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Experimental Study of a New Hydrocyclone for Multi-Density Particles Separation

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Abstract: A new structure of hydrocyclone is designed to meet the demand of separating particles heavier or lighter than water simultaneously. Based on the conventional hydrocyclone, the structural modifications with a section in the middle and a volute chamber on the top of the hydrocyclone to accumulate the separated low density particles. Some factors that influence the separation efficiency of hydrocyclone were investigated in this paper. For the heavy phase, those influencing factors included the inlet flow rate and underflow split ratio. For the light one, different outlets for discharging the light phase were taken into account. The results show that there exists an optimum inlet flow rate for a series of underflow split ratios. The top outlet for separating light phase particles is better than the side outlet's.

Keywords: Hydrocyclone, light phase particle, multi-density particles separation, separation efficiency, short circuit flow

INTRODUCTION

Hydrocyclone is always used as the first step to remove particles from ballast water (1,2). These particles are different in size and density (3). Conventional hydrocyclone can perform well when the densities of the particles are higher than that of the marine water, because the centrifugal force is proportional to the particle density. However, it would be not

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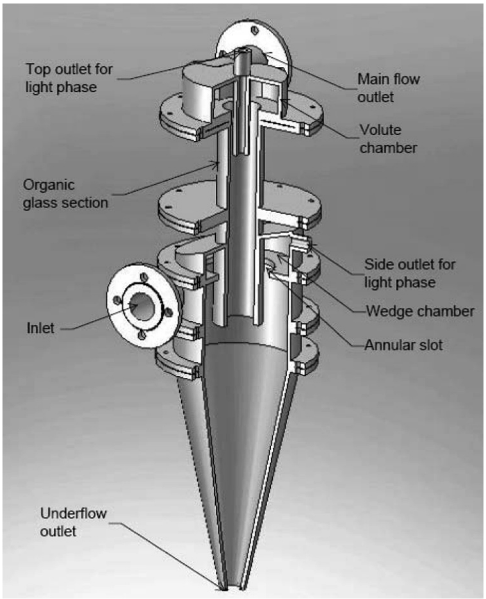

Figure 1. Structure of the new hydrocyclone.

wise to choose conventional hydrocyclone to separate those particles whose densities are lower than that of marine water. In order to solve this problem, the conventional hydrocyclone needs to be modified, as shown in Fig. 1.

The separation efficiency can be affected by the inlet flow rate and the physical properties of particles and fluid (4). The main purpose of this work is to investigate how the separation efficiency changes with different operating conditions.

EXPERIMENTAL METHODS

Apparatus

This research was carried out in the fluid dynamics laboratory of Tsinghua University, Beijing, China. In order to investigate the relationship between pressure drop and inlet flow rate, a regulating valve was used to adjust it. Two electromagnetic flow meters were adopted to detect the flow rate online. The underflow rate can be obtained by subtracting the main flow outlet reading from the inlet reading. Two particle counters (Model PC2400D, Hach, USA) were used to analyze the diameters of the particles and concentrations of the inlet and the main flow outlet respectively. The particle counter is used to count and "size" (i.e., sort by size) particles ranging from 2 to 400 microns in diameter. It typically operates at a flow rate of 100 ml/min. A constant head overflow device is used to maintain this flow. Flow adjustment is accomplished by moving the low flow detector up or down the weir assembly, which decreases or increases flow.

Design of the New Hydrocyclone Structure

A new hydrocyclone was designed for separation of both heavy phase and light phase, as illustrated in Fig. 1. The hydrocyclone was made up of an inlet, a volute chamber, a main flow outlet (5), a cylindrical part, a cone part, a light phase outlet, and an underflow outlet, and each of the two parts were connected by a flange and could be disassembled.

The hydrocyclone prototype's main geometric parameters (6) are shown in Fig. 2. The inlet flow, entering tangentially the hydrocyclone, is divided into the underflow, the main outlet flow, and the outflow for the

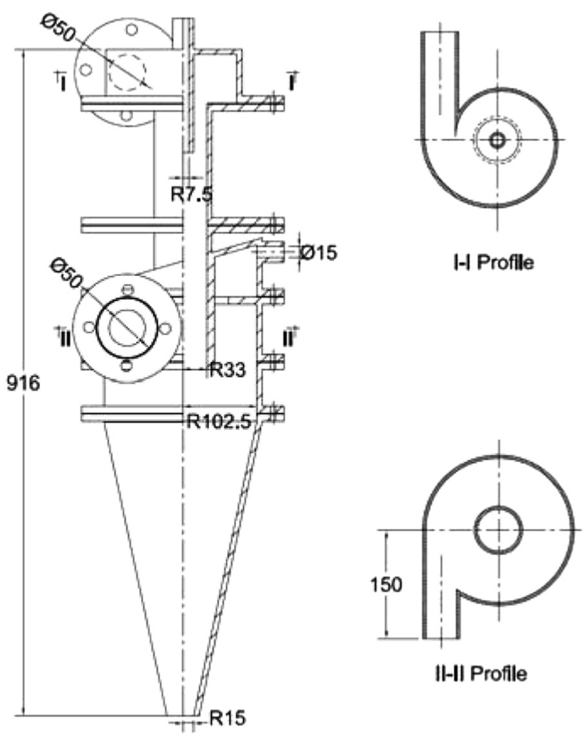

Figure 2. Main geometric parameters of the new hydrocyclone.

light phase particles. The underflow outlet, like the traditional hydrocyclone, was designed to discharge those heavy phase particles. The light phase particles accumulated at the center under the centripetal force and then are discharged through the top outlet. The side outlet is used to discharge those particles taken away by the eddy flow through the annular slot.

Liu et al. (7), used a volute chamber with a pre-sedimentation function to enhance the classification of hydrocyclone. In this experiment, the function of the volute chamber is different. In order to utilize the energy (8,9) of the strong swirling flow of forced vortex in the center, a volute chamber, as shown in Figs. 1 and 2, was designed on the top of the new structure. A top outlet was opened to discharge light phase particles which accumulated in the center because of centripetal force. A portion of light particles were carried away by the secondary flow (10,11) through the annular slot (as illustrated in Fig. 1) and then accumulated in the wedge chamber so a side outlet was opened on the top of the wedge chamber to capture those light phase particles.

PROGRAM

To determine the separation efficiency (12,13) of the new hydrocyclone in a wide range of particle density, talcum powder was used in this experiment as the heavy phase particle. The density of the talcum powder used in this experiment is 2,050 kg/m^3. Non-broken pine pollen was used as the light phase particle with the density of 500 kg/m^3. The experimental liquid used was tap water; the diameters of the testing particles ranged from 20 to 100 μm; the mass flow rate of the inlet was from 20 t/h to 36 t/h at intervals of 2 t/h; and the particles' mass concentration of the inlet was about 30 g/t.

As is shown in Fig. 3, the inlet flow rate was measured by the electromagnetic flow meter. A regulating valve was used to adjust the inlet flow rate. A manual regulating valve was installed to adjust the flow rate of the underflow. The pressure drop of the hydrocyclone could be obtained by taking down the readings of the pressure gauges. The particle counter was used to determine the separation efficiency. It can give the distribution of the diameters and the concentration of the particles. In order to obtain accurate data, two particle counters were placed in both the inlet and the main flow outlet of the hydrocyclone.

The grade efficiency $G(x)$ can be obtained from formula (1), as shown below:

$$G(x) = \frac{Q_i C_i(x) - Q_o C_o(x)}{Q_i C_i(x)} = 1 - (1 - R_f) \frac{C_o(x)}{C_i(x)} \tag{1}$$

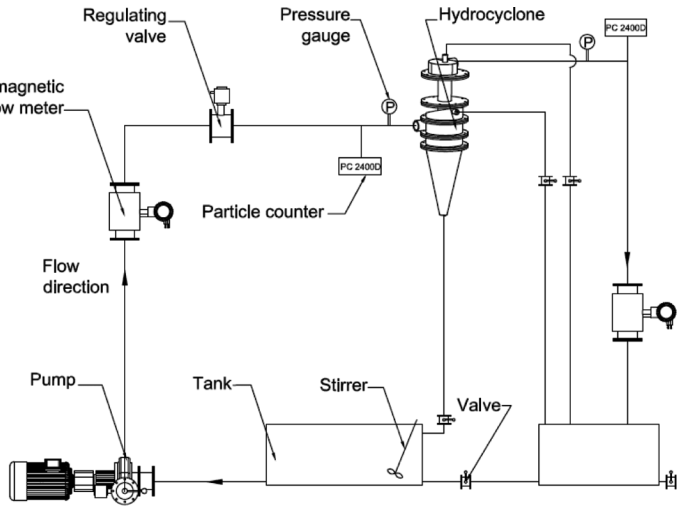

Figure 3. Simplified flow sheet of the test rig.

$$R_f = \frac{Q_u}{Q_i} = \frac{Q_i - Q_o}{Q_i} \tag{2}$$

where $C_o(x)$ and $C_i(x)$ are concentrations of the particles, with a diameter of $x\,\mu$m, in the main outlet and the inlet respectively. Both of them can be measured by the particle counters. In fact, the particle counter has 8 channels. A diameter range should be set for each channel, such as a $50 \sim 60\,\mu$m for channel 4. Q_i and Q_o are flow rates of the inlet and main outlet respectively. These two parameters can be obtained by the two electromagnetic flow meters installed in the inlet and main outlet, as shown in Fig. 3.

As mentioned before, this new pact design of hydrocyclone can separate both the heavy and light phase simultaneously. However, it is not easy to analyze the separation efficiencies (14) of both phases in one experiment. Because the particle counter cannot distinguish particles with different densities, the experiments were divided into two groups according to the particle densities. For heavy phase particles (15) separation, the inlet flow rate and the underflow split ratio were considered to be variables to find which affected the performance of hydrocyclone the most. For light phase particles separation, the inlet flow rate and the underflow split ratio were taken into account. Two outlets for discharging the light phase were experimented in this paper in order to find which one was better.

RESULTS AND DISCUSSION

Pressure Drop of the New Hydrocyclone

A comparison was made between the new hydrocyclone (Tsinghua) and the conventional one (NETAFIM, USA). The part number of the conventional hydrocyclone from NETAFIM is 24HC8V. The diameter of the hydrocyclone is 200 mm. The inlet and the outlet are both 50 mm in diameter.

There are numerous equations describing the correlations between pressure drop and inlet flow rate. One such equation that can be found in the book written by Ladislav Svarovsky (16) is

$$Q_i = 278k\rho_m (d_i d_o)^m \sqrt{\frac{\Delta p}{\rho_r}} \tag{3}$$

where ρ_r is the relative density of the particle compared with water, and ρ_m is the mixture density of the inlet flow. Many authors take $m = 1$; the coefficient k is related to the friction factor λ, the effective hydrocyclone diameter D, the length L, and a geometrical factor ξ:

$$k = \sqrt{\frac{1}{\lambda}\frac{D}{L}\frac{1}{\xi}} \tag{4}$$

$$\xi = \frac{1}{3}\left(\frac{d_i}{d_o} + \frac{d_o}{d_i} + 1\right)$$

The equation suggests that the pressure drop Δp should be a function of D, d_i, d_o, L, Q_i, and ρ_r. The first four are hydrocyclone geometrical factors; the fifth is the inlet flow rate and the last is particle property dependent.

As shown in Fig. 4, the inlet flow rate of the new hydrocyclone is larger than the conventional one when the pressure drops of these are the same. This indicates that the energy loss coefficient of the new hydrocyclone is smaller than that of the conventional one.

Grade Efficiency for Heavy Phase Particles

Two parameters were changed in this experiment; one is the inlet flow rate and the other is the underflow split ratio. The first one varies from 20 t/h to 35 t/h at intervals of 5 t/h. The latter is from 4% to 8% at intervals of 2%. The experiment results were shown in Fig. 5 to Fig. 8.

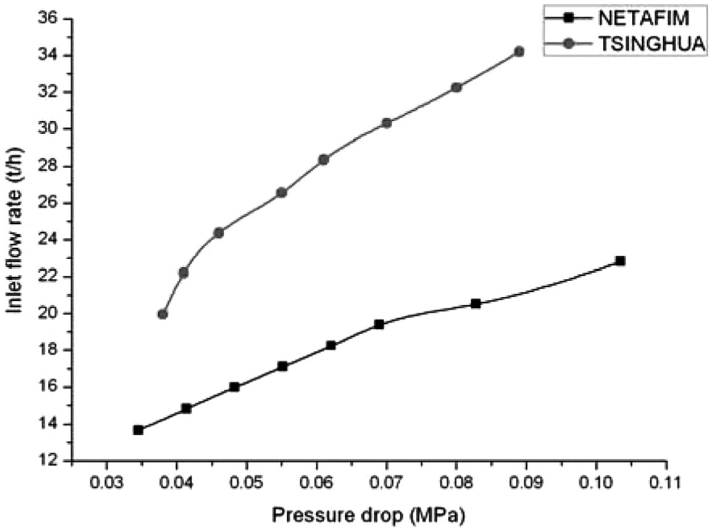

Figure 4. Plot of pressure drop against inlet flow rate of the new hydrocyclone.

Figures 5 to 7 show the grade efficiency curves for different inlet flow rates and different underflow split ratios. As shown above, for each underflow ratio, there is an optimum inlet flow rate. The grade efficiency

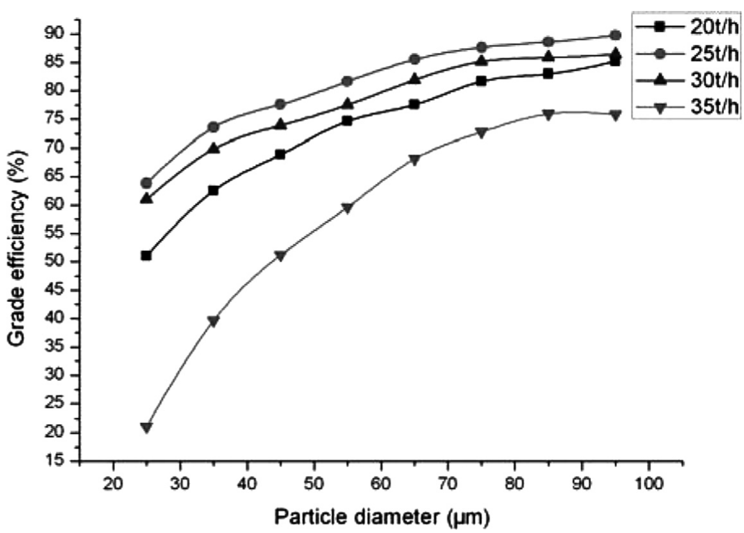

Figure 5. Grade efficiency curves for different inlet flow rates; underflow split ratio: 4%.

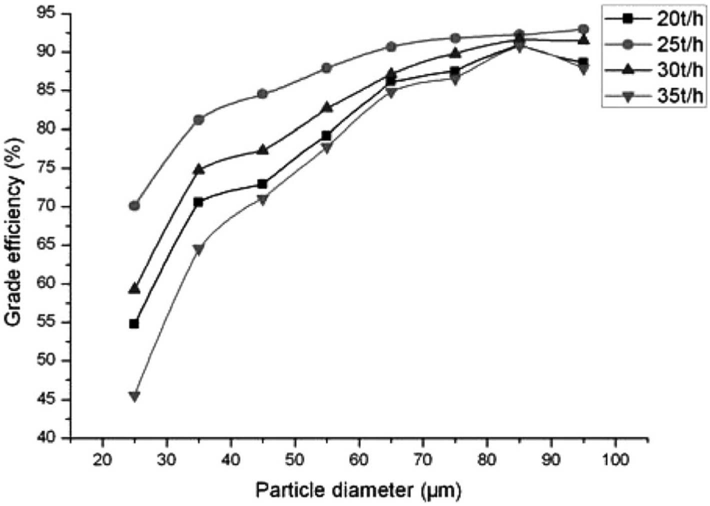

Figure 6. Grade efficiency curves for different inlet flow rates; underflow split ratio: 6%.

increases as the inlet flow rate increases given the inlet flow rate is below the optimum value. As the inlet flow rate exceeds this value, the grade efficiency decreases with the increase of the inlet flow rate. The optimum value of the inlet flow rate is 25 t/h in this experiment.

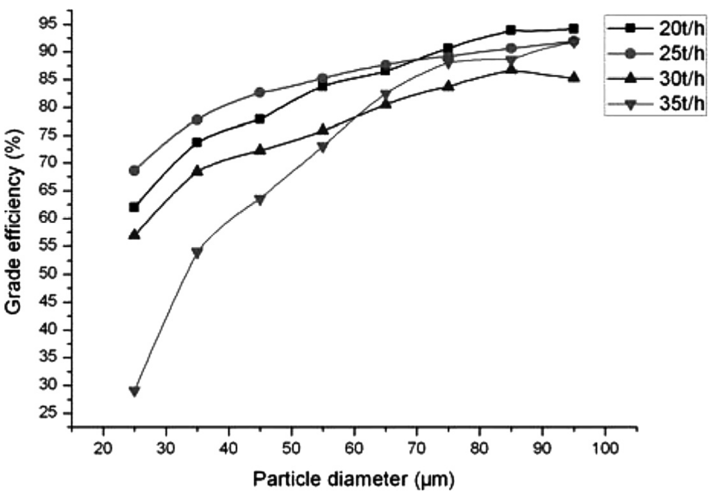

Figure 7. Grade efficiency curves for different inlet flow rates; underflow split ratio: 8%.

In order to find which underflow split ratio is best for the optimum inlet flow rate, a plot was shown in Fig. 8 for different underflow split ratios.

As illustrated in Fig. 8, the underflow split ratio 6% is in its best performance among all the split ratios experimented with.

Grade Efficiency for Light Phase Particles

Two outlets were tested in the experiment in order to find which one is better for separating the light phase particles. The flow rate of the top outlet ranges from 1.2 t/h to 1.6 t/h corresponding to the inlet flow rate increasing from 20 t/h to 30 t/h. For the side outlet, the flow rate range is about $1.9 \sim 2.8$ t/h.

As shown in Fig. 9, the grade efficiency increases as the diameter of particle increases. For a certain outlet, there is an optimum inlet flow rate under which the new hydrocyclone is in its best performance. In this experiment, this value is also 25 t/h.

It is obvious that the top outlet is better for separating light phase particles than the side one. However, the gap between them is not so large. The grade efficiency for the top outlet is about 3% higher than that of the side. But the flow rate of the top outlet is smaller than the side

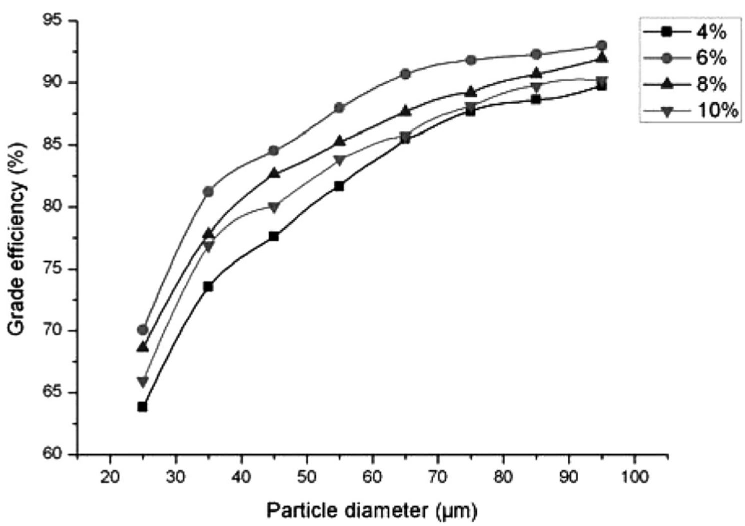

Figure 8. Grade efficiency curves for different underflow split ratios; inlet flow rate: 25 t/h.

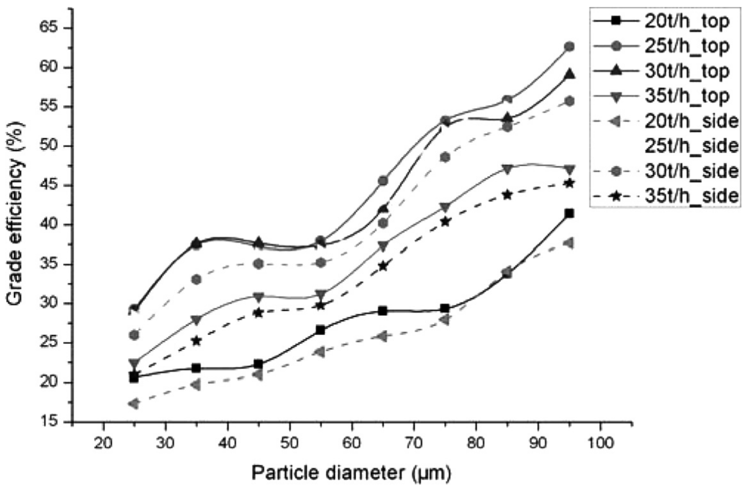

Figure 9. Grade efficiency comparison between two outlets under different inlet flow rates.

one's under the same inlet flow rate. So the performance of the top outlet is better than that of the side one. Experiments were also carried out to find out the correlation between grade efficiency and the underflow split ratio. The results are shown below in Fig. 10.

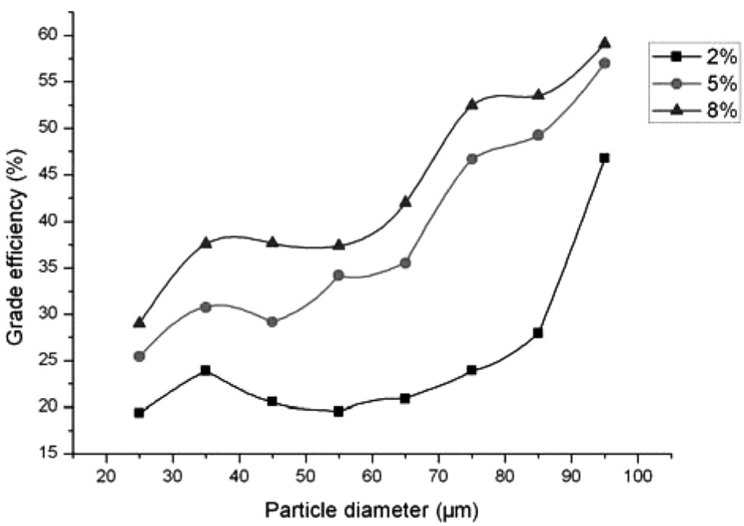

Figure 10. Grade efficiency curves for the top outlet under different underflow split ratios.

Figure 10 show the grade efficiency curves for the top outlet under different underflow split ratios. The grade efficiency increases with the increase of underflow split ratio. The highest grade efficiency is about 60% for the particles diameter between 90 μm and 100 μm and split ratio between 5% and 8%.

CONCLUSIONS

The energy loss of the new hydrocyclone with a volute chamber is less than that of the conventional one. This indicates that the volute chamber is effective in reducing energy loss of hydrocyclone. For the separation of heavy phase particles, the optimum inlet flow is 25 t/h and the best underflow split ratio is 6%. The cut size of the new hydrocyclone under the optimum parameters condition is below 20 μm. For the separation of light phase particles, the optimum inlet flow is also 25 t/h and the better outlet is the top outlet. The highest grade efficiency is about 38% for the top outlet. It is well known that the density difference between the continuous fluid and the dispersed particle is an important factor in determining the separation efficiency. The density difference is only 500 kg/m^3 for the light phase separation. That is perhaps one reason for explaining why the grade efficiency is so low for the separation of the light phase compared with the separation of the heavy phase.

ACKNOWLEDGEMENT

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NOMENCLATURE

D	hydrocyclone diameter (cm)
d_i	hydrocyclone inlet diameter (cm)
d_o	hydrocyclone main flow outlet diameter (cm)
L	hydrocyclone length (cm)
Δp	pressure drop (MPa)
$G(x)$	grade efficiency function (–)
Q_o	main outlet flow rate (t/h)
Q_i	inlet flow rate (t/h)
$C_o(x)$	particle concentration of main outlet (counts/ml)
$C_i(x)$	particle concentration of inlet (counts/ml)

ρ_r relative density of the particle compared with water (–)
R_f underflow split ratio (–)

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