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Performance monitoring of a hydrocyclone based on underflow discharge angle

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ABSTRACT

The performance of a hydrocyclone as a separation device is never perfect and rigorous research efforts are still continuing along various directions towards achieving optimum solutions. The modus operandi of performance optimization is important for quick and non-invasive monitoring of hydrocyclone performance. Therefore, in the present study, an application potential of spray angle as a performance monitoring tool has been explored to investigate the operation state of a hydrocyclone. In this context, phenomenological features of spray discharge over a wide range of injection pressure and feed solid concentration have been investigated. The emphasis of the present study is to verse the amendment of the hydrocyclone operational state with the corresponding change in underflow discharge pattern. The pattern of the underflow discharge profile was captured using a digital camera and analyzed based on an image processing algorithm to detect the discharge angle under different operating and design conditions. Stability and reproducibility of the spray angle at fixed operating condition have also been confirmed. Subsequent analysis shows that the spray angle is sensitive to variations of operating and design variables. More specifically the effect of feed slurry concentration has been characterized and is of major importance for the transition to roping. On this basis, an attempt has also been made to develop an empirical correlation based on experimental data. The developed correlation shows that the discharge angle could possibly be used as a reliable tool to monitor hydrocyclone performance.

1. Introduction

It has been long advocated that spray angle can be used as a performance monitoring tool for hydrocyclone. Various works have also been carried out in the past which indicate the significance of using underflow discharge pattern as one of the most important process control technique as an alternative to various empirical (Marlow, 1973; Lynch and Rao, 1975; Plitt, 1976; Nageswararao, 1978; Castro, 1990) and theoretical (Hsieh and Rajamani, 1991; Barrientos and Concha, 1992; Monredon et al., 1992) modeling techniques, which suffers from inherent limitations of their own (Neesse, Schneider, Dueck, et al., 2004a; Neesse, Schneider, Golyk and Tiefel, 2004b; Petersen et al., 1996; Van Deventer et al., 2003). Industrial application of using spray angle as an indicator is also advantageous as the spray pattern is easily visible and spigot diameter is the only design variable which can be easily replaced.

Using the underflow discharge angle as an indicator for monitoring the performance of a hydrocyclone, it was imperative to convert the discharge pattern from the underflow of a hydrocyclone in a quantifiable parameter. Various attempts were made in the past to achieve similar conclusions using various mathematical, theoretical and visualization techniques. Van Deventer et al. (2003) and Neesse, Schneider, Dueck, et al. (2004a) proposed that the flow geometry of the spray discharge arises from velocity pattern at the outlet orifice of the underflow. To calculate the spray angle, simulated values of the radial, axial and azimuthal velocities at underflow exit were used. An attempt was made to develop a tool to control underflow discharge using a two-dimensional electrical impedance tomography (Williams et al., 1997). A technique, based on the measurement of the pressure exerted by the underflow to monitor the spray angle was proposed (Viljoen, 1993). Petersen et al. (1996) and Van Vuuren et al. (2011) also made attempts to measure spray angles and spray width respectively using image processing techniques. Spray angle is an important factor to be considered when investigating spray shape in a pressure swirl atomizer. It was calculated using 'Image J software' and was further linked with design and operating variables (Rashid et al., 2012). However, none of the above-mentioned techniques have found the day of light in industrial application probably due to lack of versatility and huge financial aspect associated. The method we propose, has more prospects for industrial implementation due to its limited cost and the technology required is simple.

An image processing based algorithm on MATLAB™ platform to quantify the discharge profile in terms of spray angle in a 2-inch Tega hydrocyclone running with water only was demonstrated by

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Nomenclature

A	*level of significance*
A_c	*Effective cross sectional area for underflow* (m^2)
A_i	*Feed inlet area* (m^2)
B/P	*Bypass flow*
d	*Equivalent diameter of inlet (m)*
d_a	*Air core diameter in the spigot region (m)*
D_o	*Vortex finder diameter (m)*
D_u	*Spigot diameter (m)*
k	*No of independent variable*
K,a,b,c,d	*Constants*
n	*No. of observation for each k*
P_g	*Pressure gauge*
Q_i	*Feed inlet volumetric flow rate* ($m^3.s^{-1}$)
Q_u	*Underflow volumetric flow rate* ($m^3.s^{-1}$)
R_S	*Fraction of feed solid to underflow*
R_f	*Fraction of feed water to underflow*
R_V	*Volumetric recovery of slurry to underflow w.r.t. feed*
Re_i	*Inlet Reynolds number*
U	*Overall head velocity* ($m.s^{-1}$)
u	*Velocity component in axial direction* ($m.s^{-1}$)
v	*Velocity component in radial direction* ($m.s^{-1}$)
v_i	*Feed inlet velocity* ($m.s^{-1}$)
V_1	*Feed inlet pressure control valve*
V_2	*Bypass valve*
w	*Velocity component in tangential direction* ($m.s^{-1}$)
x	*Axial velocity/overall velocity at the outlet*
y	*Angular velocity/(outlet radius X overall head velocity)*
z	*Air core radius/outlet radius at the outlet*

Greek letters

θ	*Underflow discharge spray angle (degree)*
λ	*Ratio of underflow pulp density to feed pulp density*
μ	*Viscosity of the inlet feed slurry(Pa.s) at 30 °C*
μ_0	*Viscosity of water(Pa.s) at 30 °C*
μ_u	*Viscosity of underflow slurry (Pa.s) at 30 °C*
ρ	*Density of the inlet feed* (kg/m^3)
$\varnothing$	*Volume fraction solids in feed*

Mazumdar et al. (2014). It was established that spray angle is stable and reproducible at a given operating condition to be used as an indicator for performance monitoring and control. It was further correlated and an empirical model was developed with variables affecting the formation of spray angle. It was concluded that the spray angle varies with the change in operating and design parameters with water only condition.

In view of the above, a systematical analysis of underflow spray angle as a performance monitoring tool in case of hydrocyclone running with slurry is investigated. Hence, an attempt has been made in the theoretical understanding of the hydrodynamics of spray formation and to confirm adaptability of the algorithm as described by Mazumdar et al. (2014) in the case of hydrocyclone running with slurry. The image processing based technique was then adopted to measure the underflow discharge angle of a hydrocyclone treating various concentrations of fine silica slurries. For fixed operating conditions, the spray stability has been demonstrated to establish the steady nature of the spray angle in Section 3. The change in the spray angle at different operating conditions is correlated with the process and design variables of the hydrocyclone affecting the spray formation. An empirical correlation has also been derived based on multivariate regression analysis and relevant statistical analysis has been discussed in brief to verify the developed model. In the end, the reliability of the empirical model developed has also been verified with random experimental data in Section 5. The detailed description of these forms the subject matter of this article.

2. Hydrodynamics of spray formation

Before going into the details of the experimental methodology and analogous observations, it is necessary to discuss in brief the hydrodynamic aspects of spray formation.

Mechanism of spray formation through pressure nozzles is a very popular and developed research topic in the fluid mechanics domain. The first atomizer spray angle equation was developed by Taylor, 1948 (Van Deventer et al., 2003),

$$Cos\theta = \frac{u}{U} = x + \frac{\sqrt{2}yz^2}{(1-z^2)^{3/2}}\left[\frac{1}{2}\left(\frac{1}{z^2}-1\right) + \ln(z)\right] \quad (1)$$

All parameters of this relation are defined in the nomenclature section. It has been inherently identified that the separation characteristics in a hydrocyclone are basically governed by the centrifugal action. In a hydrocyclone, fluid rotates about an axis and forms a spiral vortex which moves in the downward direction and near the spigot the fluid changes its direction and forms an inner spiral which moves in the upward direction along the axis of the cyclone. The characteristics of the vortex formed inside the hydrocyclone are a compound vortex combination of free and forced vortex also known as Rankine vortex. This consists of a rotational vortex core with constant angular velocity encompassed by an irrotational vortex.

The geometric features of the underflow discharge profile are essentially dependent on the patterns of exit velocity components. Two major features, the axial and azimuthal velocities are responsible in contributing to the resulting spray formation. However, in the spray condition the azimuthal velocity is in a direction perpendicular to the outlet. Visual inspection of hydrocyclone operation reveals that the pulp flow at the underflow exit in a predominantly tangential orientation (Van Deventer et al., 2003). At the spigot exit where spray forms the axial velocity is perpendicular to the tangential component.

The spray angle θ was mathematically described by an equation proposed by Neesse, Schneider, Dueck, et al. (2004a),

$$\theta = \arctan\frac{w}{u} = \arctan\left[\frac{\rho_m{}^{D_u}/_2}{\mu_m u}w^2\right] \quad (2)$$

In simpler terms, hydrocyclone separation process is accomplished with the highly turbulent swirling flow generated by the inlet fluid at high Reynolds number. As the fluid comes out of the spigot in the form of underflow discharge, particles compete with the amount of centrifugal force generated at the exit (azimuthal velocity), the axial flow and gravitational force. The lighter/smaller particles tend to follow the path dictated by swirling water, whereas the heavier/coarser particles are dominated by the gravitational force. Therefore, particle size distribution reporting to the underflow also affects the spray formation phenomenon. Another factor is the amount of water and solid reporting, also called underflow slurry density. Lesser water/more solid fractions will increase the dominance of gravitational force and spray will tend to follow the rope like discharge profile, whereas, in case of more water/less solid, swirling intensity will dominate resulting in a spray like discharge (umbrella shape). For this transition from spray like discharge to roping both the slurry density and viscosity (mixture equivalent viscosity) are important. This has been observed both in experiments and numerical simulations in the dense regime (Davailles et al., 2012). Geometric parameters as the diameter of the vortex and spigot will control the amount of water/solid reporting to underflow in combination with other operating and geometric parameters. Therefore, the underflow discharge pattern of a hydrocyclone is inherently associated with the intensity of fluid flow quantified in terms of inlets Reynolds number; feed solid concentration as well as the geometric configuration of the hydrocyclone. The detail dependency of each of