“ Effect of blade rotation on particle classification performance of hydro-cyclones ”

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Key Words : Hydro-cyclone, Particle separation, Cut size, Particle size,

Abstract

The effects of topblade rotation of hydro-cyclones on particle classification performance were examined experimentally and via a simulation study.

It was noticed that the cut size of a hydro-cyclone decreases as the rotational speed of the top plate increases. Compared to the standard case without rotation, the accuracy of classification with top plate rotation increases under the wide range of operational conditions.

Newly proposed type-D cyclones with a special blade indicated the smallest cut size with a high accuracy of classification. The increase of classification accuracy is due to the production of outward radial flow near the top plate and this result was simulated by a CFD calculation.

The computer simulation also agreed qualitatively with the experimental data.

Introduction

Hydro-cyclones are widely used as a separation or size classification apparatus for solid-liquid flows, because of their simple structure and low cost. Experimental studies on the separation efficiency and pressure drop of hydro-cyclones were reported by Bradley et al. and Yoshioka et al [1-3]. Several flow controlling methods at the outlet pipe of a hydro-cyclone were proposed [4-5]. On the other hand, a prediction of the flow within a hydro-cyclone was made using several turbulence models [6]. Recent research results in hydro-cyclones are included in the references [14-15]. Recent interests in industrial hydro-cyclones indicate the control of the cut size as a function of high classification performance. Recently, with improvements in movable guide plates, such as with 'additional flow' and 'under flow' methods, it has become possible to classify 5 μm to 20 μm diameter particles with a fairly high degree of precision [7-8]. By use of both the additional flow and under flow methods, Yoshida et al. reported that the amount of coarse particles in the under-flow side are more easily controlled than the under flow ratio [8-9]. A better method in order to control the cut size of a hydro-cyclone in the fine particle region, is the use of a movable circular guide plate at the inlet of the cyclone. But in the case when the clearance at the inlet becomes small, the pressure drop of the cyclone increases under the constant inlet volume flow rate. On the other hand, a forced-vortex type separator in a dry-cyclone, uses moving blades in order to change the cut size.

It might then be expected that the cut size in the hydro-cyclone will also change by using the moving blades attached in the upper particle separation zone. However, the cut size control of a hydro-cyclone by use of moving blades has not yet been clearly investigated.

This paper describes the effect of rotating blades on the classification performance of hydro-cyclones. Several new types of rotating blades are proposed and their classification performance were examined under various experimental conditions. In order to classify the particles with high classification performance, the turbulence production by the blades should be minimized. This paper proposes special, new blades that indicate a particle classification with high performance.

A three-dimensional, numerical simulation of fluid flows, as well as a particle trajectory calculation, were conducted to estimate and to verify the reliability of experimental values with and without the rotating upper blades. Several, new information regarding particle classification were obtained.

Experimental apparatus

Figure 1 shows a schematic diagram of the hydro-cyclone used in this study. The cyclone diameter was 40mm and each of the dimensions was determined by a standard cyclone [2,3]. In order to move a 50% cut size, the upper plate of the cylindrical part (except the outlet pipe) was modified to rotate easily. The rotational speed could be changed from 0 to 10000 rpm. In the case where the upper plate is not rotating, some particles entering into the region near the upper plate tended to move from the outside to the inside radial position and descend near the outer region of the outlet pipe; finally exiting by the overflow side. But in the situation of the upper plate rotating, the radial flow direction near the upper plate is directed from the inside to the outside radial direction due to the centrifugal force. In this situation, it is expected that the amount of coarse particles in the overflow side would be reduced by the rotation of the upper plate. As a result, the particle classification accuracy might be increased with the rotation of the upper plate. Only the upper plate can be rotated by use of the motor ⑤ attached in the upper part of the cyclone. The test particles were pure silica, with a mass median diameter of about 10.3 μm and a true density of 2200kg/m^3. In order to reduce the number of agglomerated particles in the feed slurry, the slurry concentration was set at 2wt%, and the liquid flow rate was changed from 400 to 700 l/h. In order to change the 50% cut size by another method, the guide plate method as shown in Fig.1 was used and compared separation performance with the plate rotation method.

Cut size control due to the upper plate rotation.

(1) Cut size control due to the movable inlet guide plate.

The partial separation efficiency, $\Delta\eta$, was calculated using Equation (1).

$$\Delta\eta = \frac{m_c f_c \Delta D_p}{m_c f_c \Delta D_p + m_s f_s \Delta D_p} \qquad (1)$$

In the above equation, m_c and m_s are the masses of the collected particles in the coarse and fine sides, respectively; while f_c and f_s are the particle size frequency distributions for each size range. The particle size distributions were measured by Laser-light scattering (Horiba, Co. , Ltd. LA-920). In order to indicate the performance of the guide plate, the inlet width defined by Equation (2) was used.

$$G = \frac{b}{b^*} \qquad (2)$$

The symbols b and b* indicate the inlet width with and without the guide plate. In the case without the guide plate, the value of G is equal to 1.

Figure 2 shows the dimensions of the hydro-cyclone. The type O is the standard hydro-cyclone, but the circular upper plate can rotate at any rotational speed. The outlet pipe does not rotate and the upper plate was fixed by the use of four screws.

Experimental results

Effects of the rotational speed of the upper plate on particle separation efficiency were examined first. Figure 3-a shows the experimental results of the partial separation efficiency for various rotational speeds of the type O cyclone. We noticed that the 50% cut size decreases as the rotational speed increases. The slope of the partial separation efficiency with the rotational condition is larger than that of the case without rotation. In order to increase the rotational region, the performance of the type A cyclone, with a small impeller (see Fig.3), was also examined and compared with the separation performance from the Type O cyclone. Figure 3-b shows the separation performance of both types with a rotational speed of 6000 rpm. The cut size of the type A is smaller than that of the type O cyclone. This is due to the increased rotational region, near the upper plate of the Type A cyclone.

The effect of the upper plate impeller shape on partial separation efficiency was examined next. Figure 4 shows the various impeller types used in the experiments. In order to decrease the turbulence production caused by the impeller, it was determined the area of the impeller should be as small as possible. Compared to the type O cyclone, which has no impeller, the type B,C and D cyclones provided smaller cut size results. The minimum cut size of 6.83 μm was obtained when the type D cyclone was used. In order to move the cut size to the smaller region, the number of impeller blades on the partial separation efficiency was examined by use of the type D cyclone.

Figure 5 shows the experimental results with respect to the number of impeller blades in the type D cyclone. As a reference, the performance of the type O cyclone is also shown. Experimental conditions were that the impeller rotational speed was set to 6000 rpm and the inlet flow rate was fixed at 700 l/h. It was found that the minimum cut size was obtained with 4 impeller blades of the type D cyclone. In the case where the blade number is greater than 4, it is considered that the production of fluid turbulence increases, due to the number of blades, which in turn decreases classification performance.

Numerical simulation compared with experimental data

In order to calculate the effect of the top plate rotation on separation performance, a numerical simulation was conducted. The three-dimensional Navier-Stokes equations, and equations of particle motions, were numerically solved. Table 1 summarizes the basic equations used in the simulation. The direct flow method was used to calculate the flow field in the hydro-cyclone. To calculate the convection terms, the third-order finite difference method was used for the non-linear terms. The control volume method was used in the simulation 【10,11】.

Figure 6 shows the boundary conditions and the grid distribution used in the numerical simulation. All fluid velocities (except the upper rotational plate)were set to zero. The tangential fluid velocities on the upper plate are determined by a forced, vortex type condition. Details of the simulation method were described in our previous paper 【12】. The partial separation efficiency was determined from a particle trajectory calculation of mono-sized particles entering into the cyclone inlet. By changing the particle relaxation time τ, the equation of particle motion was numerically solved using the R.K.G. method 【13】.

Simulation results

The effect of the top plate rotation on fluid flow pattern was examined first. Figure 7 shows the calculated fluid velocity distribution for various top plate rotational speeds, for the type O cyclone. In the case of a zero rpm of the top plate, the fluid vectors near the top plate are directed from the outside to the inside radial direction, and descend near the outside of the pipe. This phenomenon is due to the fact that the fluid rotational speed near the top plate is small, and that the fluid centrifugal force is smaller than that of the pressure increase in radial direction. But in the case where the top plate rotates, the fluid vectors near the plate are directed from the inside to the outside radial direction. The magnitude of the vectors increases with the increase of the rotational speed. The radial flow near the top plate descends near the cylindrical wall. It is then expected that the cut size would decrease in the case of the top plate rotation.

Figure 8 shows the simulated particle trajectories with and without the top plate rotation. The typical three particles, with the same initial particle positions, were simulated for 8 and 20 μm diameter particles, respectively. In the case of the top plate rotation, the particles tend to rotate many times near the upper cylindrical wall and then go down to the under-flow side. In the case without top plate rotation, the particles with 8μm diameters rotate many times under the outlet pipe. Finally, the two particles go to the over-flow side, and the other particle goes to under-flow side. For both cases with and without the top plate rotation, it is found that particles in the enlarged, under-flow region rotate many times. This fact indicates that tangential fluid components are still left in the enlarged region of the under-flow side.

Figure 9 shows the calculated tangential fluid velocity distribution for various axial coordinates. Figure 9 (a) indicates the velocity profiles without top plate rotation and Fig.9 (b) is the results with top plate rotation. Comparing the results of Figs.9 (a), and (b), it was found that the magnitude of tangential fluid velocity vectors with the rotational case are greater than that of the case without rotation. These characteristics are especially clearly observed at the region near the upper cylindrical wall. It is then expected that particles moving in the upper cylindrical region would be strongly affected by the centrifugal force in the case of top plate rotation. The cut size of the cyclone with the top plate rotation would then be considered to be smaller than that of the case without rotation. The calculated results without top plate rotation in the cylindrical part show a solid body rotation near the inside radial region and a semi-free vortex at the outside region. But in the case of top plate rotation, the regions of solid body rotation increase near the conical wall. This effect is due to the fact that the top plate rotation changes the region of tangential velocity profiles from a semi-free vortex to a solid body rotation.

Experimental results and discussion

Figure 10 shows the experimental and calculated partial separation efficiencies for various rotational speed conditions. The cut size decreases as the top plate rotation speed increases. The experimental 50% cut size with 0 rpm is about 12 μm, but it changes to 10 μm and 9 μm for rotational speeds of 3000 and 6000 rpm, respectively. The calculated results also show the decrease in the cut size as the rotational speed increases. But the differences were found for cut size between the calculated and experimental results. This might be due to the fact that the equation of particle motion considers only fluid resistance, gravity and buoyant forces. By considering historical and other related forces acting on the particles, the difference might be smaller. It was also found from experimental and calculated results that the slope of the partial separation efficiency curve becomes steeper as the rotational speed of the top plate increases.

In order to change the cut size of hydro-cyclone, the other method is to use the moving circular guide plate proposed by Yoshida et al [7,8].
Figure 11 shows the change in cut size of the hydro-cyclone by using top plate rotation and the circular guide plate. The cut size decreases as the top plate rotational speed increases. In this case, the slope of the partial separation efficiency curve is nearly constant under various rotational speed conditions. But, in the case of the guide plate method, the slope of the partial separation efficiency curve decreases as the inlet width decreases. This fact indicates that

inward radial flow near the top plate still remains when the guide plate is used. Then, in order to change cut size with high classification accuracy, the top plate rotational method is recommended for practical applications.

Figure 12 shows the relationship between the accuracy of classification and a 50% cut size, as a result of the top plate rotation and the guide plate methods. The accuracy of classification decreases with the decrease of a 50% cut size for the guide plate method. But, it is confirmed that the accuracy of classification is nearly constant and the value becomes small when the top plate rotational method is used. The simulated fluid velocity distribution shown in Fig.12 also indicates that inward radial flow near the top plate still exists in the case of the guide plate method. On the other hand, outward radial flow near the top plate is found in the case of the top plate rotation method.

Conclusion

The effect of top plate rotation of a hydro-cyclone on particle classification performance was examined and the following conclusions were obtained.

(1) The cut size of a hydro-cyclone decreases as the rotational speed of the top plate increases.

(2) The accuracy of classification is nearly constant under a wide range of top plate rotational speed conditions.

(3) The type D cyclone with special blades indicated the smallest cut size with a high accuracy of classification.

(4) Compared to the guide plate method, the top plate rotation method indicates high classification accuracy. This fact is due to the production of outward radial fluid flow near the top plate, and this phenomenon was

simulated by a CFD calculation.

(5) The three-dimensional computer simulation also agreed with the trend in the experimental data.

Nomenclature

b, b* inlet width, with and without the guide plate (m)

C_D drag coefficient of a particle (-)

D_p particle diameter (μm)

D_{p50} 50% cut size of cyclone (μm)

D_{pc} 50% cut size without apex cone (μm)

D cyclone diameter (m)

$f_c(D_p)$,$f_s(D_p)$ particle size distributions of coarse and fine sides, respectively (-/μm)

g gravity acceleration (m/s^2)

G inlet width calculated by Eq.(2) (-)

G_1 gravitational parameter (m/s^2)

m_c,m_s mass of the collected particles for coarse and fine sides, respectively (kg)

p dimensionless pressure (-)

Q liquid flow rate (l/h)

Re(=$Du_0 \rho / \mu$) flow Reynolds number (-)

Rep(=$D_p \rho \sqrt{(u_z - v_z)^2 + (u_r - v_r)^2 + (u_\vartheta - v_\vartheta)^2} / \mu$) particle Reynolds number (-)

S_ϕ general function of production term (-)

t dimensionless time (-)

r, z dimensionless radial and axial coordinates (-)

u_z,u_r,u_θ axial, radial and tangential fluid velocities (m/s)

u, v, w dimensionless axial, radial and tangential fluid velocities (-)

u_0 inlet velocity of cyclone (m/s)

$\Delta\eta$ partial separation efficiency (-)

ϕ general function of conservation equation (-)

θ circumferential coordinate (-)

Γ diffusion coefficient (-)

ν (=1/Re) dimensionless viscosity (-)

μ fluid viscosity (Pa・s)

ρ, ρ_p fluid and particle density (kg/m^3)

τ particle relaxation time (s)

κ accuracy of classification defined by Eq.(3) (-)

ω rotational speed of top plate (rpm)

Literature Cited

(1) D.Bradley, Ind. Chemist, Sept., (1958), 473

(2) N.Yoshioka and Y.Hotta, Chem. Eng., 19, (1955), 632

(3) N.Yoshioka ; “Ekitai-saikuron”, Nikkan Kogyo (1962)

(4) L.Y.Chu, W.M.Chen and X.Z.Lee : “Enhancement of hydro-cyclone performance by controlling the inside turbulence structure”, Chem. Eng. Sci., 57, (2002), 207-212

(5) K.Yamamoto and X.Jiao: “Hydro-cyclone with a perforated inner cylinder”, Trans. Japan Soc. Mechanical Engineers, Ser.B, 63,615, (1997), 133-138

(6) C.A.Petty and S.M.Parks : ”Flow prediction within hydro-cyclone”, Filtration and Separation, Vol.28, (2001), 28-34

(7) H. Yoshida, T. Saeki, T. Fujioka, T. Ueda and T. Fuyuki ; “Fine Particle Separation by Revised Type Air-cyclone Classifier,” Kagaku Kogaku Ronbunshu , 19, (1993), 476-482

(8) H.Yoshida, S. Akiyama, K.Fukui and A.Kumagaya ; “Particle Classification with Improved Hydro-cyclone Separator” , J.Soc.Powder Tech., Japan, Vol.38, No.9, (2001), 626-632

(9) Y. Isshiki., K.Fukui, H.Yoshida and A. Kobayashi ; “Control of Particle Size Separation by use of a Hydro-cyclone”, J.Soc.Powder Tech., Japan, Vol.34, No.9, (1997), 690-696

(10) T. Kawamura ; “Numerical Study of High Reynolds Number Flow Around a Circular Cylinder,” Ph. D. Thesis , Tokyo Univ., Japan (1980)

(11) Patankar,S.V.; “Numerical Heat Transfer and Fluid Flow”, Hemisphere Pub., Washington, USA , (1980), 113-137

(12) H.Yoshida, T. Saeki, K. Hashimoto and T. Fuyuki ; “Size Classification of Submicron Powder by Air Cyclone and Three-dimensional Analysis,” J. Chem. Eng., Japan , 24, (1991), 640-647

(13) Society of Chemical Eng., Japan Ed. “Kgaku Kogaku Programing Ensyu”, Baifukan (1976), 148-154

(14) H.Heiskanen, “Particle Classification”, Chapman & Hall, (1993)

(15) L.Savrosky, “Solid-Liquid Separation”, L. Savrosky Ed., Butterworths, (1990), 202-250

Figs. and Tab. Caption

Table 1 Equations of fluid and particle motion

$$\frac{\partial}{\partial t}(r\phi)+\frac{\partial}{\partial z}(ru\phi)+\frac{\partial}{\partial r}(rv\phi)+\frac{1}{r}\frac{\partial}{\partial \theta}(rw\phi)=$$

$$\frac{\partial}{\partial z}(r\Gamma\frac{\partial\phi}{\partial z})+\frac{\partial}{\partial r}(r\Gamma\frac{\partial\phi}{\partial r})+\frac{\partial}{r\partial\theta}(\Gamma\frac{\partial\phi}{\partial\theta})+S_\phi$$

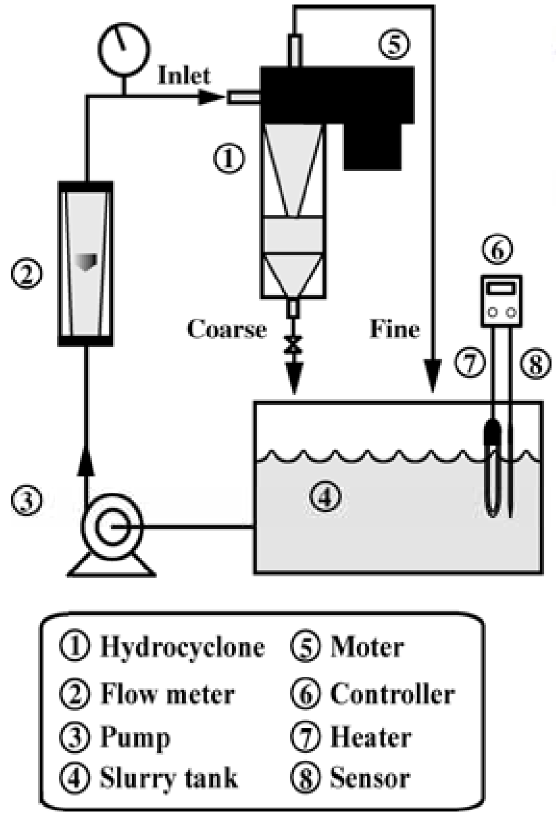
ϕ	Γ	S_ϕ
u	ν	$-r(\frac{\partial p}{\partial z})$
v	ν	$-r\frac{\partial p}{\partial r}+w^2-\frac{\nu v}{r}-\nu\frac{2}{r}\frac{\partial w}{\partial\theta}$
w	ν	$-\frac{\partial p}{\partial\theta}-vw-\frac{\nu w}{r}+\nu\frac{2}{r}\frac{\partial v}{\partial\theta}$
Particle's Eq. of Motion		

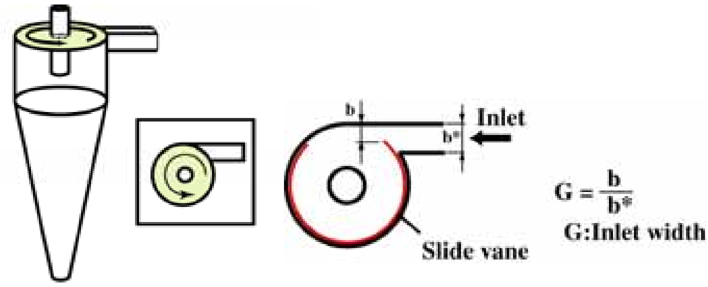
$$(\frac{d^2r}{dt^2}-r(\frac{d\theta}{dt})^2)=-(\frac{C_D Re_p}{24})\frac{1}{\tau}(\frac{dr}{dt}-v)$$

$$(2\frac{d\theta}{dt}\frac{dr}{dt}+r\frac{d^2\theta}{dt^2})=-(\frac{C_D Re_p}{24})\frac{1}{\tau}(r\frac{d\theta}{dt}-w)$$

$$\frac{d^2z}{dt^2}=-(\frac{C_D Re_p}{24})\frac{1}{\tau}(\frac{dz}{dt}-u)+G$$

$$\tau=\frac{(\rho_p+\frac{1}{2}\rho)D_p^2}{18\mu} \qquad G=\frac{(\rho_p-\rho)g}{(\rho_p+\frac{1}{2}\rho)}$$





Rotational top plate of hydrocyclone
(Type O)

Inlet guide plate

Table 1 Experimental condition

Tested powder	SiO_2
Mass median diameter	10.3 μ m
Density	2200kg/m^3
Dispersion medium	water
Concentration of slurry	2wt%
Flow rate	400~700l/h
Temperature of slurry	30℃
Blow down ratio	10%
Rotation speed	0~10000rpm

Fig.1 Experimental apparatus

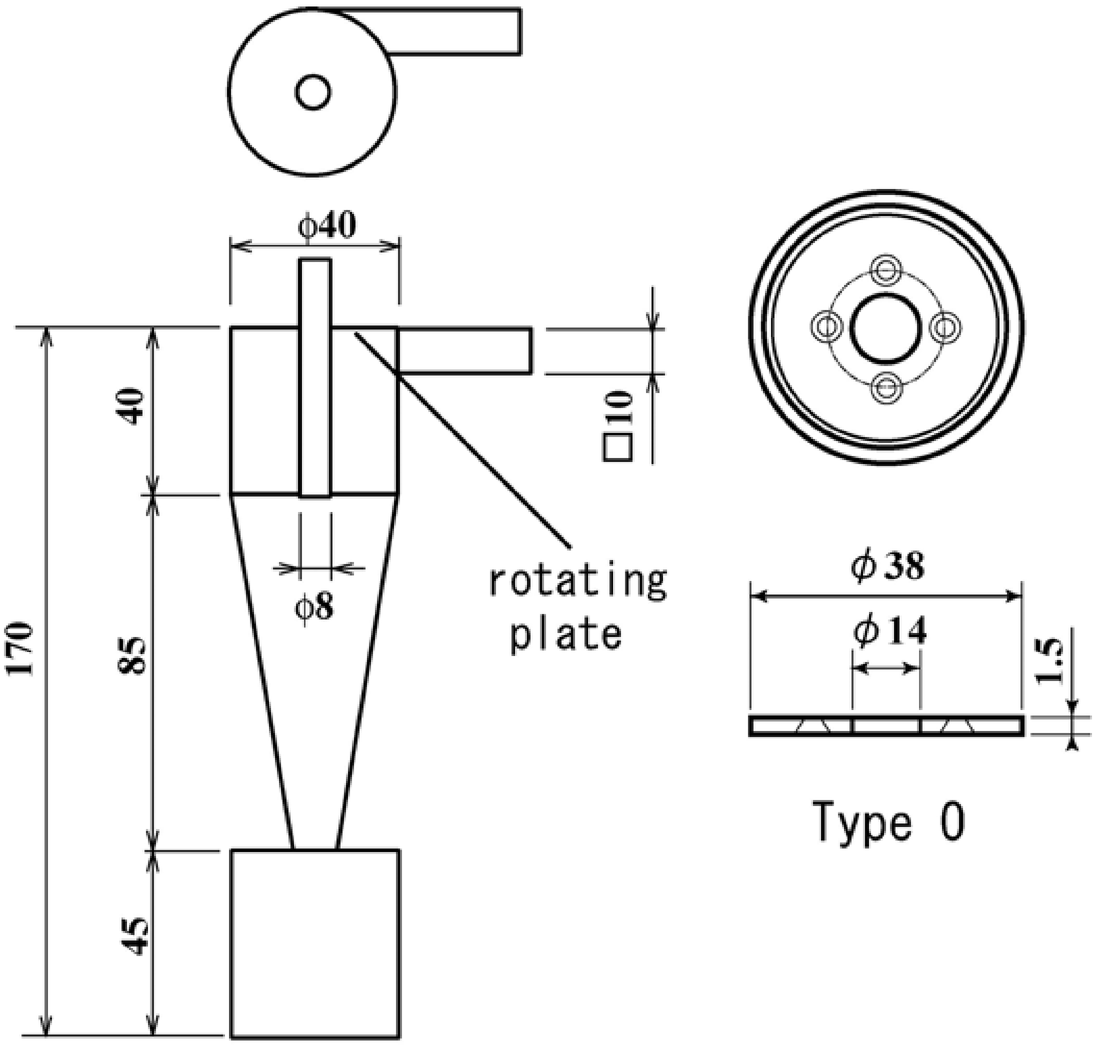
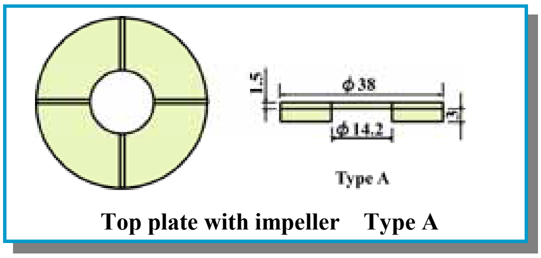


Fig.2 Hydro-cyclone with top plate rotation



Top plate with impeller Type A

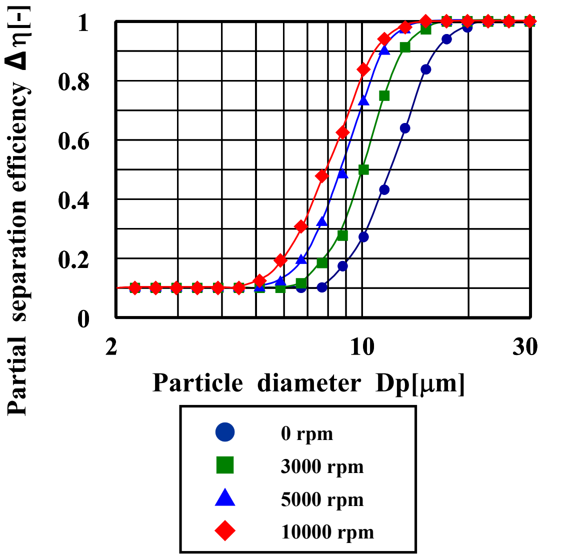


Fig.3-a Partial separation efficiencies for various rotation speed (Type O)

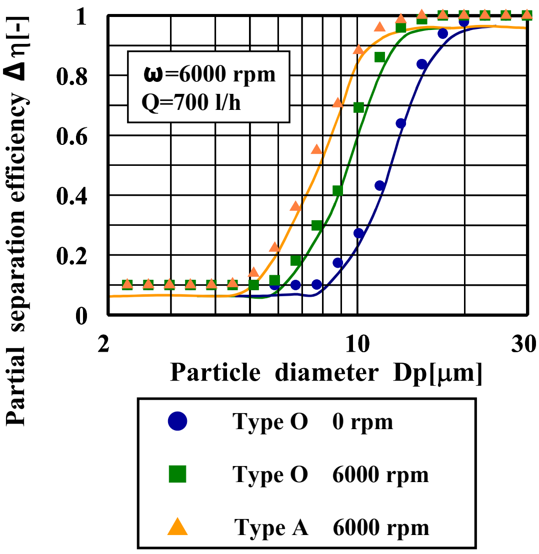
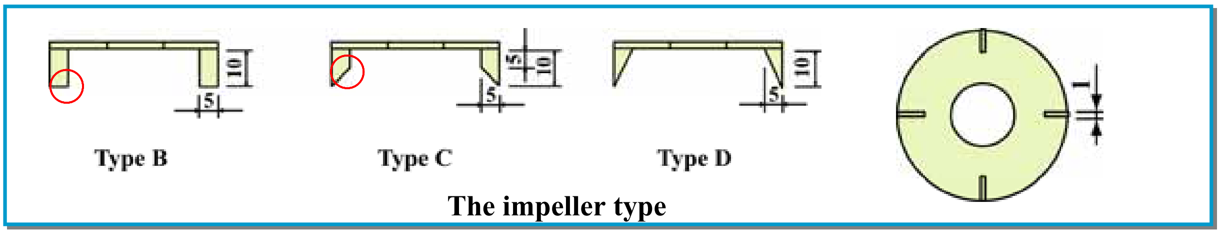
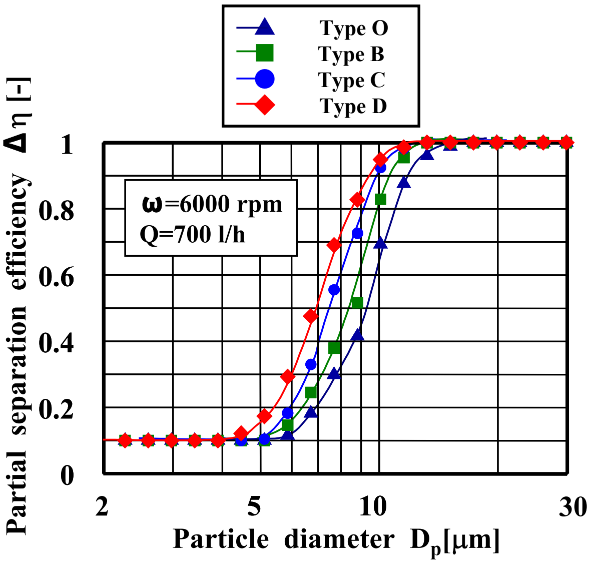


Fig.3-b Partial separation efficiencies for various top plates





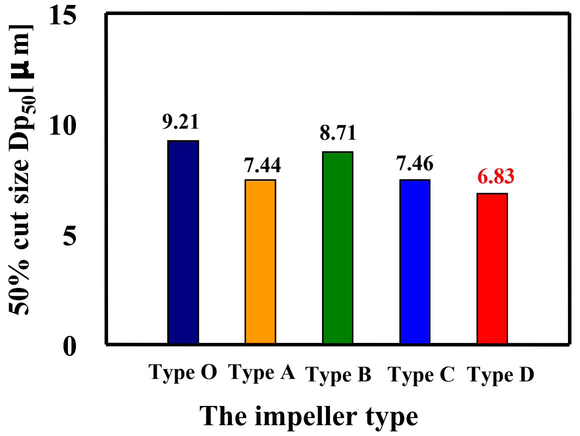


Fig. 4 Partial separation efficiencies for various impeller types

50% cut size with various impellers

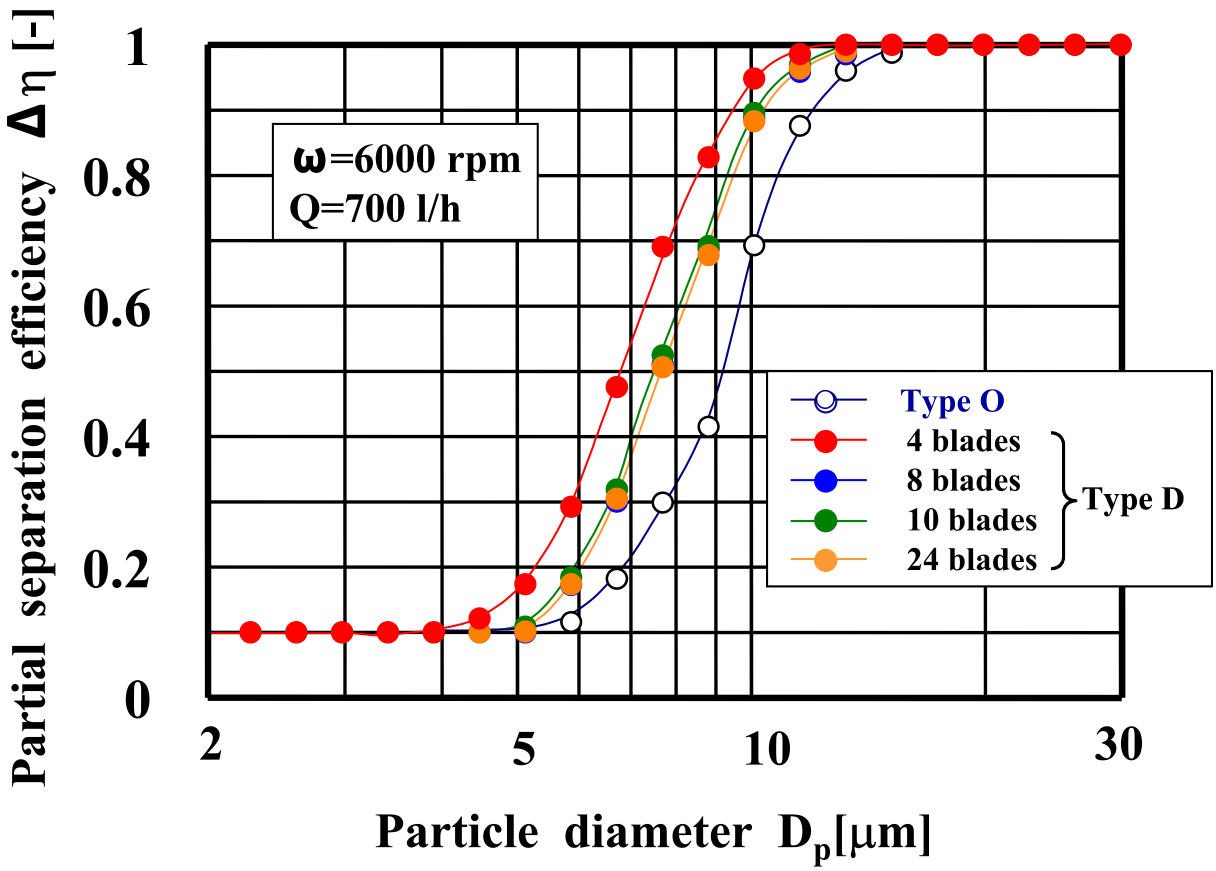


Fig.5 Effect of blade number on partial separation efficiencies

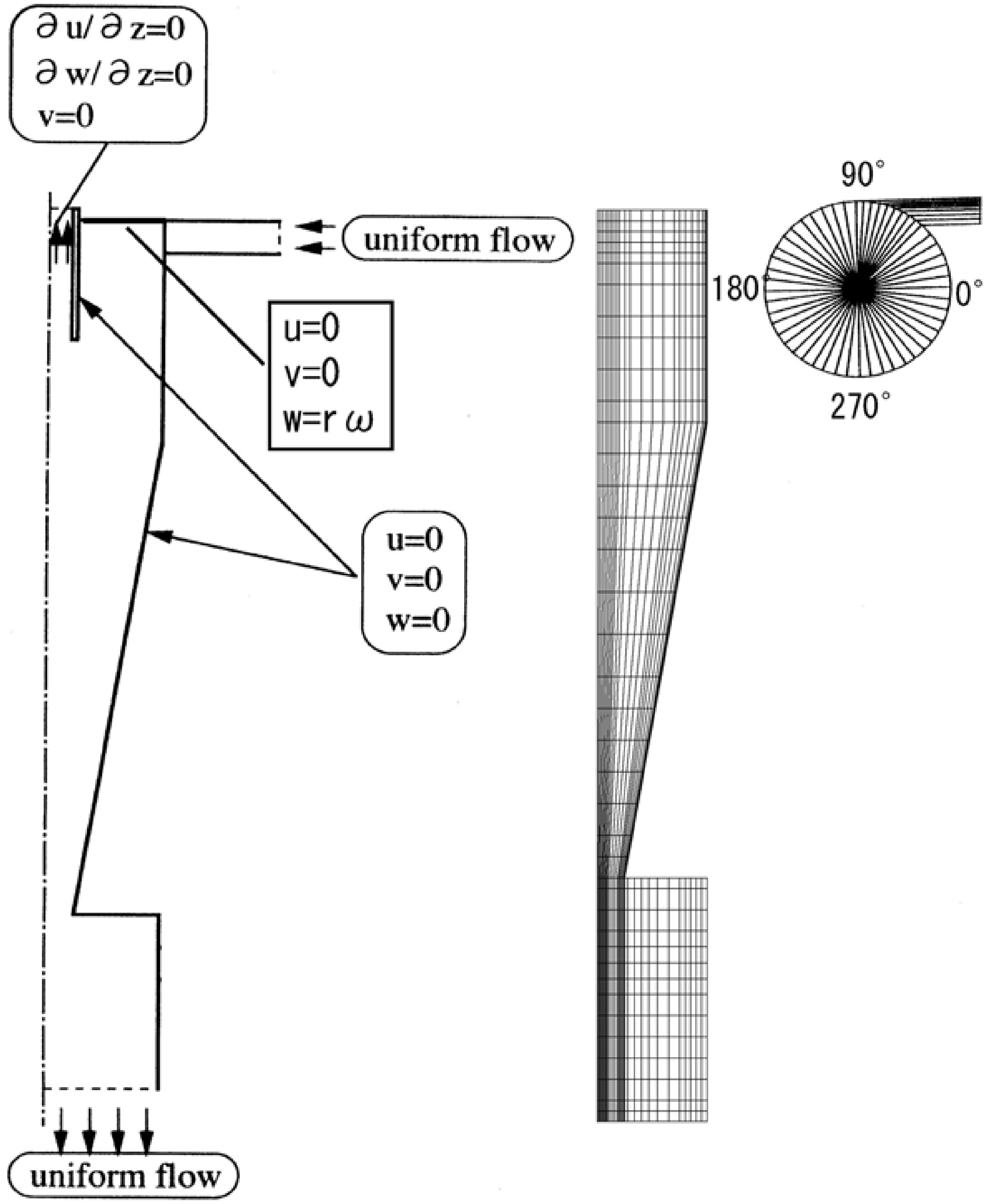
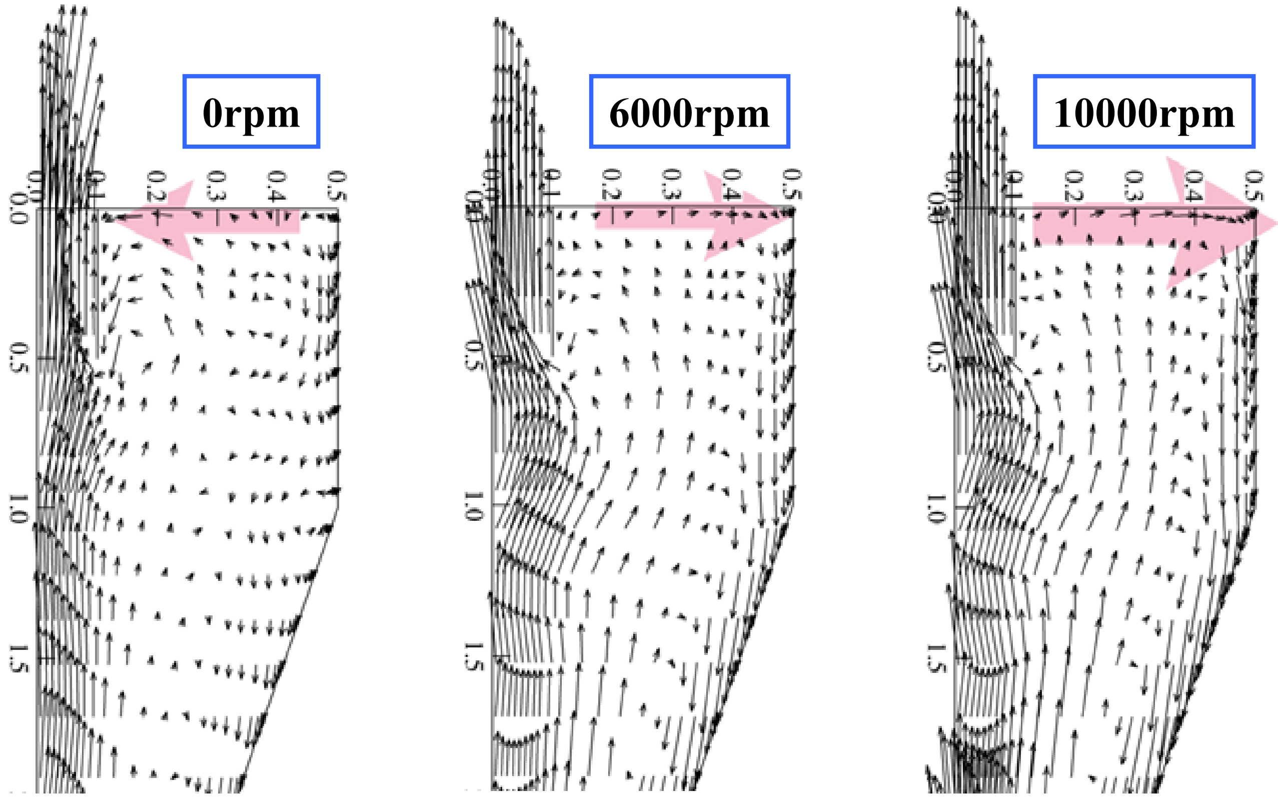


Fig. 6 Grid shape and boundary condition



(a) Without rotating (0 rpm) **(b) With rotating (6000 rpm)** **(c) With rotating (10000 rpm)**

Fig.7 The predicted fluid velocity distribution

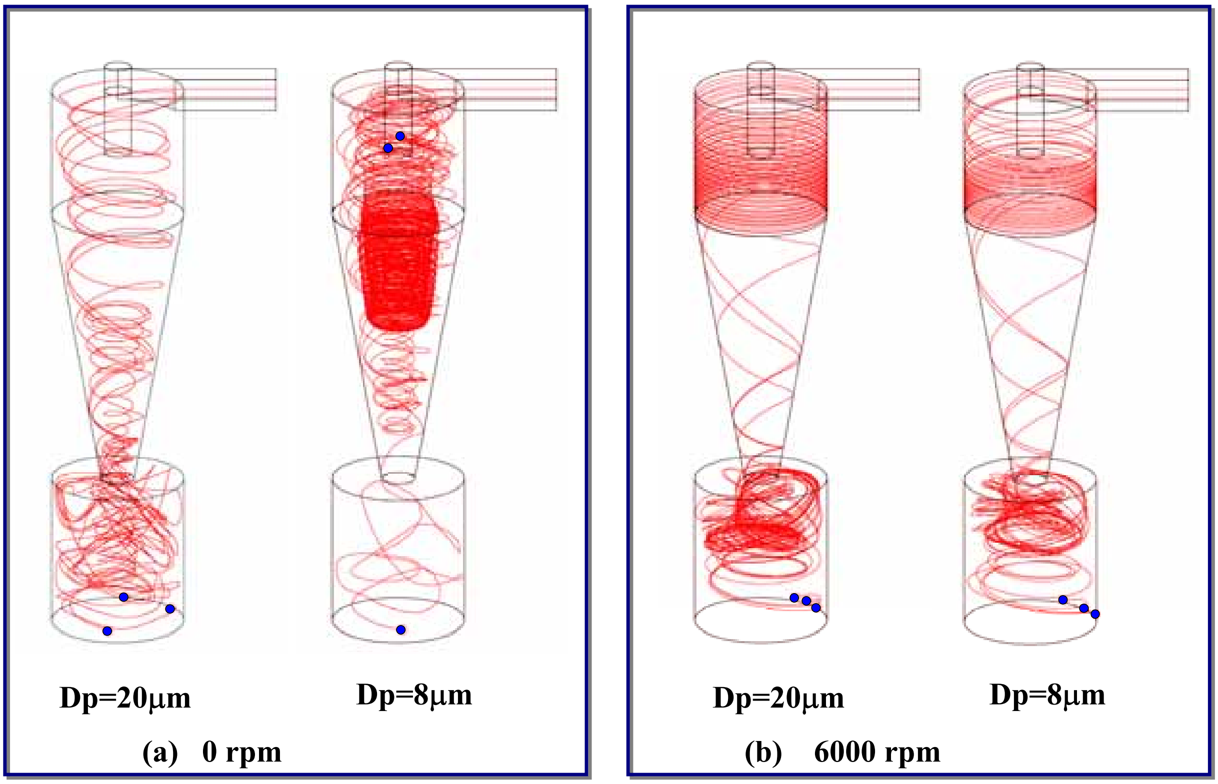


Fig. 8 Simulated particle trajectories for the Type O cyclone

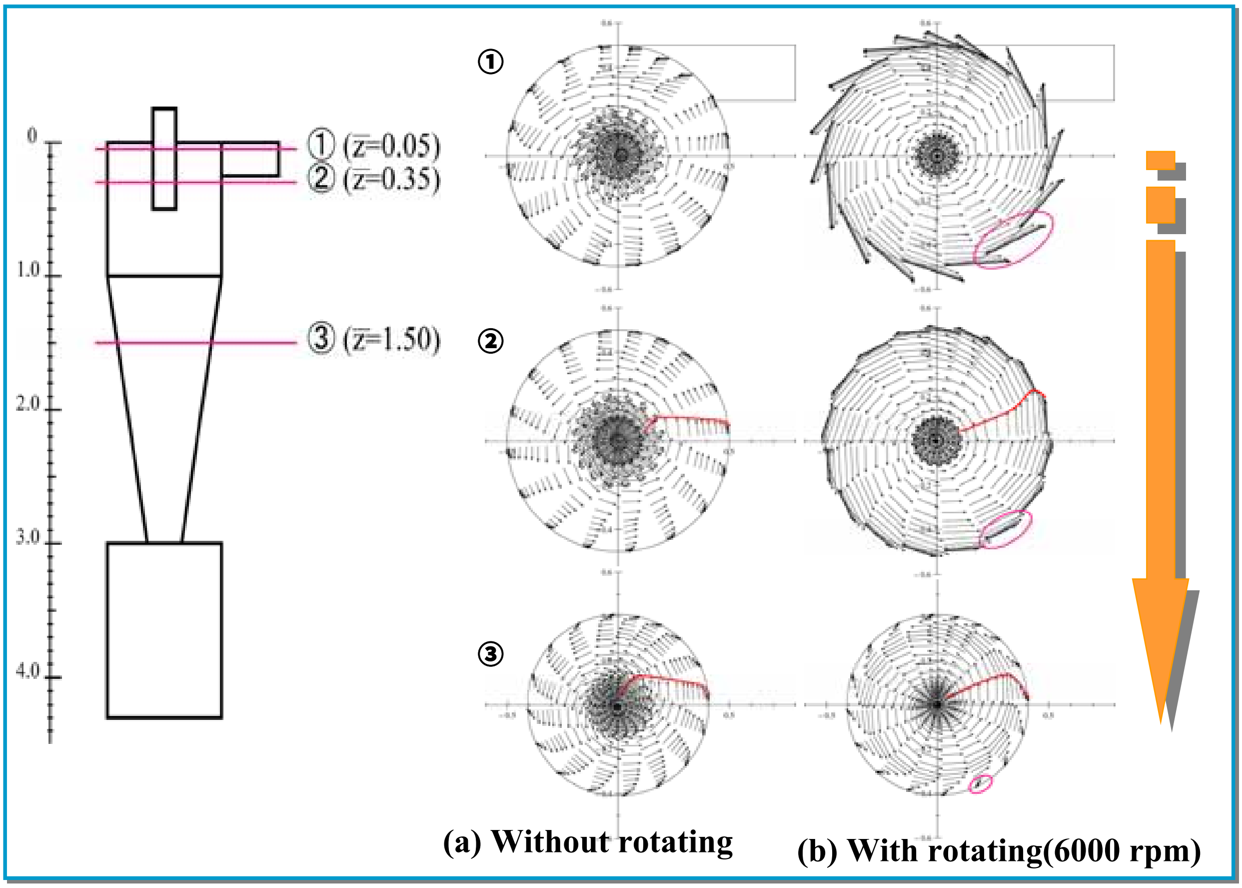


Fig.9 The predicted fluid velocity distribution

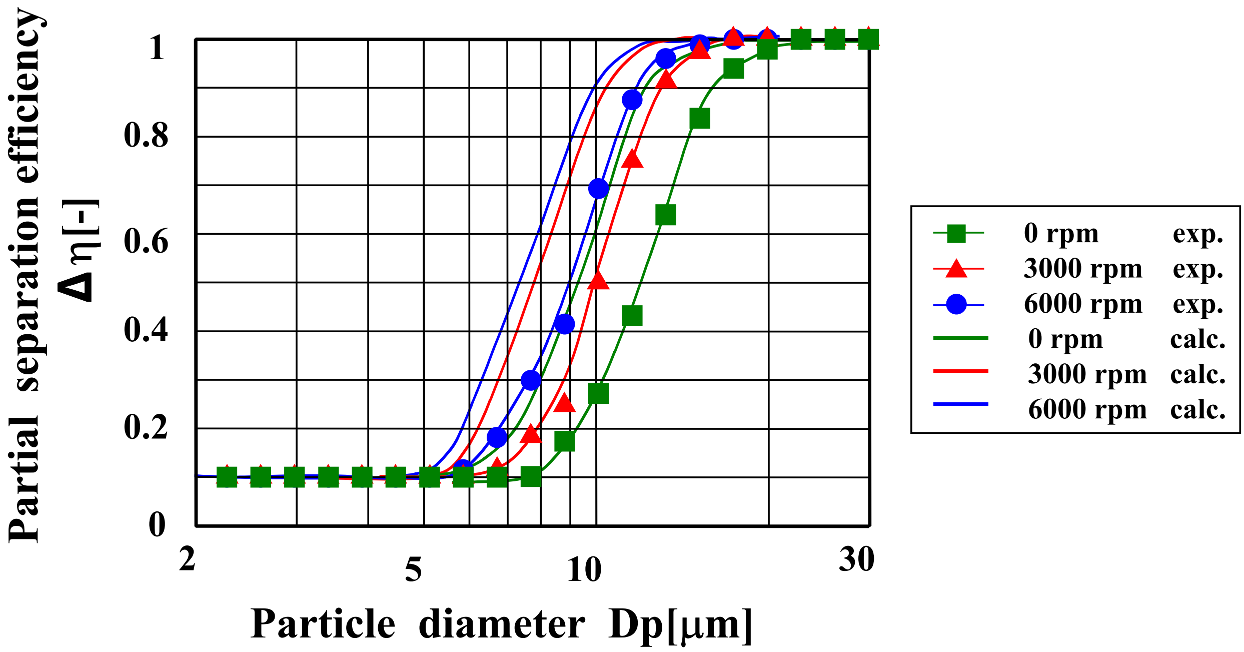
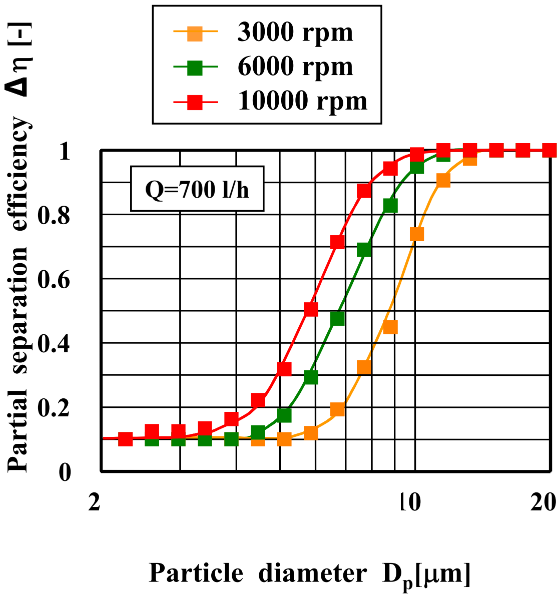
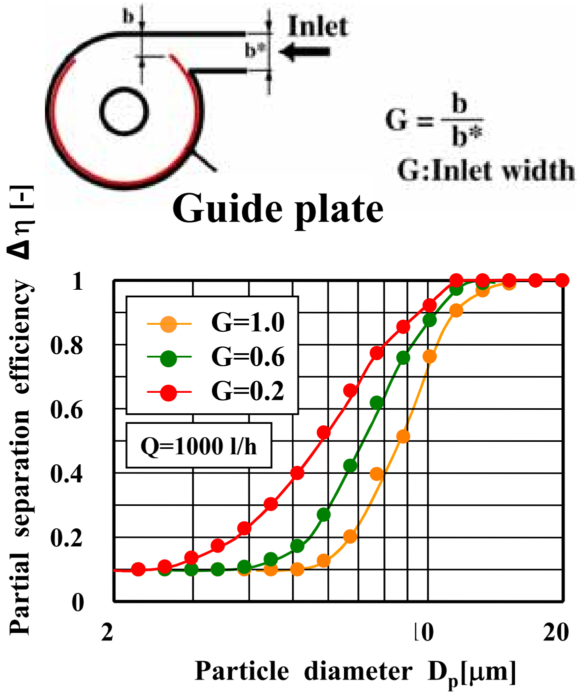


Fig.10 Comparison between experiment and calculated partial separation efficiency



(a) Partial separation efficiencies for various rotation speed (Type D)



(b) Partial separation efficiencies for various inlet width (Without rotating)

Fig.11 Cut size control by use of top plate rotation and guide plate

Accuracy of classification $\kappa = \dfrac{D_{P75}}{D_{P25}}$

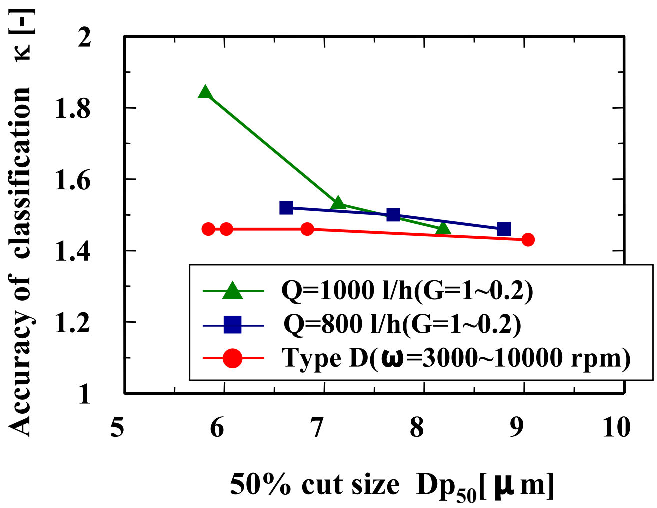
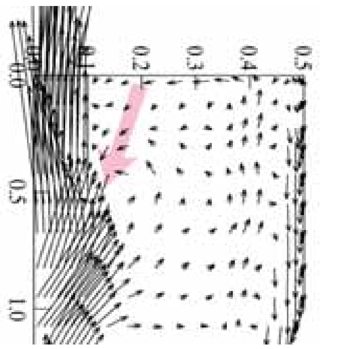
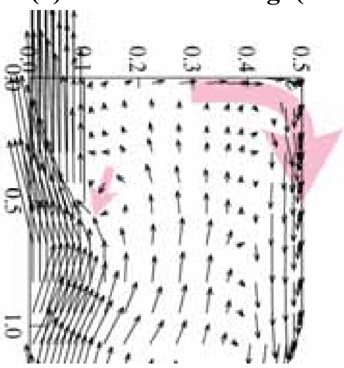


Fig.12 Relation between accuracy of classification and 50% cut size



(a) Without rotating (G=0.2)



(b) With rotating (without impeller,10000rpm)

Simulated fluid velocity distribution