Korean J. Chem. Eng., **25**(4), 754-757 (2008)

Design and performance evaluation of hydrocyclones for removing micron particles suspended in water

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(*Received 28 March 2007 • accepted 17 January 2008*)

Abstract−A hydrocyclone for collecting micron-sized hydrosols efficiently has been studied through experimentation. Hydrocyclones separate particles of the dispersed phase from the liquid on the basis of the density difference between the phases. The purpose of this study was to design and evaluate the performance of a high-capacity hydrocyclone for the removal of submicron-sized particles suspended in liquid. Furthermore, the performance of three types of hydrocyclone was evaluated with regard to solid particle density using fly ash and coagulation sludge. The particle cut-size decreases with reducing inlet area and increasing inlet velocity in the hydrocyclone. The hydrocyclones have good performance, which is demonstrated by the optimal cut-size of 20 μm in mass median diameter at the inlet diameter per body diameter ratio of 0.21 and the pressure drop of 72.5 kPa with a particle density of 2,500 kg/m^3.

Key words: Cut-size, Hydrocyclone, Separation Efficiency, Micron Particles

INTRODUCTION

A cyclone technology based on the principle of centrifugal sedimentation is gaining more and more interest in solid-liquid treatment facilities and industries. The suspended particles in the suspension are subjected to a centrifugal field, which separates them from the fluid. Also, hydrocyclones have no moving parts, require low installation and maintenance cost and are simple to operate. These devices are widely used in the mineral, chemical, petrochemical, textile and metallurgical industries.

Generally, the hydrosol filtration system has the problem of continuous operation, because the high velocity of the suspension circulating within the equipment allows the filter cake to build up. But the hydrocyclone has the advantage of the existence of high shear forces in the flow and classification of solids because it breaks and agglomerates filter cake, a pressure drop decrease a general solid-liquid filtration system [1-5]. The hydrocyclone consists of tangential inlet, apex bottom outlet, and overflow through vortex finder. Major parameters regarding cyclone configuration and operation conditions are cyclone body size, inlet shape, depth of vortex finder, geometrical structure of over and under flow discharges, cyclone length, and cone angles, concentration of feed hydrosol, fluid retention time and inlet velocity [6].

The hydrocyclone separates particles of the dispersed phase from the liquid on the basis of the density difference between the phases. Compared to solid-gas phases, solid-liquid phases have a fairly low density difference. It is difficult for hydrocyclone to separate a micron particle of the hydrosol. The purpose of this study was to design and evaluate the performance of a high-capacity hydrocyclone for the collection of fine particles suspended in liquid. Parametric studies of cyclone configuration, particle density and inlet velocity were carried out with fly ash and coagulated sludge.

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MATERIALS AND EXPERIMENTS

1. Test Particles

Table 1 shows the properties of coal fly ash and coagulated sludge in this study. Fig. 1 shows the particle size distribution of coal fly ash with the density of 2,500 kg/m^3. Test ash particles are spherical with 13.4 μm in mass median diameter (MMD).

Fig. 2 shows the particle size distribution of the coagulated sludge

Table 1. Properties of fly ash and coagulated sludge in the study

Test particle	Density (kg/m^3)	Total solid content (wt%)	Mass median diameter (μm)
Fly ash	2500	3±0.3	305.5
Coagulated sludge	1030	3±0.3	13.4

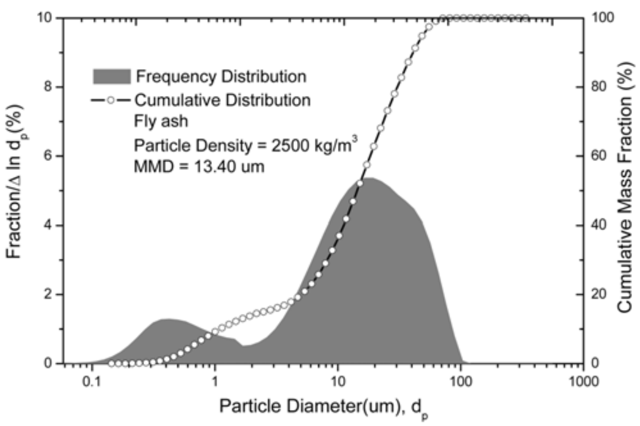

Fig. 1. Size distribution of test ash particles.

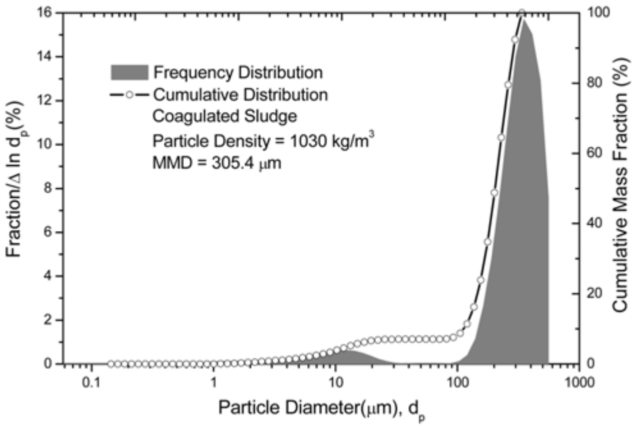

Fig. 2. Size distribution of the coagulated sludge as test particles.

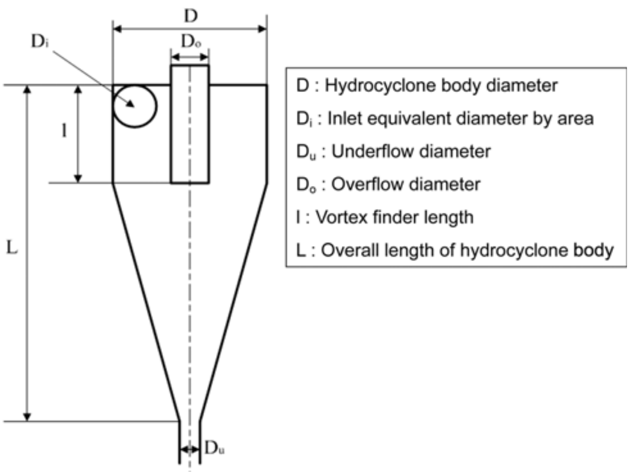

Fig. 3. Schematic diagram of the hydrocyclone used in this study.

with a density of 1,030 kg/m^3 as real particles for industrial applications. The particle size of the coagulated sludge measured by a particle counter [Malvern Instruments, MasterSizer] is 305.5 μm, in MMD. The coagulated sludge generated from the belt press dewatering system is taken from sewage treatment plants. All coagulated sludge is placed in an ice-cooled container immediately after sampling for transportation back to the laboratory, where they are transferred immediately to a refrigerator and stored at 4 until required for experiment. No samples are kept for longer than 5 days. The coagulated sludge contains 3±0.2% solid by weight.

2. Experimental Apparatus and Test Procedures

Fig. 3 shows a schematic diagram of a typical hydrocyclone. It consists of a cylindrical section joined to a conical portion. The suspension of micron particles in a liquid is injected tangentially through the inlet opening in the upper part of the cylindrical section and, as a result of the tangential entry, a strong swirling motion is developed within the cyclone. A portion of the liquid containing the fraction of fine particles is discharged through a cylindrical tube fixed at the center of the top and is projected into the cyclone; the outlet tube is called the overflow pipe or vortex finder. The remaining liquid and the fraction of coarse particles leave through a circular opening at the apex of the cone, called the underflow orifice [4].

Table 2. Geometries of the hydrocyclones used in the study

Hydrocyclone	D	D_i/D	D_u/D	D_o/D	l/D	L/D	Cone angle (°)
Type I	100	0.45	0.18	0.36	0.60	5.50	8
Type II	100	0.25	0.25	0.40	0.85	2.70	10
Type III	100	0.21	0.20	0.34	0.40	5.00	10

D: Hydrocyclone body diameter, mm
D_i: Inlet equivalent diameter by area
D_u: Underflow diameter
D_o: Overflow diameter
l: Vortex finder length
L: Overall length of hydrocyclone body

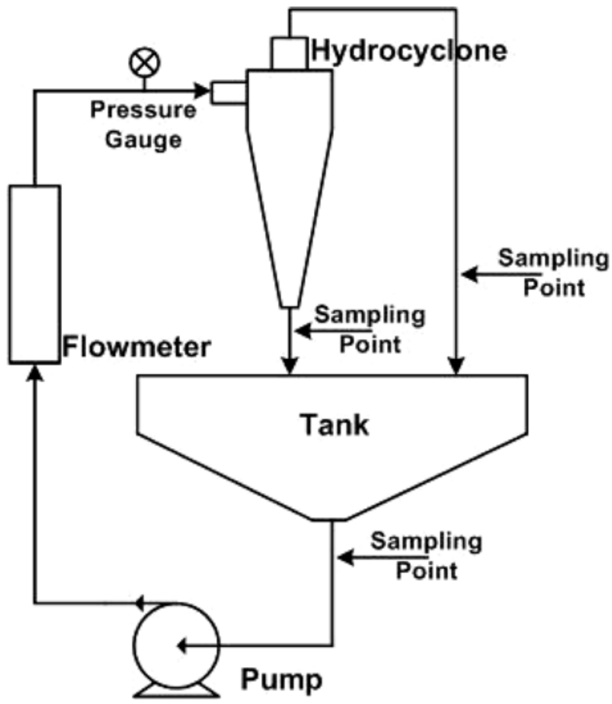

Fig. 4. Schematic diagram of the experimental set-up.

Table 2 shows the geometries of the hydrocyclones used in this study. Three types of hydrocyclones based on the Rietema standard geometry are changed for the purpose of increasing feed flow rates [4,6]. Hydrocyclone Types I, II and III have the dimension of 100 mm in body diameter. Geometry configurations characterized by inlet diameter, underflow diameter, overflow diameter, vortex finder length, overall length and cone angle are shown in Table 2.

Fig. 4 shows an experimental apparatus of the hydrocyclone system used in this study. It consists of a tank with the volume of 0.5 m^3, a pump [Wilo-LG Inc., 0-0.3 m^3/min], a flowmeter [Korea Flowmeter Inc., 0-0.4 m^3/min], a pressure gauge and the hydrocyclone. The laboratory-scale experiments of hydrocyclone were performed by using the coagulated sludge in the washing water of filter cloth in a belt press dewatering system and coal fly ash as test particles. Flow rates in the range of 0.15-0.2 m^3/min were tested and the flowmeter was cleaned to prevent contamination by the fine particles. The feed concentration was 300 mg/liter in all the separation experiments. Experiments were conducted with different hydrocyclone configurations and inlet velocities. The optimal conditions of the high-capacity hydrocyclone system for maximizing the separation efficiency were investigated.

EXPERIMENTAL RESULTS AND DISCUSSION

Particle size which is separated at 50% efficiency is referred to as the 'cut-size' and is commonly used to characterize the performance of the hydrocyclone.

Eq. (1) shows the total efficiency (E_T) of the hydrocyclone as follows:

$$E_T = \frac{M_c}{M} \tag{1}$$

where M is the mass flow of the feed and M_c is the mass flow rate of the coarse material in the underflow [4]. Eq. (2) shows the reduced efficiency representing the hydrocyclone functions as a flow divider. When looking at the performance of separators, it is then desirable to observe the net separation effect, i.e., to subtract the contribution of the dead flux [1]. This reduced efficiency (E_T') concept is widely used in evaluation of hydrocyclones as follows:

$$E_T' = \frac{E_T - R_f}{1 - R_f} \tag{2}$$

where R_f is the underflow-to-throughout ratio by volume, which is the minimum efficiency due to the dead flux and E_T is the total efficiency [4].

Fig. 5 shows the test results of the reduced efficiencies of the hydrocyclone I as a function of the inlet velocity by using fly ash and coagulated sludge at a D_i/D ratio of 0.45. The inlet velocity is closely related to the separation of most centrifugal devices. It is evident that a lower inlet velocity decreases the centrifugal force and thus gives a coarser cut-size. The cut-sizes through the hydrocyclone at the inlet velocity of 2.65 m/s and the inlet diameter (D_i) of 45 mm are approximately 164 μm for fly ash and 190 μm for coagulated sludge water, respectively. The fly ash resulted in more effective separation by hydrocyclone than coagulated sludge due to heavy density.

Fig. 6 shows the test results of the reduced efficiencies of the hydrocyclone II as a function of the inlet velocity at the D_i/D ratio of 0.25. The cut-sizes through the hydrocyclone at the inlet velocity of 5.33 m/s and the inlet diameter (D_i) of 25 mm are approximately 42 μm for fly ash and 220 μm for coagulated sludge, respectively.

Fig. 7 shows the reduced efficiencies of the hydrocyclone III as a function of the inlet velocity at the D_i/D ratio of 0.21. The cut-sizes through the hydrocyclone at the inlet velocity of 8.42 m/s and the inlet diameter (D_i) of 21 mm are approximately 20 μm for fly ash and 60 μm for coagulated sludge, respectively.

Table 3 shows the comparison of the reduced efficiencies as a

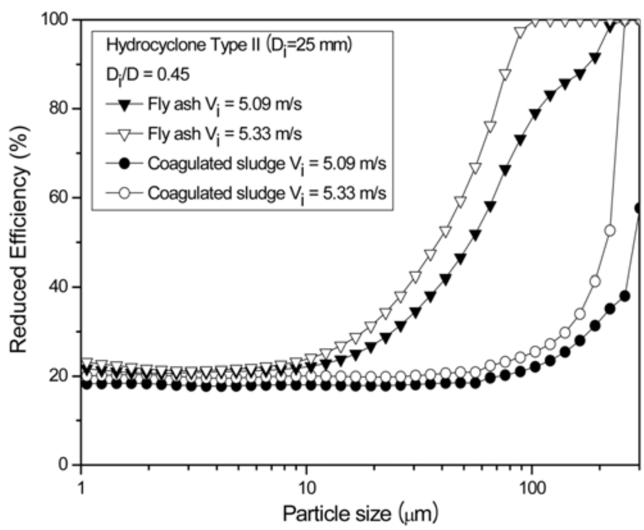

Fig. 6. Results of the reduced efficiencies of the hydrocyclone II, as a function inlet of velocity using fly ash and coagulated sludge at the D_i/D ratio of 0.25.

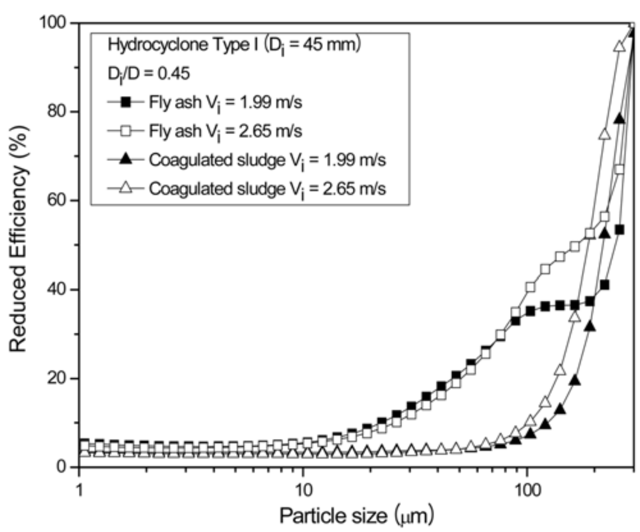

Fig. 5. Results of the reduced efficiencies of the hydrocyclone I, as a function of inlet velocity using fly ash and coagulated sludge at the D_i/D ratio of 0.45.

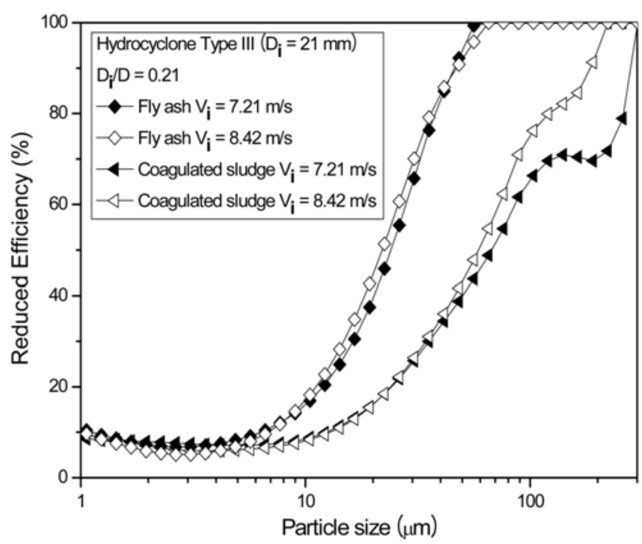

Fig. 7. Results of the reduced efficiencies of the hydrocyclone III, as a function of inlet velocity using fly ash and coagulated sludge at the D_i/D ratio of 0.21.

Table 3. Comparison of the reduced efficiencies as a function of the various inlet velocities

Hydrocyclone	V_i (m/s)	P (kPa)	R_f	d_{50c} (um)	Test particle
Type I	1.99	10.8	0.03	258	Fly ash
				222	Coagulated sludge
	2.65	24.5	0.04	164	Fly ash
				190	Coagulated sludge
Type II	5.09	48.0	0.16	56	Fly ash
				300	Coagulated sludge
	5.33	64.7	0.17	42	Fly ash
				220	Coagulated sludge
Type III	7.21	50.2	0.19	24	Fly ash
				70	Coagulated sludge
	8.42	72.5	0.20	20	Fly ash
				60	Coagulated sludge

function of the various inlet velocities. The cut-sizes through the hydrocyclone at the inlet velocity of 1.99 m/s and 8.42 m/s are approximately 258 μm and 20 μm for fly ash, respectively, while the cut-sizes are approximately 300 μm and 60 μm using the coagulated sludge, respectively.

The inlet diameter is the most important geometrical factor affecting reduced efficiency in the hydrocyclone system. Further, inlet diameter influences on inlet velocity and decreasing inlet diameter due to stronger centrifugal forces at the small inlet area.

CONCLUSIONS

In this paper, the design and performance evaluation of the high-capacity hydrocyclone were conducted to meet the collection of suspended fine particles in a hydrosol system instead of a conventional filter system. The separation efficiencies of the fly ash with the density of 2,500 kg/m^3 and coagulated sludge with the density of 1,030 kg/m^3 suspended in the water for the high-capacity hydrocyclone were evaluated experimentally. The hydrocyclone for the particle density of 2,500 kg/m^3 has a good performance, which is demonstrated by the optimal cut-size of 20 μm in mass median diameter at the inlet diameter per body diameter ratio of 0.21, the flow rate of 0.2 m^3/min, and the low pressure drop of 72.5 kPa. The hydrocyclone shows potential to be an effective method for removing micron particles in a solid-liquid separation system.

ACKNOWLEDGMENT

This work was supported by the Korea Research Foundation Grant funded by Korea Government (MOEHRD, Basic Research Promotion Fund) (KRF-2005-214-D00242).

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