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Research Article

Simulation of Hydrocyclone Circuit

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ABSTRACT:
A hydrocyclone is a widely used equipment for solid-liquid separation process. The form of multiple hydrocyclone units connected together into a circuit form is also commonly found if the specific separation performance cannot be achieved by using a single unit alone. In general, a hydrocyclone circuit is normally designed by mass balance principle. Though the method and its effectiveness of the mass balance method are rarely reported in literatures. This paper focuses on the development and clarification of such method. It is found that, while the hydrocyclone's efficiency curve is assumed to be known, the required inputs for the calculation consist of volume flowrate, particle distribution, and fluid concentration. The calculation outputs are also these variables but for each hydrocyclone unit. The calculation results show that the developed method is able to predict the separation performance of the hydrocyclone circuit, especially if the fluid concentration at each stage is of interest, which is normally the case for actual industrial applications. The dependence between the fluid concentration and the volume flowrate also reflects the actual hydrocyclone circuit operation as the flow control valve is commonly used at different parts of the hydrocyclone circuit to adjust or control the circuit's separation performance.

Keywords: *Hydrocyclone Circuit, Separation, Simulation, Mass Balance*

1. INTRODUCTION

Among many other separation techniques or technologies, a hydrocyclone is one of the commonly found choices [1]. The hydrocylone can be used for solid-solid, solid-liquid, or liquid-liquid separations. This flexibility makes the hydrocylone a popular choice for the separation process in many manufacturing such as oil industry, mineral process, powder process and food manufacturing. The typical hydrocyclone unit has one inlet located on the side, and two outlets, one on the top and one at the bottom of the unit. The top outlet is generally called the overflow, while the bottom outlet is known as the underflow. The separation capability of the hydrocyclone relies on centrifugal force created by injecting mixture to the hydrocyclone in tangential direction. According to the Equilibrium Orbit Theory, large size particles within the mixture move outward to the hydrocyclone's wall and downward to the hydrocyclone's underflow. On the other hand, small size particles move toward the inner (air core) part of the hydrocyclone and upward to the hydrocyclone's overflow [1]. The hydrocyclone's geometries directly affect the separation performances or the efficiency of hydrocyclone, usually defined by solid recovery percentage, the ratio or percentage of the flowrate at the overflow and underflow as compared to the inlet flowrate, or many other forms. Therefore, some degrees of the separation performance can be achieved by changing or specifically designing the hydrocyclone's geometries [2].

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Another way to improve the separation efficiency is by connecting multiple hydrocyclone units into a circuit form. From a single unit with one inlet and two outlets, connecting two hydrocyclone units together can be constructed in many formats. The circuit structure can be in many formats and complex, especially when there are more hydroclyclone units involved. Williams [3] summarized the structure and its effectiveness of the commonly found hydrocyclone circuit formations. Aldrich [4] though suggested that there are only two types of circuit, namely a counter current circuit and multi-step circuit. The counter current circuit is commonly used for dewatering or increasing the mixture concentration, and the multi-step circuit is used for improve efficiency of hydrocyclone. Berthiaux and Dodds [5] proposed a Markov chains method to predict the separation characteristics (or efficiency or performance) of the hydrocyclone circuit. According to Berthiaux and Dodds's work, the separation characteristics of each individual hydrocyclone in the circuit must be previously known. For a hydrocyclone in general, the simplest form of the separation characteristic is presented by the probability of separating a specific particle size from the mixture. Therefore, the result of the Markov chains method can then only report the probability of each particle size to appear at each exit way. In general actual manufacturing process though, fluid concentration of the process mixture is a more useful characteristic for process control than the particle size within the process mixture. Therefore, the proposed Markov chains method might not be useful for real world applications unless other types of the separation characteristics, such as the fluid concentration, of each individual hydrocyclone is known. While the best way to identify the separation efficiency of the hydrocyclone is by laboratory testing, but for the real-world application, the separation efficiency is usually needed to be known or estimated prior to the hydrocyclone fabrication process. Therefore, mathematical models that can predict the hydrocyclone efficiency have been developed by many researchers [6-9]. It is found that the model proposed by Amini, Mowla, and Golkar [10], which is based on Li and Wang's model [8], relied on rather rational assumptions and the model also showed good agreements between the predictions and the experimentation results. While most of the hydrocyclone efficiency model developments have not much concentrated on the prediction of the fluid concentration at the hydrocyclone's exit ways, the fluid concentration, as mentioned earlier, is one of the important variables used for process control.

Based on the above reviews, this paper focuses on developing a method to simulate the separation performance of the hydrocyclone circuit. Especially, the type of circuit of interest here is the one that is used in tapioca starch manufacturing during dewatering process. The outline of the paper is the followings. The literature survey results about the hydrocyclone circuit simulation is presented in this section. The proposed hydrocyclone circuit simulation method is presented in section 2. The proposed simulation algorithm is then presented in section 3. Section 4 presents the resulted calculations based on the proposed method using parameters from the tapioca starch manufacturing process. Section 5 gives the conclusion of the paper.

2. Model Development

2.1 Separation efficiency model

The separation efficiency in the form of an efficiency curve is widely used when the performance of a hydrocyclone is discussed. This efficiency curve predicts the particle sizes within the mixture that would move downward to underflow. In particular, the y-axis of the efficiency curve shows probability presented in percentage 0 – 100% while the x-axis is the particle size diameter. A point on the efficiency curve then indicates the probability of particles with the particular diameter to move to underflow. Therefore, the efficiency model of the hydrocyclone is the mathematical model that is used to draw the efficiency curve. Based on initial reviews, the practically reasonable model is the one developed by Amini, Mowla and Golkar [10] shown in equation (1). Their model is based on Li and Wang's model, which was developed based on the equilibrium orbit theory. Based on the above model, the efficiency curve affected by the feed flowrate (Q_f), mixture viscosity (μ_f) and some geometries of a hydrocyclone. In particular, the feed flowrate affects tangential velocity inside the hydrocyclone, hence affects the separation efficiency. μ_f is the kinematic viscosity of the mixture and is directly related to the fluid concentration. n is an index parameter that concerns with the tangential velocity. The nominal value of n is 0.5-0.9 [10]. ρ_p and ρ_l is the density of particle and the density of the fluid respectively. d_p is the particle size diameter. h is the hydrocyclone's cylindrical high. r_2 r_1 and r is radial positions at center to cylindrical, center to vortex finder and center to maximum tangential velocity point, respectively. Finally θ_T is the number of rounds for the particle motion rotating inside the hydrocyclone. The equations (2) – (4) are used to estimate θ_T as proposed by Li and Wang [8].

$$eff = 1 - \exp\left(- \frac{(1-n)(\rho_p - \rho_l)Q_f^2 d_p^2}{18\mu_f h(r_2^{1-n} - r_1^{1-n})r^n(r_2 - r_1)} \right)\theta_T \quad (1)$$

$$\theta_T = \frac{2\pi(S+L)}{a} \quad (2)$$

$$L = 2.3D_O\left(\frac{D_C^2}{ab}\right)^{1/3} \text{ for } L \le H - h \quad (3)$$

$$L = H - s \text{ for } L > H - h \quad (4)$$

The above efficiency model considers only the tangential velocity effect, which is the main principle of separation. Though, in order to determine characteristic of the mixture at each exit, the axial velocity effect that conveys particle up or down then out from hydrocyclone must also be considered. The axial velocity can be represented by volume flowrate ratio which is the ratio of volume flowrate at underflow and the feed volume flowrate. So, the efficiency of the hydrocyclone at underflow can then be described by equation (5).

$$eff_u = (1 - \dot{Q}_V) \times eff + \dot{Q}_V \quad (5)$$

So, the overflow efficiency can then be described by equation (6).

$$eff_o = 1 - eff_u \quad (6)$$

As stated, the fluid viscosity is directly related to the fluid density. And for the mixture of solid-liquid, the viscosity of the mixture is found to be a function of the percentage of the dried solid in the mixture (*%DS*). Therefore, ther fluid viscosity here is simply described by equation (7).

$$\mu_f = f(\%DS_f) \quad (7)$$

Noting that, the above equation (7) is found by curve fitting with experimentation data.

2.2 Concentration calculation

The probability of particular particle sizes appearing at each exit is usually not a control variable for manufacturing process, but rather the flowrate and fluid concentration. The latter can be described or interpreted by *%DS*. Therefore, it is necessary to find relationship between *%DS*, the flowrate, and the estimation of the efficiency. The relationships between $\%DS_\alpha$ and $\%DS_f$ is

$$\%DS_\alpha = (C_{ratio\alpha}) \times \%DS_f \quad (8)$$

Here, α represents the subscript of underflow (u) or overflow (o). C_{ratio} is the factor that is created to predict the output $\%DS_\alpha$ when $\%DS_f$ is the input of hydrocyclone. Specifically, it is a ratio between the recovery percentage $\%R_\alpha$, which is a proportion of overall mass fraction for the output particles (i.e. overflow or underflow) and the overall mass fraction for the input particles of the hydrocyclone, and mass flow rate ratio $\dot{Q}_{M\alpha}$ [1].

$$C_{ratio\,\alpha} = \frac{\%R_\alpha}{\dot{Q}_{M\alpha}} \quad (9)$$

Knowing that the efficiency model is a function of particle sizes diameter, the particle sizes distribution in specific concentration of the kind of fluid of interest is now considered in order to find the recovery percentage. Here, it is found that the recovery percentage can be calculated by integrating the multiplication between number of particles known from the particle size distribution at the inlet and the efficiency of the hydrocyclone, divided by the integration of the number of particle at the inlet. The graphical representation of this assumption is shown in figure 1. From the figure, the mass of all output particles is represented by the area of the nominator curve, while the mass of all input particles is represented by area of the denominator curve. This calculation of the recovery percentage can then be written as the equation (10).

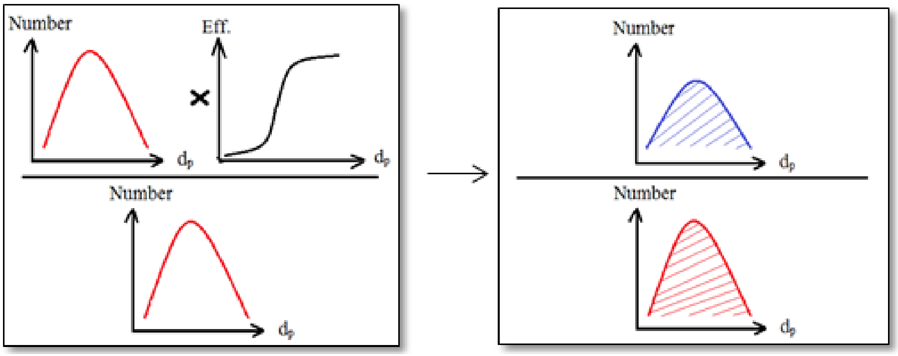


Fig. 1. Illustration of percent recovery.

$$\%R_{\alpha} = \frac{\int_{d_{p min}}^{d_{p max}} N_{f(dp)} \times eff_{\alpha} dd_p}{\int_{d_{p min}}^{d_{p max}} N_{f(dp)} dd_p} \tag{10}$$

The simple relationships between the mass flowrate and volume flowrate are,

$$\dot{Q}_{M\alpha} = \left(\dot{Q}_{V\alpha}\right) \times \frac{\rho_{\alpha}}{\rho_f} \tag{11}$$

$$\rho_{\varepsilon} = a\left(\%DS_{\varepsilon}\right) + b \tag{12}$$

Where, ρ is the fluid density, that has a direct relation with $\%DS$ as a linear function, a and b are constants depending on experimental data. All equations are rearranged by substituting equation (9) – (12) into equation (8), which the result shows an equation in quadratic form as,

$$a\left(\%DS_{\alpha}\right)^2 + b\left(\%DS_{\alpha}\right) = \frac{\int_{d_{p\min}}^{d_{p\max}} N_{f(dp)} \times act.eff_{\alpha} dd_p}{\int_{d_{p\min}}^{d_{p\max}} N_{f(dp)} dd_p \times \dot{Q}_{V\alpha}} \times \left(a\left(\%DS_f\right)^2 + b\left(\%DS_f\right)\right) \tag{13}$$

This equation can be written in a simpler form as,

$$a\left(\%DS_{\alpha}\right)^2 + b\left(\%DS_{\alpha}\right) - \Psi_{\alpha} = 0 \tag{14}$$

where,

$$\Psi_{\alpha} = -\frac{\int_{d_{p\min}}^{d_{p\max}} N_{f(dp)} \times act.eff_{\alpha} dd_p}{\int_{d_{p\min}}^{d_{p\max}} N_{f(dp)} dd_p \times \dot{Q}_{V\alpha}} \times \left(a\left(\%DS_f\right)^2 + b\left(\%DS_f\right)\right) \tag{15}$$

Therefore, equation (14) can be solved to find $\%DS_\alpha$ using simple quadratic solutions as shown in equation (16).

$$\%DS_\alpha = \frac{-b+\sqrt{b^2-4a\Psi_\alpha}}{2a} \tag{16}$$

2.3 Summation point

Interconnections among hydrocyclone units mean that the input of each hydrocyclone affects the next or is affected by the previous hydrocyclone. Figure 2 shows an example of the hydrocyclone circuit known as the multi-step classification circuit. Here, there are three hydrocyclones denoted by x, y and z and seven states that represent pipe connection of hydrocyclone circuit denoted by A, B, C … G. At the feeding of the hydrocyclone y, stages A, B and C are gathered. Based on the proposed model, each state has its own solution which are volume flow rate Q_{ST}, particle size distribution N_{ST} and concentration $\%DS_{ST,}$ where, ST is represent stage name (A, B, C … G.). So, properties of the mixture at this summing point are changed by mass balance principle as Eqs. (17) – (19).

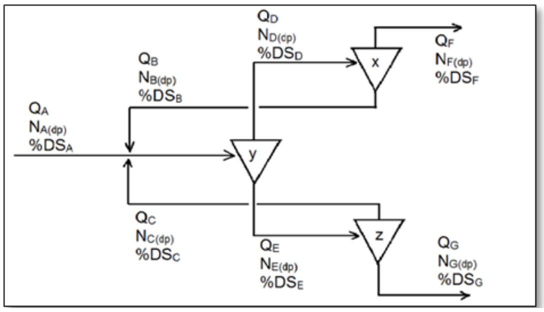


Fig. 2. Parameters at each stage.

$$Q_{sum} = Q_A + Q_B + Q_C \tag{17}$$

$$N_{(dp)_{sum}} = N_{A(dp)} + N_{B(dp)} + N_{C(dp)} \tag{18}$$

$$\rho_{sum} = \frac{\rho_A Q_A + \rho_B Q_B + \rho_C Q_C}{Q_A + Q_B + Q_C} \tag{19}$$

3. System Setup for Simulation

The example of the multi – step classification process, Figure 2, is shown here. The simple schematic showing interconnections among hydrocyclones is shown in Figure 3. There are six stages in this hydrocyclone circuit example. Here, all parameters Q_{ST}, N_{ST} and $\%DS_{ST}$ at stage A is assumed firstly known since they are inputs of the system. The volume flow rate ratios ($\dot{Q}_{Vx}$, $\dot{Q}_{Vy}$, $\dot{Q}_{Vz}$) are defined as controlled parameters that regulate the output of the system. Each of other stages has three unknowns , namely the volume flow rate (Q), the number of particle distribution (N) and the fluid concentration (%DS), as described by equation (20) and (21).

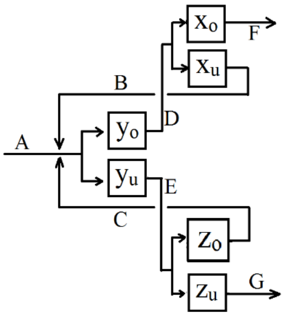


Fig. 3. Block diagram for system simulation.

$$\left(A,B,C..G\right)= \begin{matrix} Q_{ST} \\ N_{ST} \\ \%DS_{ST} \end{matrix} \tag{20}$$

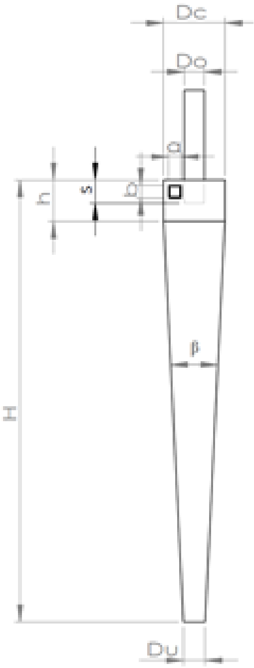
$$\left(x_\alpha, y_\alpha, z_\alpha\right)= \begin{matrix} \dot{Q}_{V\left(x_\alpha, y_\alpha, z_\alpha\right)} \\ eff_{\left(x_\alpha, y_\alpha, z_\alpha\right)} \\ \dfrac{-b+\sqrt{b^2-4a\Psi_{\left(x_\alpha, y_\alpha, z_\alpha\right)}}}{2a} \end{matrix} \tag{21}$$

Equations (20) and (21) are solved by numerical method based on Gauss-Seidel method. Letting all of the unknown variables (Q_B, Q_C, $N_{B(dp)}$, $N_{C(dp)}$, $\%DS_B$ and $\%DS_C$) are zero at the first iteration, the second iteration uses the result of first iteration to repeat the calculation process again and again until the result is convergent.

4. Simulation & Result and Discussion

4.1 Hydrocyclone geometries

The hydrocyclone being used for this study comes from the actual dewatering process in tapioca starch production. The specific geometries of this particular hydrocyclone are shown in Figure 4.



Symbol	Dimension
D_o	2 mm
D_c	10 mm
D_u	2 mm
a	2 mm
b	2 mm
H	86 mm
h	8 mm
S	4.5 mm
β	6 (degree)

Fig. 4. Hydrocyclone geometries.

4.2 Fluid properties

The starch fluid or starch slurry, which is a mixture of water and tapioca powder, is used for this simulation study. At the inlet of the circuit, starch volume flow rate is set as 0.3 m^3/hr with the concentration (%DS) as 0.105 kg of dry solid per kg of slurry. The initial estimation of starch particle's density is 3,000 kg/m^3. Based on equation (1), n is assumed to be 0.8. The particle sizes distribution at 0.105 starch slurry concentration is depicted from information from literature [11], and can be shown in Figure 5.

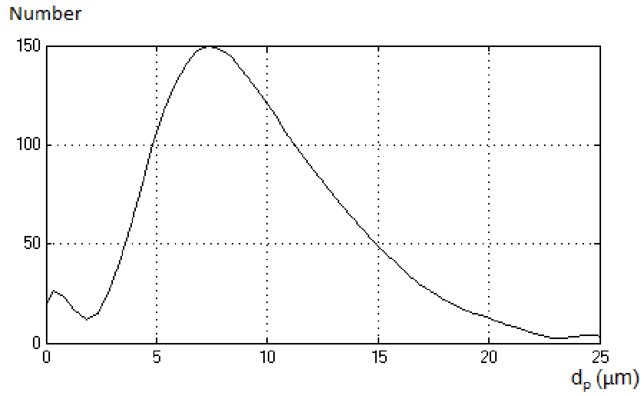


Fig. 5. Particle distribution at stage A.

Based on the information from the manufacturer, the relationships between the amount of dry solid in the slurry mixture and the fluid density and viscosity can be defined by experimentation curve fitting, and presented by equation (22) and (23), respectively.

$$\rho_{(\ )} = 426.82\left(\%DS_{(\ )}\right) + 998.98 \tag{22}$$

$$\mu_{(\ )} = -0.003\left(\%DS_{(\ )}\right)^2 + 0.0036\left(\%DS_{(\ )}\right) + 0.001 \tag{23}$$

4.3 Calculation results

For this example, there are 6 unknown stages namely stage B, and stage C to F. Each stage described by 3 equations, i.e. the volume flow rate, particle size distribution, and fluid concentration. So, there are 18 equations to be solved altogether. Here, the ratios $\dot{Q}_{Vx}$, $\dot{Q}_{Vy}$, $\dot{Q}_{Vz}$ are assumed to be 0.4, which represent the case that 40% of volume moves downward to underflow, or 60% of volume moves upward to overflow. In the real application, $\dot{Q}_V$ can be adjusted by using flow control valves. Figure 6 shows results from the calculations. It can be seen that the flowrate at stages E B and G are 40% of the flowrate input, or the flowrate at stages D C and F are 60% of the flowrate input. For the fluid concentration, it can be seen that the concentration at the underflow is higher than the overflow.

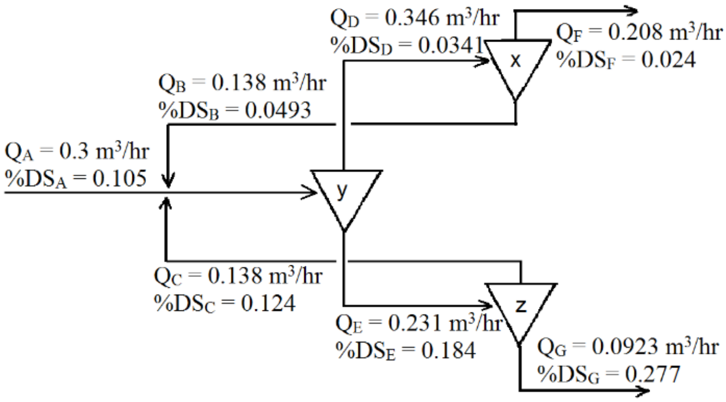


Fig. 6. Result from calculations.

Figure 7 shows the fluid concentration based on the proposed mathematical model and the calculation at stage G. It can be seen that the result converges at about 8 iterations of calculation, and reaches steady value at about 12 iterations of calculation. More iteration required more calculation time. Mathematically though, the mathematical model of this system is yet to be proven for its nature of convergence.

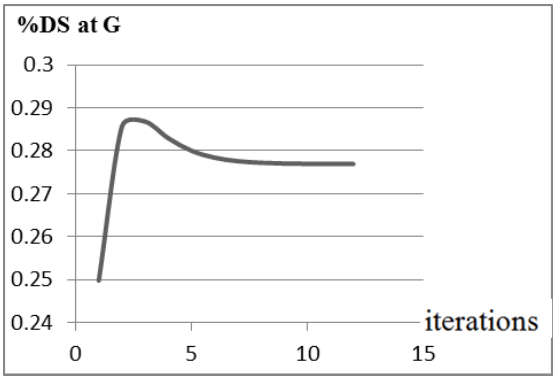


Fig. 7. result at state G for every calculation's round.

5. Conclusion

This study proposes a model which consists of a set of equations that can be used to predict the characteristics of a hydrocyclone circuit. This method requires properties of the fluid input, which are the volume flowrate, the particle size distribution and the fluid concentration (%DS). The volume flowrate is a controlled variable that is used for regulating or controlling the output quality or property. The model is able to predict the separation characteristics, particularly the fluid concentration and the fluid flowrate, at each state of the hydrocyclone circuit. Example of the calculation and results are shown based on a multi-step classification type hydrocyclone circuit, which is normally found in tapioca starch production process. Though the validation of the presenting method and results are authors' on-going work, the developed method will be beneficial not only for the control and operation of the hydrocyclone circuit, but also for the future modifications or improvement to be made to the design of a hydrocyclone unit.

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