Sl. No.	Variables	Levels	Range of variables
1	VFD (mm)	4	16, 19, 22, 25
2	SPD (mm)	5	9, 11, 13, 15,17
3	P (psi)	4	10, 20, 30, 40
4	VFL (mm)	4	40, 42, 44, 46
Total Number of Experiments = 4 x 5 x 4 x 4 = 320			

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Total 320 experiments, one variable at a time, were carried out to understand the effect of each variable on the water split behavior in a hydrocyclone.

RESULTS AND DISCUSSION

It is well known that the size and the stability of an air core created inside a hydrocyclone depend on the intensity of pressure drop in between the conical and the cylindrical portion (Nowakowski et al., 2004). This is because the centrifugal force generated inside a hydrocyclone due to the tangential entry increases with decreasing cyclone diameter. The performance of an industrial hydrocyclone is generally controlled by using suitable spigot diameters keeping other variables unchanged. Any change in spigot diameter will, therefore, change the pressure drop. Again any change in spigot diameter also changes the inlet velocity of fluid as the nature of restriction at the hydrocyclone outlet changes automatically.

Similarly, any change in the vortex finder diameter and the feed inlet pressure also change the inlet velocity of fluid and as a result the pressure drop in between the conical section and the cylindrical section inside a hydrocyclone also changes. Any change in vortex finder length also changes the distance between the two discharge ends i.e. the distance between the vortex finder and the spigot.

It is imperative from the above discussions that water split behavior in a hydrocyclone is strongly influenced by the feed inlet pressure (P), spigot diameter (D_u), vortex finder diameter (D_o) and the vortex finder length (VFL).

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Therefore, the effects of the afore-mentioned variables on the water split behaviour at different operating conditions have been shown in the following graphs (figure 2 -5) and the general trends of the data have been explained based on the general understanding of working principles of a hydrocyclone. To calculate the water partitioning at each operating condition the following equation has been used:

% Overflow = [flow rate through vortex finder (Q_o) / Total flow rate] x100

Effect of Spigot Diameter (Du)

The variations of % overflow with spigot diameter at different vortex finder diameter at a given pressure shown in figure bellow. At different operating pressure the nature of the curve remains identical

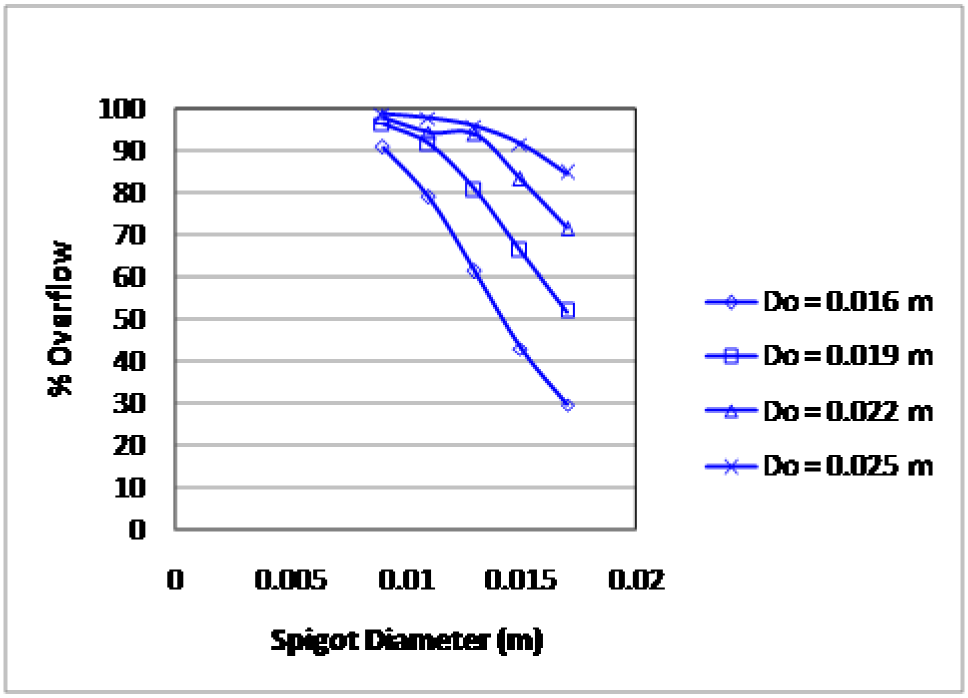

Figure 2: Effect of Spigot Diameter

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From the above figure it may be observed that at a constant feed pressure, vortex finder length and vortex finder diameter the % overflow decreases considerably with increasing spigot diameter. It may further be observed that at a constant level of other three variables studied, the % overflow increases with increase in vortex finder diameter. The trends of the data presented as above, can be mathematically expressed as:

$$R_{of} = K_1(D_u)^{n_1} \qquad (1)$$

Based on regression analysis, n_1 values are calculated and are presented in Table 2 below.

Table 2: Calculated Values of the Exponents (n_1)

Pressure (p) in PSI	**Vortex Finder Length (VFL) in mm**	**Over flow Diameter (Do) in m**	**Exponent (n_1)**
10	40	0.016	-0.22
10	40	0.019	-0.45
10	40	0.022	-0.95
10	40	0.025	-1.75
20	42	0.016	-0.14
20	42	0.019	-0.32
20	42	0.022	-0.76
20	42	0.025	-1.56
30	44	0.016	-0.12
30	44	0.019	-0.30
30	44	0.022	-0.72
30	44	0.025	-1.48
40	46	0.016	-0.10
40	46	0.019	-0.36
40	46	0.022	-0.49
40	46	0.025	-1.50

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From Table 2, it is interesting to note that the exponent value ranges from a minimum of 0.10 to a maximum value of 1.75. The negative sign represents the negative effect of Du on the % Overflow. This huge variation in the exponent value establishes the strong influence of Du on the % Overflow. Taking average for all the values of we get a value of - 0.70. Incorporating this value in Eq. (1) we may write

$$R_{of} = K_1(D_u)^{-0.70} \qquad (1a)$$

Effect of vortex finder diameter (Do)

The variations of % overflow with vortex finder diameter at different spigot diameter at a given pressure shown in figure bellow. At different operating pressure the nature of the curve remains identical

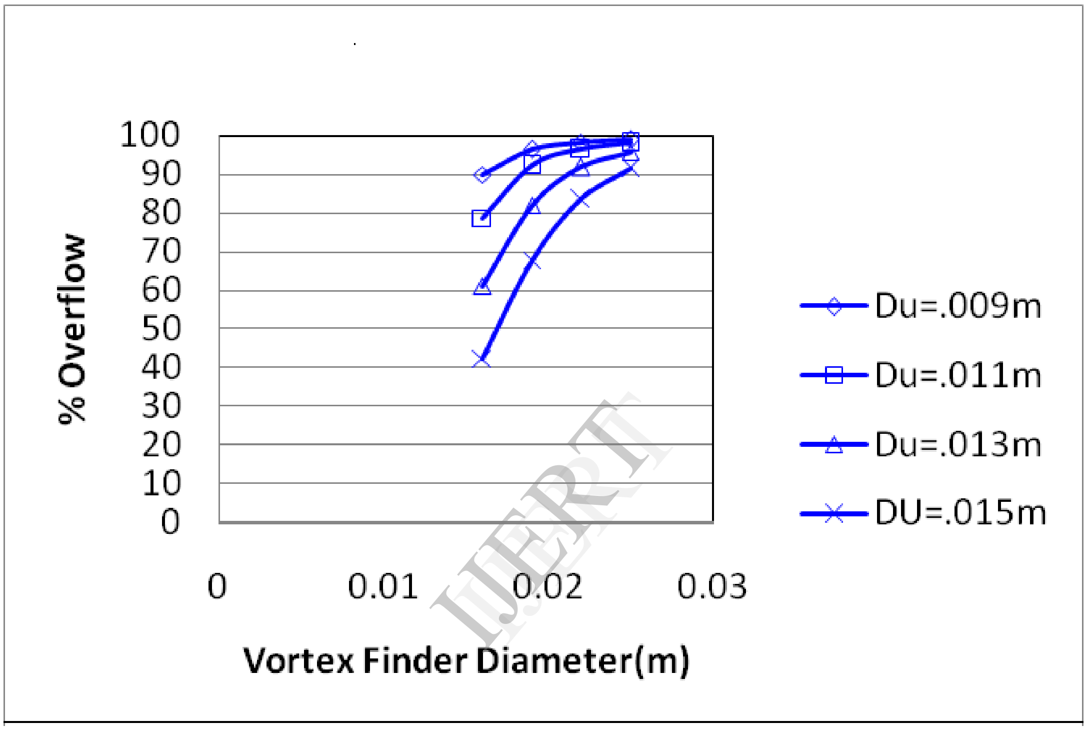

Figure 3: Effect of Vortex finder Diameter

The effect of vortex finder diameter on percentage overflow is shown in Fig. 3. To quantify the effect of vortex finder diameter on experimental data may, therefore, be expressed in an exponential form as

$$R_{of} = K_1(D_o)^{n}{}_2 \qquad (2)$$

The n_2 values are calculated by regression analysis, and are presented in Table 3 below.

Table 3: Calculated Values of the Exponents (n_2)

Pressure(p) in PSI	Vortex Finder Length (VFL) in mm	Spigot Diameter (Du) in m	Exponent (n_2)
10	40	0.009	0.117
10	40	0.011	0.315
10	40	0.013	0.812
10	40	0.015	1.442
20	42	0.009	0.121
20	42	0.011	0.317
20	42	0.013	0.810
20	42	0.015	1.372
30	44	0.009	0.171
30	44	0.011	0.319
30	44	0.013	0.749
30	44	0.015	1.378
40	46	0.009	0.109
40	46	0.011	0.290
40	46	0.013	0.688
40	46	0.015	1.307

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From Table 3, it may be observed that the exponent value ranges from a minimum of 0.109 to a maximum value of 1.442. This huge variation in the exponent value establishes as well the strong influence of Do on the % Overflow. Taking average for all the values of n_2 we get a value of 0.645. Incorporating this value in Eq. (1) we may write

$$R_{of} = K_2(D_o)^{0.645} \qquad (2a)$$

Effect of feed inlet pressure

The variations of % overflow with feed pressure at different spigot diameter at a given vortex finder diameter is shown in figure bellow.

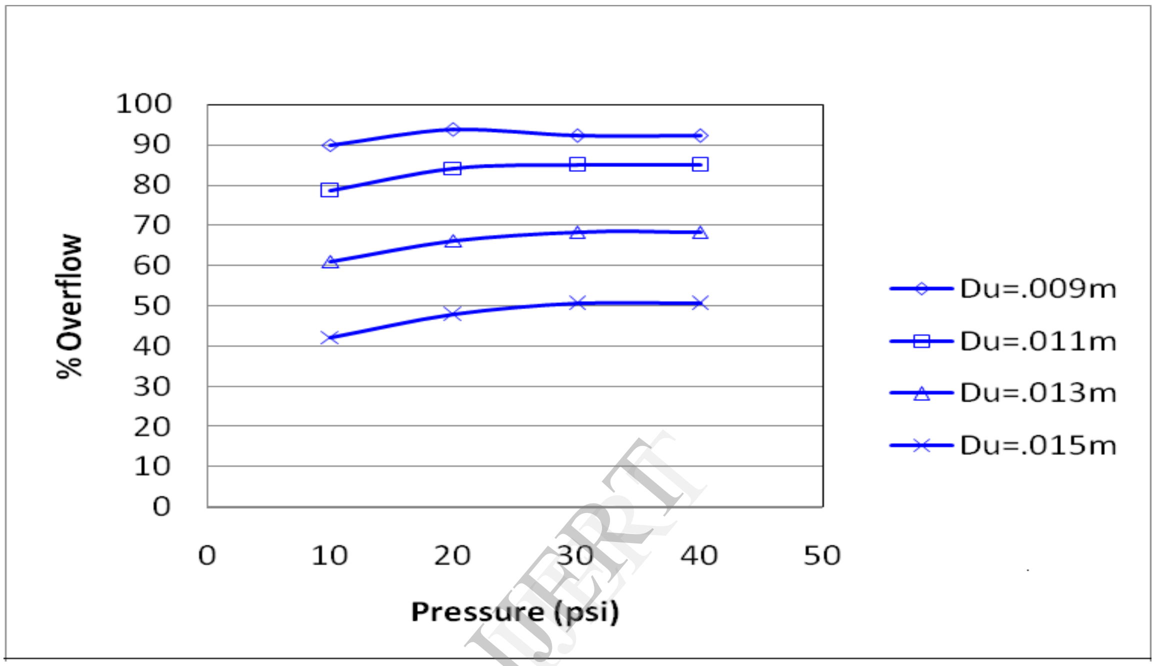

Figure 4: Effect of feed inlet pressure

From figure 4 it is observed that the % Overflow increases marginally with increasing feed inlet pressure at a constant Du and Do. As the variation in data is marginal, no attempt has been made to quantify the trends of the data observed.

Effect of vortex finder length

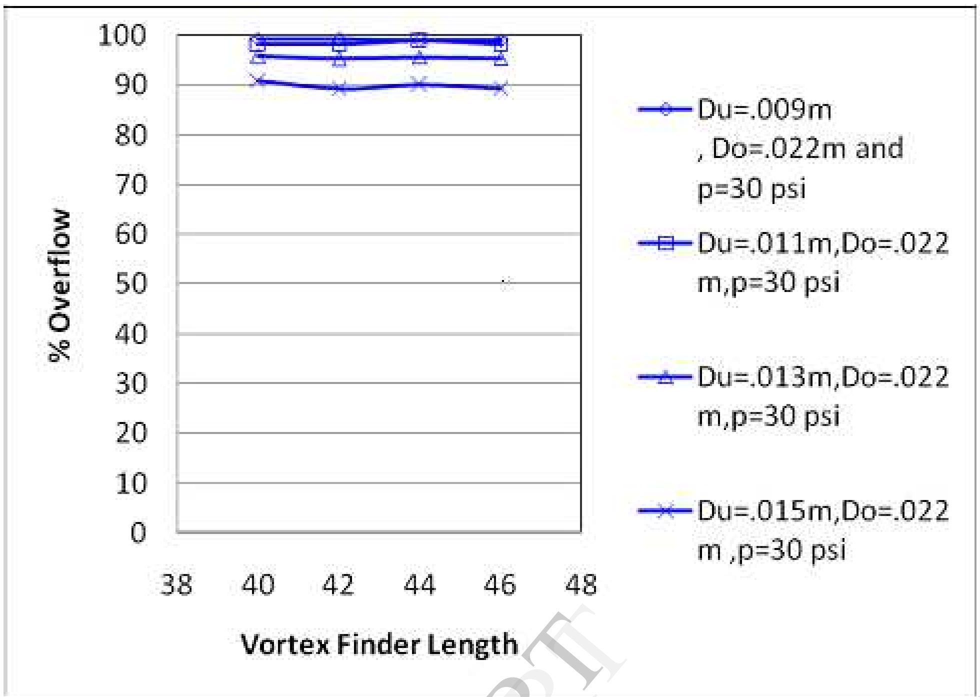

Figure 5: Effect of Vortex Finder Length

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It is also observed from the Figure (5) that the % Overflow increases marginally with increasing vortex finder length at a constant Du and Do and feed inlet pressure, P. As the variation in data is marginal, no attempt has been made to quantify the trends of the data observed.

From the above discussion it is interesting to note that amongst the four variables studied only Du and Do are the most sensitive variables causing water split in a classifying cyclone. However, the text books and the literature mention that feed inlet pressure and vortex finder length are also sensitive variables in controlling the water split behavior. An attempt has, therefore, been made here to provide possible justifications for this new observation.

The fluid, in this case it is water, enters the cyclone through the feed inlet tangentially at a high pressure which creates a swirling motion of the fluid inside. Water then tries to pass through the underflow opening. However, because of the swirling motion of the fluid and the cylindro-conical geometry of the hydrocyclone, huge pressure drop is developed automatically in between the underflow and the overflow openings because of the G-force differential in between these two regions which is a strong function of the internal diameter of the hydrocyclone. Due to this huge pressure drop created inside, air is sucked from the underflow opening to maintain equilibrium condition inside the hydrocyclone and as a result an inner spiral is developed which is referred to as air core in the related literature. The air thus sucked tries to escape through the overflow in a spiraling mode at a very high velocity which drags water to pass through the overflow as well. As there exists a pressure gradient inside a hydrocyclone because of the conical geometry in the bottom part the diameter of this air core also increases as it moves upwards. As a result the amount of water to be passed through the two outlets, underflow and the overflow, will depend on the pressure drop created and on the effective cross-sectional areas available through each outlet at a particular operating condition.

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Based on the above simple explanation of the water split mechanism it is imperative that the water split behavior in a hydrocyclone should be functions of the inlet velocity, cone angle and the outlet diameters. The hydrocyclone used for the experimental data generation had a feed inlet diameter of 10 mm throughout whereas the Du and Do values were varied from 9 mm to 15 mm and 16 mm to 25 mm respectively. This means that the inlet diameter was much less than the sum of the two exit diameters. Therefore, the inlet water velocity should ideally depend on the inlet diameter only but in reality it is just opposite to this common belief. Actually, the exit diameters i.e. underflow and overflow diameters, will be filled mostly with air when the hydrocyclone is operated at a reasonably high feed inlet pressure. As a result the sum of the effective exit diameters for water to pass through would be much less than the feed inlet diameter. This means that the feed inlet velocity is actually dependent on the effective exit diameters but not on the inlet diameter. As a result when the feed inlet pressure increases from an optimum value for a particular cyclone configuration, it will not increase the inlet velocity further as the increase in further inlet pressure will be due to back pressure only. Possibly due to this reason the change in % Overflow while changing the P at a constant levels of Du, Do and VFL is observed to be marginal at all the experimental conditions. This hydrodynamic explanation also establishes the strong dependence on the Du and Do of the % Overflow of water at various operating conditions.

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The distance between the two exits is actually dependent on the VFL when the other variables are kept at constant levels. Therefore, the amount of water to be lifted to the overflow opening i.e. Do should ideally depend on VFL. However, the effect of VFL should be evident only when the pressure drop between the two exits is much less than a critical value. To calculate this critical value is a challenging task, however, it is evident from the data presented that VFL has marginal effect in changing the % Overflow. This suggests that at all the operating conditions the pressure drop generated was above the critical value.

Conclusions

1. Out of four major variables - spigot diameter, vortex finder diameter, feed inlet pressure and vortex finder length only spigot diameter and vortex finder diameter play significant role in water partitioning.

2. Inlet pressure has little role to play in water split behavior. This is opposed to the conventional understanding of the water split mechanism as explained in the literature. Actually, feed inlet pressure controls the inlet water velocity which is dependent on the effective cross-sectional areas of the spigot and the vortex finder when the hydrocyclone is in operation. Therefore, the increase in feed inlet pressure beyond a critical limit will not increase the inlet water velocity further as the increase in inlet pressure beyond a certain limit will be due to back pressure only which will have no impact on inlet water velocity.

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3. Vortex finder length also does not affect much on the water split behavior.

4. Regression analyses of the data reveal that both spigot diameter and vortex finder diameter have equal impact on the water split in hydrocyclone.

Nomenclature

- Du Spigot diameter in meter
- Do Vortex finder diameter in meter
- Di fee inlet diameter in meter
- Dc cyclone cylindrical diameter in meter
- k_1,k_2 &k constants
- R_{of} percentage recovery in overflow
- Q_o water flow rate in overflow, kg/s
- Q_u water flow rate in underflow, kg/s

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