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Minerals Engineering 20 (2007) 349–354

MINERALS ENGINEERING

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Air core formation in the hydrocyclone

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Received 1 August 2006; accepted 15 January 2007
Available online 20 February 2007

Abstract

Air core formation has been investigated in hydrocyclones operated with clear water and a lucid suspension of glass balls. Hydrocyclones form a central air core which extends over the complete hydrocyclone length. Air is sucked in the core at the underflow discharge. The air core diameter can be determined balancing the positive pressure gradient and the centrifugal force in the rotational flow field. In dense flow separation (high feed solids content) the air core in the conical part of the hydrocyclone is suppressed. The hydrocyclone operates as it is air sealed because the solids are discharged trough the underflow as a rope. Then, air can be introduced to the hydrocyclone only on the feed side. In practice, feed suspension always contains more or less dissolved or dispersed air. Observations in a transparent hydrocyclone show that dissolved gas is released due to the pressure drop inside the hydrocyclone. The generated micro bubbles grow by coalescence and move in the centrifugal field toward the centre, where an air core is formed.

Keywords: Hydrocyclone; Classification; Modelling; Fine particle processing

1. Introduction

Air is the often the neglected third phase of the 3-phase flow in the hydrocyclone. The air core at the center of the hydrocyclone is an unavoidable phenomenon in the rotational flow field which does not directly influence the classification process in the apparatus. However, this is different in new applications of the apparatus to flotation (Puget et al., 2004) and to separations in multi-phase systems involving vapors and gases (Madge et al., 2004) where the air core plays a more active role. Furthermore, the geometry and movement of the air core were identified as being sensitive indicators of the operational state of hydrocyclones (Neesse et al., 2004a,b,c). Therefore, in recent years studies on the air core in hydrocyclones have been the subject of intensive research. At present, the knowledge on air core behaviour is limited and based mostly on observations in transparent hydrocyclones (Ternovsky and Kutepov, 1994). Air core monitoring using electrical impedance was carried out by Williams et al. (1995). Numerous data on air core diameters dependent on hydrocyclone parameters were collected and summarised in empirical and semi-empirical formulas by Abduramanov (1986), Barrientos et al. (1993), Castro et al. (1996), Davidson (1995), Povarov (1961) and Ternovsky and Kutepov (1994). However, only a few theoretical investigations on the subject were published by Dreissen (1951), Dyakowski and Williams (1995) and Steffens et al. (1993). Therefore, the complex process of air core formation starting from instabilities of the multiphase flow up to the stable air core remains poorly understood and described. Here, we report some recent findings providing new insights into this highly complex mechanism.

2. Air flow through the hydrocyclone

Fig. 1 presents schematically the air balance of the hydrocyclone. Generally, two ways of air input can be

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doi:10.1016/j.mineng.2007.01.007

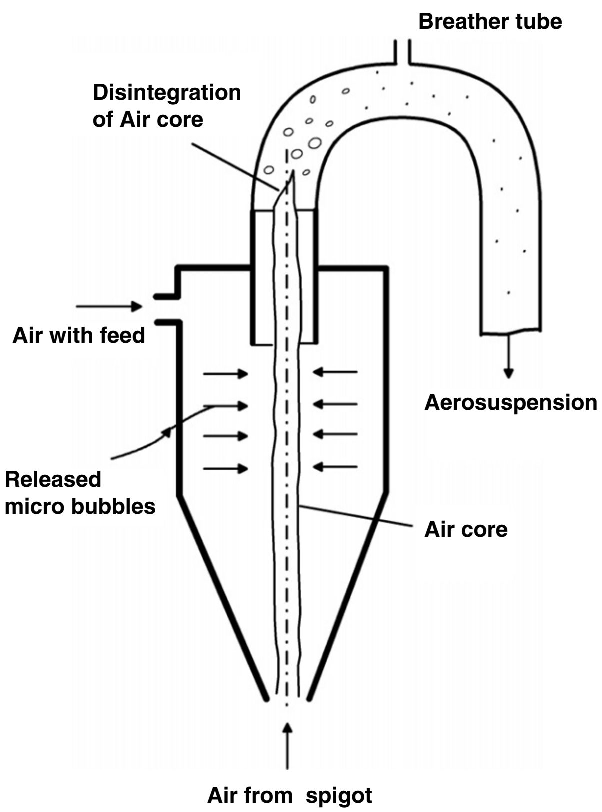

Fig. 1. Air balance in the hydrocyclone.

distinguished. In dilute flow separation (spray discharge in the underflow) air is sucked through the spigot to the centre of the hydrocyclone. However, also feed suspension always contains a certain amount of air in a dispersed or diluted form. As illustrated later, this amount of air also contributes to the air core formation.

The steady air input causes a continuous air flow through the core upwards to the overflow. In the overflow pipe the centrifugal force is reduced thus not enabling a stable air core further to exist. Hence, the air core is disintegrated to bubbles which are discharged with the overflow.

3. Air core formation in separation of dilute flow

If a suspension is pumped to a hydrocyclone the air core at the centre is formed due to the force balance in the flow. In dilute flow separation (low feed solids content) this air core extends over the complete length of the hydrocyclone ending as spray discharge in the underflow. This discharge shape can be described with the discharge angle α which has been computed by Neesse et al. (2004c) according to the following relation:

$$\alpha = \arctan\frac{v}{u} \approx \arctan\left[\frac{\rho_m \frac{D_u}{2} w^2}{\mu_m}\right].$$

Here, u, v, w are the axial, radial and tangential suspension velocities, ρ_m is the density, μ_m is the effective viscosity of

Table 1
The hydrocyclone and feed parameters for the computer simulation

Hydrocyclone diameter	150 mm
Inlet nozzle	25 × 80 mm
Vortex finder	72 mm
Depth of the vortex finder	100 mm
Wall thickness of the vortex finder	5 mm
Spigot diameter	38 mm
Length of the spigot	150 mm
Height of the cylindrical section	350 mm
Cone angle	18°
Feed pressure	1 bar
Solids content in the feed mixture	100–400 g/l
Maximum particle size in the feed	1 mm

the suspension and D_u is the spigot diameter. These quantities were computed at the spigot exit using the simulation of Dueck et al. (2000) which is based on the Navier–Stokes equations, considering the reaction of the solids content of the suspension on the flow parameters.

A spray discharge at the spigot exit can only exist if at this point the axial velocity is negative meaning, it is directed inside the hydrocyclone toward the overflow. This is a condition for air sucking through the underflow. The simulation at the spigot exit was conducted with the data of a 150 mm hydrocyclone listed in Table 1. As shown in Fig. 2 an air core at the spigot exit only occurs in dilute suspensions (solids content in the feed 100 g/l). At 400 g/l the axial velocity indicates positive values over the complete radius resulting in rope discharge. At the transition point the axial velocity oscillates around zero value and causes discontinuous air suction into the hydrocyclone.

3.1. Stable air core

Under stable conditions the air core is characterised by constant dimensions. The core diameter can be determined based on the radial pressure distribution in the hydrocyclone considering the radial projection of the Navier–Stokes equations at steady-state:

$$\frac{dp}{dr} = \rho_l \frac{v_\varphi^2}{r}. \tag{1}$$

where p is the pressure, ρ_l is the liquid density, v_φ is the tangential velocity and r is radial coordinate in the hydrocyclone.

Eq. (1) indicates that the positive pressure gradient is balanced by the centrifugal force.

The integration Eq. (1) leads to:

$$p(R) = p_{in} - \int_R^{R_c} \rho_l \frac{v_\varphi^2}{r} dr, \tag{2}$$

where p_{in} is the pressure at the inlet and R_c is the nominal radius of the hydrocyclone. The term $-\int_R^{R_c} \rho_l \frac{v_\varphi^2}{r} dr$ denotes the pressure drop between R_c and R.

In Eq. (1) for v_φ a semi-empirical relationship of Heiskanen (1993) or Ternovsky and Kutepov (1994) can be used:

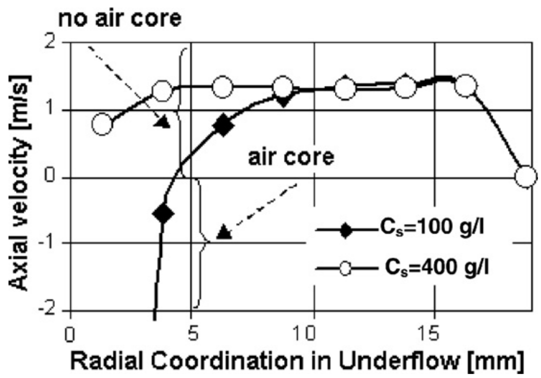

Fig. 2. Calculated axial velocity at the spigot exit of a 150 mm hydrocyclone.

$$v_\varphi(r) = v_w \left(\frac{R_c}{r}\right)^n, \tag{3}$$

where v_w is the tangential velocity at the hydrocyclone entrance. Heiskanen (1993) and Ternovsky and Kutepov (1994) determined the constant being $n = 0.8$.

Setting Eq. (3) in Eq. (2) and integrating from R_a to R_c and further, assuming that the pressure at the core boundary is equal to p_u yields:

$$\frac{R_a}{R_c} = \left[1 + \frac{2n}{\rho_l}\frac{p_{in} - p_u}{v_w^2}\right]^{1/2n}. \tag{4}$$

According to Joshioka and Hotta (1955), the tangential velocity v_w at the hydrocyclone entrance can be empirically approximated as follows:

$$v_w = 3.7\left(\frac{R_{in}}{R_c}\right)u_{in}, \tag{5}$$

with R_c, R_{in}, being the radii of the hydrocyclone and the feed nozzle, and u_{in} is the velocity at the inlet, which is determined by the hydrocyclone throughput Q according to the relation of Ternovsky and Kutepov (1994):

$$Q = \pi R_{in}^2 u_{in} = 4kR_{in}^2\left(\frac{R_o}{R_{in}}\right)^m \sqrt{\frac{p_{in} - p_a^*}{\rho_l}}. \tag{6}$$

where R_o is the overflow radius and p_a^* is the effective double pressure drop due to the two discharges of the hydrocyclone. Considering that the hydraulic resistance in the overflow normally being higher than in the underflow, it can be assumed: $p_a^* \approx p_o$.

According to Heiskanen (1993), Povarov (1961) and Ternovsky and Kutepov (1994) the empirical constants k and m depend on hydrocyclone geometry. As mean values $k = 0.27$ and $m = 1$ are representative.

Thus, from Eq. (6) yields $u_{in} = \frac{4k}{\pi}\left(\frac{R_o}{R_{in}}\right)^m\sqrt{\frac{p_{in}-p_o}{\rho_l}}$ and Eq. (5) changes to:

$$v_w = \frac{14.8k}{\pi}\left(\frac{R_{in}}{R_c}\right)\left(\frac{R_o}{R_{in}}\right)^m \sqrt{\frac{p_{in} - p_o}{\rho_l}}. \tag{7}$$

Combining Eqs. (7) and (4) leads to a dimensionless relation for the air core radius R_a as function of hydrocyclone radius R_c, inlet radius R_{in}, overflow radius R_o and the pressures in the spigot p_u and in the overflow p_o:

$$\frac{R_a}{R_c} = \left[1 + \frac{2n}{k_w^2}\left(\frac{R_c}{R_{in}}\right)^2\left(\frac{R_{in}}{R_o}\right)^{2m}\left(\frac{p_{in} - p_u}{p_{in} - p_o}\right)\right]^{-1/2n}. \tag{8}$$

With $k = 0.27$ the constant in the previous equation is $k_w = \frac{14.8k}{\pi} = 1.28$.

In case of high inlet pressure and free discharge $\left(\frac{p_{in}-p_u}{p_{in}-p_o} \approx 1\right)$ from Eq. (8) follows, that R_a depends only on geometrical parameters of the hydrocyclone:

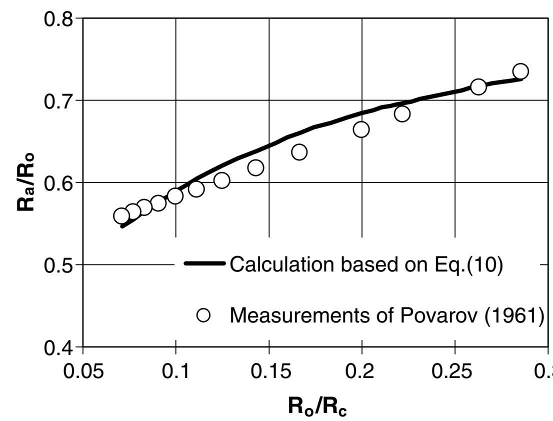

Fig. 3. Comparison of theoretically (Eq. (10)) and experimentally (Povarov, 1961) determined air core radii.

Table 2
The parameters of the hydrocyclone used for the air core measurements

Hydrocyclone diameter	75 mm
Inlet nozzle	18 mm
Vortex finder	25 mm
Spigot diameter	10 mm
Length of the spigot	150 mm
Height of the cylindrical section	300 mm
Cone angle	9°

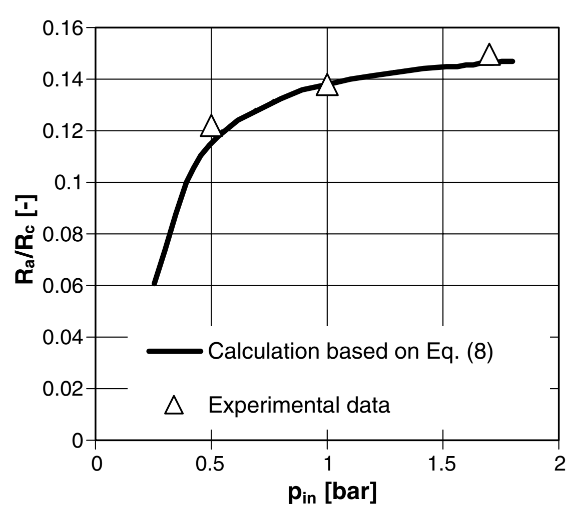

Fig. 4. Air core diameter in a 75 mm water hydrocyclone versus feed pressure ($p_0 = 0.2$ bar).

$$\frac{R_a}{R_c} = \left[1 + \frac{2n}{k_w^2}\left(\frac{R_c}{R_{in}}\right)^2\left(\frac{R_{in}}{R_o}\right)^{2m}\right]^{-1/2n}. \tag{9}$$

For $m = 1$ and $n = 0.8$ Eq. (9) can be converted to

$$\frac{R_a}{R_o} = \left(\frac{R_c}{R_o}\right)\left[1 + 0.975\left(\frac{R_c}{R_o}\right)^2\right]^{-0.625}.$$

The previous equation can be approximated as

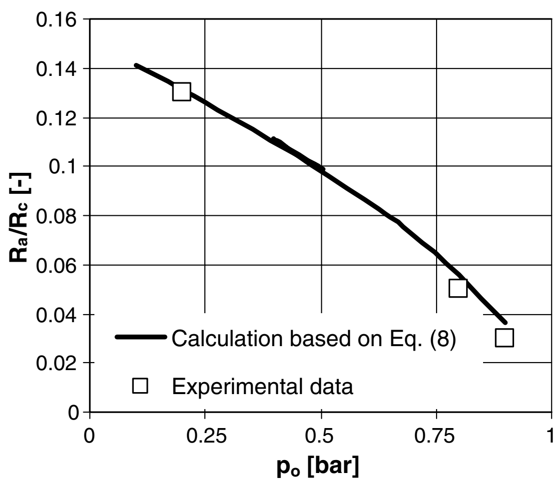

Fig. 5. The dependency of air core diameter in water hydrocyclone on pressure in the overflow ($p_{in} = 1.2$ bar).

$$\frac{R_a}{R_o} = 0.48 + 0.85\frac{R_o}{R_c}. \tag{10}$$

As can be seen in Fig. 3, calculated radii according to Eq. (10) correspond to the experimentally determined values of Povarov (1961).

3.2. Experiments

Air core measurements were accomplished at a transparent 75 mm polycarbonate hydrocyclone ($R_u/R_o = 0.4$, $p_o = 0.2$ bar) operated with water. The hydrocyclone parameters are listed in Table 2. Air core diameters were obtained by evaluation of scaled photographs. Measured and computed data of the air core diameter dependent on feed pressure and overflow pressure are depicted in Figs. 4 and 5. Fig. 4 illustrates the expected weak dependence of the air core radius on feed pressure. The experimental data of Fig. 5 confirm the increasing suppression of the air core with growing overflow pressure according to Eq. (8).

4. Air core formation in dense flow separation

Further experiments with the 75 mm hydrocyclone were conducted using a lucid suspension of 2 mm glass balls. Under these conditions the air core remains visible even in dense flow separation. Fig. 6a displays a fully developed air core for low solids concentration. In dense flow separation at high feed solids content (Fig. 6b) the hydrocyclone

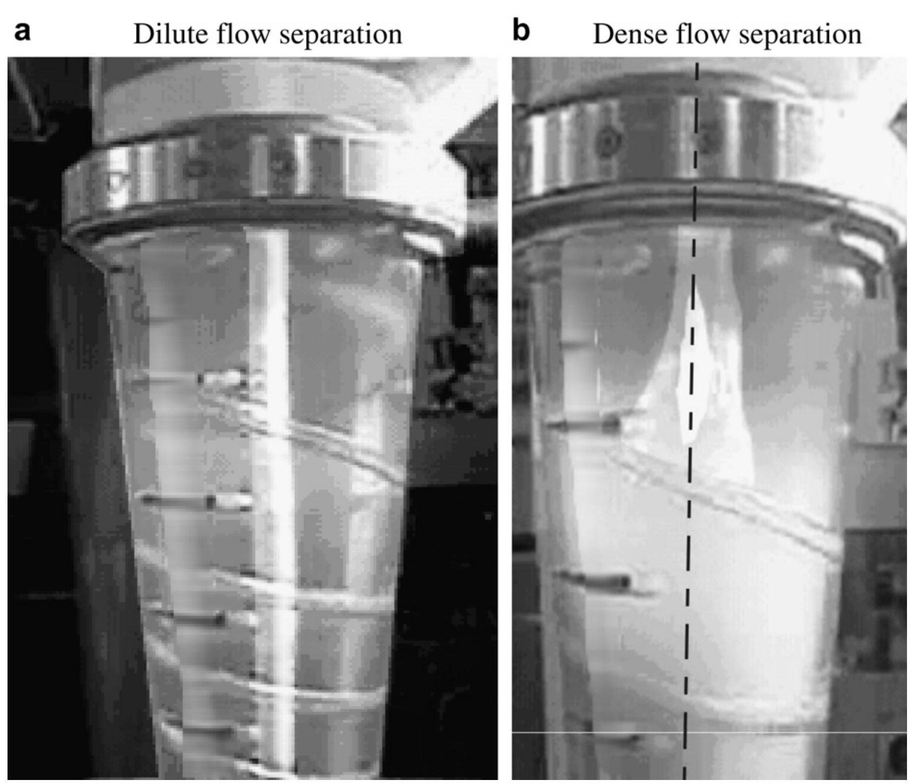

Fig. 6. Air core in the conical part of the hydrocyclone for a glass balls suspension in a 75 mm – hydrocyclone (inlet pressure $p_{in} = 2.0$ bar).

operates as it is air-sealed at the underflow. Consequently, the air core terminates in the sediment stored in the conical part of the hydrocyclone. Then, air can only penetrate to the hydrocyclone together with the feed flow. To examine this operational situation, a special experimental set up was used by Golyk (2006) which is sketched in Fig. 7. In a closed hydrocyclone circuit the discharges of overflow and underflow were immersed under the water surface of the pump sump. Therefore, no air penetrated the hydrocyclone from outside. Before starting the pump, the hydrocyclone was filled with water. The question was whether an air core can develop under these conditions. As shown in Fig. 8, a small bubble column became visible in the centre of the hydrocyclone shortly afterwards. Eventually these bubbles are combined (Fig. 8d and e) to form a small diameter-air core. This process can be explained as follows:

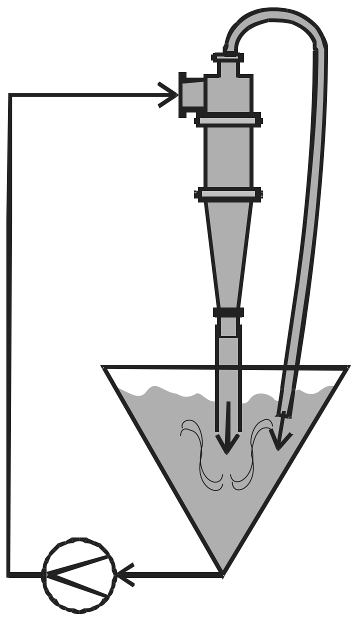

Fig. 7. Experimental set up for air core observation with air sealed discharges of overflow and underflow.

Usually, technical suspensions fed to a hydrocyclone contain a certain amount of air in a diluted form and/or as micro-bubbles. According to Eqs. (2) and (3) a radial pressure drop exists inside the hydrocyclone:

$$\frac{p}{p_{\text{in}}} = 1 - \frac{\rho_L \cdot v_w^2}{2np_{\text{in}}}\left[\left(\frac{R_c}{r}\right)^{2n} - 1\right].$$

Due to this pressure drop according to the Henry-law air bubbles are generated in the hydrocyclone. The radial bubble transport leads to bubble enrichment and bubble growth due to coalescence (Fig. 8a and b). Thus, at the centre single core legs (Fig. 8c and d) are produced which finally unify to a small diameter – air core (Fig. 8e).

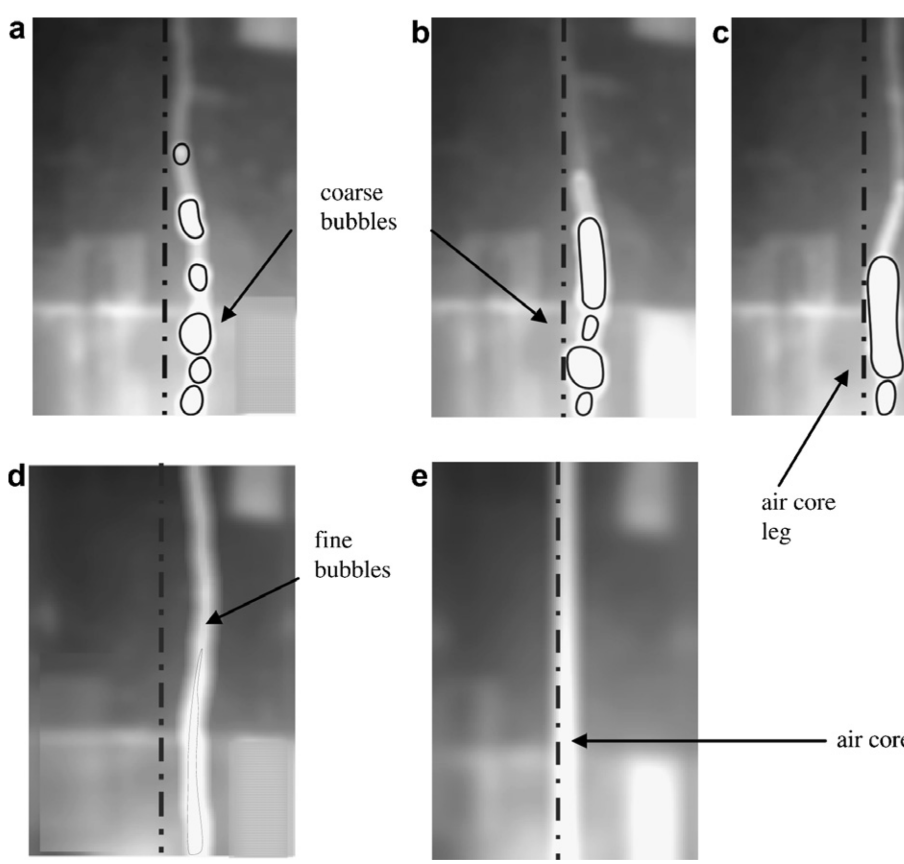

Fig. 8. Air core formation in the hydrocyclone starting from an air suspension.

Due to the stochastic character of bubble coalescence in turbulent flow, the air core is not strongly centred. As can be seen in Fig. 8 at the central line, the radial air core movement is characterized by random eccentricity.

5. Conclusions

Geometry and movement of the air core are sensitive indicators of the operational state and can be used in hydrocyclone monitoring. The air core radius can be estimated based on the Navier–Stokes equations assuming the force equilibrium between pressure gradient and centrifugal force at the boundary liquid–gas. This physical consideration leads to Eq. (8) which indicates that the air core radius is primarily determined by the hydrocyclone geometry. Of practical interest is the question under which conditions the air core could be suppressed. According to Eq. (8) this can be obtained by increasing the pressure in the overflow. To note, the standard operating conditions are not taken in account here. However, this may be the case under special circumstances, i.e. if the hydrocyclone operates against pressure in a reactor downstream or if the overflow is discharged above the level of the overflow nozzle resulting in a hydrostatic backpressure. The air core and the continuous air flow through the apex are interrupted if at high solids content the underflow is discharged as a rope. Then, the air core in the apex region is suppressed. Nevertheless, even under these conditions an air core may exist or might even be formed. Moreover, one has to consider that air not only penetrates the apparatus through the underflow but also through the feed nozzle. In practice every feed suspension contains a limited amount of air in a diluted form or as micro bubbles. First of all, feed air causes the well known twitching movement of the fully developed air core. Additionally, under roping conditions feed air may even form an air core. A special experiment confirmed this process resulting in an air core of special state. The movement of this small diameter-core is characterized by random eccentricity. This phenomenon affects hydrocyclone vibration and can be used in the monitoring of the apparatus.

To conclude, air core formation by feed air is a novel finding which underlines the expectation that in normal functioning hydrocylones the total suppression of the air core seems to be impossible.

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