ON THE SPIN-UP TIME AND THE RESIDUE TIME OF THE TURBULENT ROTATIONAL AIR FLOWS IN THE SPECIAL FORMS OF THE CYCLONE DUST COLLECTORS*

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There have been many papers on the experimental and theoretical investigations of the rotational flow characteristics of the standard forms of cyclone dust collectors, or of cylindrical vortex chambers. However up to this time, the experimental studies of the rotational air flows in the spherical forms of cyclone dust collectors or in the semi-sphere and cone combined cyclone dust collectors have seldom been published throughout the world. Therefore in order to recognize the fluid dynamic characteristics of the turbulent rotational air flow in the returned flow types of cyclone dust collectors, the spherical forms and the semi-spherical and cone combined forms of the cyclones were made of transparent acrylic resin. Then, the distributions of the tangential and axial velocities, and also the distributions of the static pressures were measured by the cylindrical Pitot-tube in the five kinds of cyclones. In this paper, the experimental results of the velocity index n of the quasi-free vortex, those of the maximum tangential velocities $V_{\theta M}/V_0$ and those of the coefficients of the pressure drops which were related to the dimensionless time $T=T_2/F$ were described in detail, where T_2 means the spin-up time and F means the residue time in the cyclones.

Key words: Sphere cyclone, Cone cyclone, Spin-up time, Residue time, Centrifugal effect, Pressure drop, Velocity index, Turbulence.

1. INTRODUCTION

Up to this time there were many papers of the experimental and theoretical investigations of the rotational air flow characteristics on the standard forms of the cyclones or on the cylindrical vortex chambers⁽¹⁻³⁾. But experimental and theoretical studies of the rotational air flows in the spherical forms of the cyclone dust collectors or in the semi-sphere and cone combined cyclone were scarcely done in the world⁽⁴⁻⁷⁾. Thereupon it is very importance to recognize the fluid dynamical characteristics of the turbulent rotational air flow in the various forms of the returned flow types of the cyclones for estimating the centrifugal separation processes of the fine solid particles and the pressure drops of the rotational air flow. Then the two kinds of the spherical forms and the semi-spherical and cone combined form of the cyclones were made of the transparent acrylic resin. Here the distributions of the tangential and axial velocities and also the distributions of the static pressures in the normal form, in the cone form and in the above stated three kinds of the forms of the cyclones were measured by a cylindrical Pitot-tube of the diameter 2 mm. Accordingly in this paper, the experimental results of the velocity index n of the tangential velocities of the quasi-free vortex, those of the maximum tangential velocities $V_{\theta M}/V_0$ and those of the coefficients of the pressure

drops which were related to the dimensionless time $T=T_2/F$ were described in detail, where V_0 means the mean inlet velocity in the tangential inlet pipe, T_2 means the spin-up time and F means the residue time of air flow in the cyclone.

2. MAIN SYMBOLS

a (m): a representative radius for the maximum tangential velocity,
 D_0 (m): diameter of the tangential inlet pipe,
 D_1 (m): diameter of the cyclone dust collector,
 D_2 (m): diameter of the exit pipe,
 D_3 (m): diameter of the throat,
 F (s): residue time of air flow in the cyclone,
 H_i (m): imaginal cylindrical length,
 n (1): velocity index of the quasi-free vortex,
 p (Pa): static pressure,
 p_a (Pa): atmospheric pressure,
 Δp_{ca} (Pa): apparent static pressure drop,
 Δp_{cc} (Pa): static pressure difference,
 Δp_c (Pa): pressure drop of the cyclone,
 Δp_{ST} (Pa): static pressure depression in cyclone,
 Q_0 (m³/s): flow rate of gas,
 Re (1): Reynolds number,
 T (1): dimensionless time,
 T_2 (s): spin-up time,
 V_{CB} (m³): volume of the main body of cyclone excluded the volume of the exit pipe volume,
 V_{θ} (m/s): tangential velocity,
 $V_{\theta M}$ (m/s): the maximum tangential velocity,
 V_0 (m/s): mean inlet velocity in the inlet pipe,
 ζ_c (1): coefficient of the pressure drop,
 ν (m²/s): kinematic viscosity of gas,
 ξ (1): coefficient of the static pressure depression in the cyclone,
 ρ (Kg/m³): density of gas,
 ω_0 (rad/s): angular velocity at the vortex center of the quasi-forced vortex.

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3. EXPERIMENTAL APPARATUS AND EXPERIMENTAL METHOD

Fig.1 shows the five forms of the cyclones which were made of the transparent acrylic resin. The main dimensions are as follows;

- (a) NOR-cyclone, $D_0=39$ mm, $D_1=115$ mm, $D_2=39$ mm;
- (b) CONE-cyclone, $D_0=29.7$ mm, $D_1=99.7$ mm, $D_2=29.7$ mm, $D_3=10.5$ mm;
- (c) SCCL-cyclone, $D_0=37$ mm, $D_1=181$ mm, $D_2=37$ mm, $D_3=61$ mm;
- (d) SCL-cyclone, $D_0=43$ mm, $D_1=161$ mm, $D_2=37$ mm, $D_3=90$ mm;
- (e) SCS-cyclone; $D_0=25$ mm, $D_1=90$ mm, $D_2=25$ mm, $D_3=32$ mm, respectively, where D_0 means the diameter of the inlet pipe, D_1 the diameter of the cyclone, D_2 the diameter of the exit pipe and D_3 the diameter of the throat. And in those figures, a symbol P-t means the location of the Pitot-tube beneath the edge of the exit pipe. And then in order to measure the distributions of the tangential V_θ and axial V_z velocities and also those of the static pressures p , a cylindrical Pitot-tube of the diameter 2 mm was used. Hence the previously established mean inlet velocities were $V_0=10.0, 15.0$ and 20.0 m/s, respectively.

Fig.2 shows the schematic illustration of the static pressure in the cyclone. A symbol $V_{\theta M}$ is the maximum tangential velocity at the radius $r=a$, and also ω_0 means the angular velocity at the vortex center ($r=0$). Thereupon the spin-up time T_2 and Reynolds number Re_c can be defined as

$$T_2 = \frac{R_2}{\sqrt{V_{\theta M} \omega_0}}, \quad Re_c = \frac{Q_0}{H_1 V} \quad (1),$$

where H_1 means the imaginary cylindrical length. Further when the volume of the cyclone main body which is excluded the volume of the exit pipe (inner pipe) denotes by V_{CB} , and the flow rate of air into the cyclones is Q_0 , so the mean residue time F of air flow in the cyclone main body may be estimated as

$$F = V_{CB}/Q_0 \quad (2).$$

Therefore a dimensionless time T can be introduced as

$$T = T_2/F \quad (3).$$

On the other hand the static pressure depression ΔP_{ST} from the outer wall to the center axis in the cyclone body can be defined as

$$\Delta P_{ST} = \xi \rho \frac{V_0^2}{2} \quad (4),$$

where ξ is the coefficient of the static pressure depression in the cyclone, in addition to this the pressure drop ΔP_c of the cyclone is defined as

$$P_c = \xi_c \rho \frac{V_0^2}{2} \quad (5),$$

where ξ_c is called as a coefficient of the pressure drop. Moreover in order to estimate the true pressure drop ΔP_c , the method as shown in Fig.2 was applied and ΔP_c can be calculated as

$$\Delta P_c = \Delta P_{ca} + \rho \frac{V_0^2}{2} \quad (6),$$

where a symbol ΔP_{ca} indicates the apparent static pressure drop between the inlet pipe and the exit pipe, and also ΔP_{cc} indicates the static pressure differences between the static pressure in the inlet pipe and the atmospheric pressure p_a .

4. EXPERIMENTAL RESULTS

4.1 VELOCITY DISTRIBUTIONS AND THE STATIC PRESSURES

Fig.3 shows the distributions of the tangential and axial velocities and also of the static pressures for (a) NORMAL, (b) CONE, (c) SCCL, (d) SCL and (e) SCS cyclones, and further the surmised flow patterns which were estimated from the results of the axial velocity distributions

Fig.1 Main sizes of the five kinds of the cyclone dust collectors.

Fig.2 Schematic illustration of the main symbols.

Fig.3 Distributions of the tangential and axial velocities and of the static pressures in the five kinds of the cyclone dust collectors.

are shown for the each cyclones. On the distributions of the tangential velocities V_θ , the velocity distribution of the quasi-free vortex can be written as

$$V_\theta r^n = \int_n = \text{const.} \quad (7)$$

The experimental relationship between n and T will be shown in Fig.6. Secondary the distributions of the axial velocities show the different peculiarity on the each cyclones except the NORMAL cyclone. Those peculiarities may be caused by the effect of the boundary layer and by the production of Görtler vortex on the solid surface of the spherical form⁽¹⁰⁾. The similar phenomenon was observed in the returned flow type of the eccentric cyclone⁽¹¹⁾. Thirdly concerning the distributions of the static pressure, it was very difficult to measure the true static pressure near the center axis, since the motion of the vortex core vibrates violently. Consequently the estimated static pressure depression ΔP_{ST} may not always show the exact static pressure depression.

4.2 RELATIONSHIP BETWEEN F AND T_2

Fig.4 shows the relationship between F and T_2 for the various kinds of the cyclones besides the above stated five kinds of cyclones of Fig.1. The main sizes D_1 and D_2 of the given cyclones and also the positions of the Pitot-tube Z beneath the edge of the exit pipe are shown in the numerical table in Fig.4. From those results, in spite of the various forms of the cyclones it tacitly looks like deep correlation between F and T_2 except one cylindrical cyclone ($D_1 = 290$ mm) of $D_1/D_2 = 5.8$, and further without exception the spin-up time T_2 increases with increasing the residue time F . Then the relationship T_2 and F for the each cyclone may be described as

$$F \propto T_2^k \quad (8)$$

and the value of the index k is shown for the each cyclone as shown in Fig.4⁽¹²⁾.

4.3 RELATIONSHIP BETWEEN n , Rec AND T

Fig.5 shows the relationship between Reynolds number Rec and the velocity index n for the various kinds of the cyclones, where the symbol indications are shown in Fig.4. From those results, it will be shown that the velocity index n can not be treated by only Reynolds number Rec which depends on the shapes and the sizes of the cyclones and the driving conditions. On the other hand as shown in Fig. 6, the values of n can be treated by the dimensionless time T except one cylindrical cyclone of $D_1/D_2 = 5.8$. And also it is very interesting to note that the high values of n are distributed near $T \approx 1$.

4.4 RELATIONSHIP BETWEEN $V_{\theta M}/V_o$ AND T

Fig.7 shows the relationship between the dimensionless maximum tangential velocity $V_{\theta M}/V_o$ and T . For the cyclones of the smooth surfaces (acrylic resin), the values of $V_{\theta M}/V_o$ are inclined to increase with decreasing the values of T , but for the cyclones of the steel plates, $V_{\theta M}/V_o$ is inclined to increase with increasing T .

4.5 STATIC PRESSURE DEPRESSION AND COEFFICIENT OF PRESSURE DROP

Fig.8 shows the relationship between the static pressure depression ΔP_{ST} (Pa) and the centrifugal effect $V_{\theta M}^2/ga$ (1) for $Rec = 2700 - 12000$. An empirical equation could be written as

$$\Delta P_{ST} = 3.15 \left(\frac{V_{\theta M}^2}{ga} \right)^{0.7} \quad (9)$$

Fig.9 shows the relationship between the coefficient of the pressure drop ξ_c and $V_{\theta M}^2/ga$ ⁽¹³⁾.

Fig.4 Relationship between T_2 and F .

Fig.5 Relationship between Rec and n .

Fig.6 Relationship between T and n .

An empirical equation ξ_c could be written as

$$\xi_c = 2.65 \left(\frac{V_{\theta M}^2}{ga} \right)^{0.15} \quad (10)$$

On the other hand, the relationship between ξ_c and T can be shown in Fig.10. From this result, it is very interesting to note that the high values of ξ_c are distributed near $T \approx 1.0$ which is corresponding to the experimental result as shown in Fig.6.

Fig.11 shows the relationship between ξ/ξ_c and T . This result indicates that the values of ξ/ξ_c increases with decreasing the values of T which are corresponding to the experimental result as shown in Fig.7.

5. CONCLUSIONS

1. As shown in Fig.4, in spite of the various forms of the cyclones there are the deep relationship between the spin-up time T_2 and the residue time F .
2. As shown in Fig.6, the velocity index n can be treated by the dimensionless time $T = T_2/F$.
3. As shown in Fig.7, the dimensionless maximum tangential velocity $V_{\theta M}/V_o$ can be represented by T .
4. As shown in Fig.8, the static pressure depression ΔP_{ST} can be represented by the centrifugal effect $V_{\theta M}^2/ga$ and can be obtained by eq.(9).
5. As shown in Fig.10, the coefficient of the pressure drop ξ_c can be represented by T . Then the high values of ξ_c and n are distributed near $T \approx 1.0$.
6. As shown in Fig.11, the values of ξ/ξ_c increase with decreasing the values of T .

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Fig.7 Relationship between $V_{\theta M}/V_o$ and T .

Fig.8 Relationship between ΔP_{ST} and $V_{\theta M}^2/ga$.

Fig.9 Relationship between ξ_c and $V_{\theta M}^2/ga$.

Fig.10 Relationship between ξ_c and T .

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Fig.11 Relationship between $\bar{P}/L_C$ and T .