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The experiments of the collection efficiencies with the fly-ash particles of the arithmetic mean diameter $X_p=2.06 \mu m$ for the returned flow type (D1=90 mm), the axial flow type (D1=90 mm) and the cone type (D1=100 mm) of the tangential inlet cyclones were done. The feed concentrations of the particles were $C_0=5 - 45 g/m^2$. The best collection efficiencies were obtained by the ordinary returned flow type of the cyclone and the worst collection efficiencies were obtained by the axial flow type of the cyclone. The main differences of those collection efficiencies were elucidated by the generation of the couple circulation zones based upon the analysis of the equi-flow rate lines in the axial flow cylindrical cyclone.

Key words: cyclone dust collector, centrifugal effect, pressure drop, flow pattern, collection efficiency, cut-size, tangential velocity.

1. INTRODUCTION

There are many papers concerning the collection efficiencies, the fractional collection efficiencies, the pressure drops, the velocity distributions and the flow patterns in the various types of the cyclone dust collectors in our country and in the foreign countries. And they say that the returned flow types of the tangential inlet cyclones show the more excellent collection efficiencies in comparison with those of the axial or uniflow types of the cyclones, since they are generally recognized that a reason why such a phenomenon is occurred is that the centrifugal effect $\phi \equiv V^2r$ which means the ratio of the centrifugal force $mv^2/r$ on a solid particle of mass $m$ to the gravitational force $mg$ of the returned flow types of the tangential inlet cyclones is stronger than that of the axial or uniflow cyclones.

Then the author had done the experiments concerning the collection efficiencies for the three types of the tangential inlet cyclones, i.e., type C1 (D1=90 mm), returned flow type; type C2 (D1=90 mm), axial flow type and type C2B (D1=90 mm), axial flow type with a vortex breaker plate; type C3 (D1=100 mm), cone type.

The best collection efficiencies $\eta_c$ were obtained by C1 cyclone, on the other hand the worst collection efficiencies $\eta_c$ were obtained by C2 and C2B cyclones.

In addition to this, the experiments of the flow patterns concerning the returned flow type of the tangential inlet cylindrical cyclone of diameter D1=140 mm and the axial flow type of the tangential inlet cylindrical cyclone of diameter D1=140 mm were done. From those experimental results, the centrifugal effect $\phi$ of the returned flow type was a little larger than that of the axial flow type. But this did not have the essential reason. One of the most important differences between the two types of the cyclones was based upon the flow patterns. As shown in Fig.1 of the schematic diagrams of the three types of the cyclones, the axial flow type showed the couple circulation zone which hindered the centrifugal separation of the fine solid particles.

In this paper the above stated experimental results are described in detail.

2. MAIN SYMBOLS

$C_0 \ (g/m^2)$: feed concentration of particles
$D_0 \ (m)$: diameter of an inlet pipe
D1 (m): cyclone diameter
D2 (m): diameter of exit pipe
D3 (m): diameter of the throat of cyclone
\( \dot{h} \) (Nm/s): energy dissipation of air flow in cyclone
Nt (m): imaginary cylindrical length
Mc (g): mass of the collected dust particles
\( \dot{F} \) (g/s): feed rate of the dust particles in cyclone
Mr (g): residue mass of the particles in inlet pipe
\( \Delta P_a \) (Pa): pressure drop of cyclone
\( \Delta P_{pa} \) (Pa): apparent pressure drop of cyclone
Q0 (m³/s): flow rate into cyclone
r (m): radius
Rn (l): number cumulative distribution of the solid particles
Vo (m/s): mean inlet velocity in an inlet pipe
Vo (m/s): tangential velocity of air flow

3. EXPERIMENTAL APPARATUS

Fig. 2 shows the schematic experimental apparatus for the pressure drops \( \Delta P_a \) and of the collection efficiency \( \eta_c \). In order to measure the pressure drop \( \Delta P_a \) of the cyclones as shown in Fig. 3, the pressure feed system was employed. Then concerning the experiments of the collection efficiencies \( \eta_c \) of the fly-ash particles which were dried on the temperature 393 K during a heated desicator, the suction feed system was employed. On the each experiment, the feed fly-ash \( N_0 \) to the cyclones through the mechanical vibrator was \( N_0 = 50 \) g. Fig. 3 shows the three types of the cyclones which were made by the transparent celluloid plate. C1-cyclone is the ordinary cyclone which had the dimensions; D0 = 39 mm, D1 = 90 mm, D1/D2 = 2.31, D1/D3 = 0.6, D1/D4 = 1.0, L = 100 mm, H = 200 mm and Hb = 100 mm. C2-cyclone is the axial flow cyclone which had the dimensions; D0 = 39 mm, D1 = 90 mm, D1/D2 = 2.0, D1/D3 = 3.1, L = 301 mm and H = 202 mm. In addition to this, C3-cyclone had a vortex breaker plate of diameter D5 = 80 mm in the dust bunker. C3-cyclone is the cone type cyclone which had the dimensions; D0 = 39 mm, D1 = 100 mm, D1/D2 = 2.56, H = 150.4 mm and Hb = 101.7 mm. Concerning this type of cyclone, KOSBACKOK (1958) measured the velocity distributions of the tangential, axial, and radial directions for the ordinary air flow in the cone type tangential inlet cyclone which had set up the three tangential inlet pipes along the outer surface of cone. He showed the very interesting flow patterns. But this flow pattern could not be applied to our experiments for the cone type cyclone, since the throat of cone vortex chamber had been shut down by a bottom plate. On the other hand, cone type of the cyclone was patented by JACO (1888, J) which had the dimensions; D1/D2 = 2.65, H/D1 = 1.52, D3 = 35.3 and D1/D0 = 4.38.

Fig. 4 shows the number cumulative distribution \( Rn(xp) \) and the number frequency distribution \( f_n(xp) \) of the test dust of fly-ash. The total measured numbers \( n \) were 11069 particles. The density \( \rho_0 \) of fly-ash was \( \rho_0 = 2.26 \) g/cm³. The arithmetic mean diameter was \( X_p = 2.65 \) μm and also the standard deviation \( \sigma \) was \( \sigma = 1.12 \) μm.

4. EXPERIMENTAL RESULTS

4.1 PRESSURE DROP

Fig. 5 shows the relationship between the pressure drop \( \Delta P_c \) (Pa) of the pure air flow and the mean inlet velocity \( \dot{V}_0 \) (m/s) in the inlet pipe. From this figure you will find that the pressure drop \( \Delta P_c \) is nearly independent of the type of the cyclones and \( \Delta P_c \) could be represented empirically as

\[ \Delta P_c (\text{Pa}) = 1.25 \cdot \dot{V}_0 \]

(1)

Here the pressure drop was defined as shown in Fig. 2 as...
4.2 Collection Efficiency

Fig. 6 shows the relationship between the collection efficiencies \( \eta (\%) \) for the fly-ash and \( V_o \). The feed concentration \( C_f (g/dust/m^3 - air) \) of the fly-ash is shown in this figure. Then the highest collection efficiencies \( \eta (\%)=95-98 \% \) were obtained. Now it is very interesting to note that the cone type of the cyclone showed the high collection efficiency \( \eta_c \approx 89-92 \% \) which the author had formerly expected. On the other hand, C2 and C2B-cyclones showed lower collection efficiencies \( \eta_c \). Especially the collection efficiencies of C2B-cyclone showed the more lower efficiencies \( \eta_c \) in comparison with those of C2-cyclone.

Fig. 7 showed the relationship between \( \eta (\%) \) and \( C_f (g/m^3) \). Increasing the feed dust concentration \( C_f \), the collection efficiencies \( \eta_c \) of C1-cyclone were decreased in contrast with those of the ordinary types of the middle scale cyclones (cyclone diameter \( D_t=0.5 \sim 1.0 \) m). On the contrary, C2B and C3 cyclones showed the increasing \( \eta_c \). Therefore it is very important to notice that it is not always increase the collection efficiencies \( \eta_c \) with increasing the feed dust concent-

Fig. 8 showed the relationship between \( \eta_c (\%) \) and \( \lambda (g/Nm) \) which means that a ratio of the feed dust rate \( M_f (g/s) \) to the rate of the energy dissipation of air flow in the cyclone \( E \) (Nm/s)\( \cdot \omega_p \cdot Q_o \). It is very interesting to note that the collection efficiencies gradually increase with increasing the values of \( \lambda \). And also from the energy consumption point of view, C1-cyclone showed the best collection efficiency \( \eta_c \). On the contrary, C2B-cyclone showed the lower collection efficiency \( \eta_c \) in comparison with C2-cyclone due to the re-entrainment by the secondary flow and by the interference effect based upon the re-separated dusts for the sedimentation of the separated dusts to the dust plume on the vortex breaker plate as shown in Fig. 9.
Fig. 9 shows the separation processes of fly-ash particles for C1, C3 and C2B-cyclones, respectively. These behaviors of the solid particles along the cyclone concave surfaces were nearly independent of $V_0=10-25$ m/s. Then one of the interesting phenomena was that the centrifugally separated solid particles were hindered the sedimentation into the dust bunker due to the vortex breaker plate of C2B-cyclone. Because of this phenomenon, the collection efficiencies $\eta$ of C2B-cyclone had gone from bad to worse.

4.3 FLOW PATTERNS IN THE RETURNED FLOW TYPE AND IN THE AXIAL FLOW TYPE OF THE CYLINDRICAL CYCLONE

Fig. 10 shows the two types of the cylindrical cyclones which were made by the transparent plastics. The main dimensions were $D_1=140$ mm, $D_0=47.5$ mm, $D_2=47.5$ mm, total length $H_t=375$ mm for returned flow type and $V_0=17$ mm for axial flow type, respectively. Fig. 11 shows the relationship between $\Delta P_0$ and $V_0$ for the two types of the cyclones.

Fig. 12 shows the distributions of the tangential velocities $V_\theta$ at the each $z$ planes beneath the edge of the inner pipe for the two types of the cyclones. In this figure, the values of $\theta_0=\theta / 360$ at the radius $r=a$ are shown. It will be find that the values of $V_\theta$ of the returned flow type are about 20% larger than those of the axial flow type. This phenomenon is one reason why returned flow type shows better collection efficiencies $\eta$ in comparison with the axial flow type.

Fig. 13 shows the diameters $X_c$ which are called in general as cut-size and $X_1$ of an equilibrium particles for $V_0=15$ m/s, defined as

$$X_c = \frac{3}{\tau_2} \frac{V_0}{\mu H_1} \sqrt{\frac{m \cdot Q_0}{P_0 \cdot H_1}}$$  (3)  

$$X_1 = \frac{3}{\tau_2} \frac{V_0}{\mu H_1} \sqrt{\frac{m \cdot Q_0}{P_0 \cdot H_1}}$$  (4),

respectively, where $a$ is the radius at which $V_0$ is corresponding to the maximum value $V_0$ and $\tau_2$ is the boundary radius between the quasi-forced vortex and the quasi-free vortex. From this figure, you will find that the cut-size $X_c$ at the each $z$ planes in the returned flow type is a little smaller than that in the axial flow type and also the particle diameter $X_1$ at the cyclone wall for the returned flow type is a little larger than that for the axial flow type. The physical meaning of the particle diameter $X_1$ is corresponding to the apparent maximum particle diameter which may be regarded as the particles having the possibility of the mechanically rotating motion on the turbulent rotational flow in the cyclone.

Fig. 14 shows the distributions of the tangential $V_0$ and axial $V_z$ velocities at $z=187$ mm in the returned flow cyclone. It is very interesting to note that the radii $a$ for the maximum tangential velocities $V_0$ are located at the radii $r=(0.5 \sim 0.657) R_2$, and that the radii $b$ of the axial veloc-
ties \( \nu_1 = 0 \) are located at the radius \( r = 0.667R \).

Fig.15 shows the distributions of \( \nu_1 \) and \( \nu_2 \) at \( 2r' = 3 \) mm in the axial flow cyclone. These velocities were measured by the cylindrical Pitot-tube of diameter 3 mm. From this figure, it is very important to notice that the axial velocity \( \nu_2 \) shows the reversed flow at the zone of the radius \( r = 30-50 \) mm. This reversed flow plays an important part which hinder the enough centrifugal separation of the fine solid particles due to the couple circulation Fig.11. The zones of air flow.

This is the most important phenomenon for elucidating the worst collection efficiency \( \eta_c \) of the axial flow cyclone.

Fig.16 shows the equi-flow rate lines \( \psi \) which were defined by \( \psi = \frac{\lambda_2 \nu_1 \nu_2}{Q_0} \) (5),

where \( Q_0 \) (m/s) is the flow rate into the cyclone. \( \gamma \) for returned flow type is \( \gamma = 10 \) m/s for \( \nu_1 = 10 \) m/s and \( \gamma = 100 \) for \( \nu_1 = 10 \) m/s and also \( \gamma \) for axial flow type is \( \gamma = 479 \) for \( \nu_1 = 10 \) m/s and \( \gamma = 818 \) for \( \nu_1 = 20 \) m/s, respectively. From this figure, it will be find that the circulation zones or the couple torus Taylor vortices along the vortex core were developed in the axial flow cyclone which was the main factor of decreasing the collection efficiencies \( \eta_c \).

5. CONCLUSIONS

1. On the same energy dissipation of fluid, the returned flow type of the tangential inlet cyclone C1 shows the best collection efficiencies \( \eta_c \) in comparison with the axial flow type of the tangential inlet cyclone.

2. The cone type of the cyclone C3 may be presented the collection efficiency \( \eta_c \), when the dimensions of the sizes of \( D_1, D_2, D_3 \) and the length of the inner pipe are modified.

3. The axial flow type of the tangential inlet cyclone C2 shows the worst collection efficiency \( \eta_c \) due to the generation of the couple eddy currents in the main separation zone for the fine solid particles.

4. The calculated cut-sizes \( X_c \) of the returned flow type of the cyclone are a little smaller than those of the axial flow cyclone, where \( a \) is the radius corresponding to the maximum tangential velocity of air flow.

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Fig.12: Distributions of the tangential velocities at the each Z-plane for the two types of the cyclones for \( \nu_1 = 15 \) m/s.

Fig.13: Calculated diameters of \( X_c \) and \( X_D \) for \( \nu_1 = 15 \) m/s.

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ACKNOWLEDGEMENT
The author should like to appreciate Prof. Dr. M. Suzuki of Saitama Univ., for indicating the several misprints and discussing the physical meaning of $\Psi$ and $\psi$, and Prof. Dr. K. Inoue of Aichi Engineering Univ. for discussing the cyclone constructions and the flow patterns and also Prof. Dr. H. Hashimoto of Tohoku Univ. for discussing the relationship between $\Psi$ and flow patterns and then the development and the critical velocity for the generation of Taylor vortices.

![Fig. 14 Distributions of Vθ and Vz at Z=187 mm for the returned flow type](image)

**Fig. 14** Distributions of $V_\theta$ and $V_z$ at $Z=187$ mm for the returned flow type

**Fig. 15** Distributions of $V_\theta$ and $V_z$ at $Z=187$ mm for the returned flow

**Fig. 16** Equi-flow rate lines for $V_\theta=10$ and 20 m/s