The Aerosol Classification Performance of A Rectangular Jet Virtual-Impactor

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Abstract

The aerosol classification performance of a newly constructed rectangular jet virtual-impactor has been studied both theoretically and experimentally. It is found that the performance is well represented by potential flow calculations with modifications for the effects of the acceleration jet and flow separation at the slit. The sharpness of the classification is not as good as that of a round jet impactor, and the variable range of the cut size is smaller. In the rectangular jet impactor, however, a higher flow rate of aerosol can be treated without changing the cut size. It is also found that higher degrees of sharpness are obtained and that the cut size is variable within a certain range by introducing clean air flows as in the round jet impactor previously developed by the authors. The separation characteristic is found to be well explained by assuming perfect mixing between the aerosol flow and the clean-air flows at both ends of the rectangular jet. The maximum inertia parameter limited by the sound velocity is also discussed, and an empirical equation representing the pressure drop of the impactor is presented.

Introduction

Particles rebound or will be reentrained by air flow when a collision type impactor is used for the measurement of particle size or for the classification of fine particles. To avoid these phenomena, a virtual-impactor (hereinafter, referred to as “V. impactor” or only “impactor”) has been developed, and its classification mechanism has been studied1-4). We have studied and shown that the efficiency of the impactor can be improved by introducing clean air into the core and sheath of the aerosol flow, and the 50% cut size and gradient of the separation efficiency curve can be adjusted within a specific range5). Moreover, we have shown that testing aerosols possessing relatively uniform particle sizes can be generated using the two-stage type V. impactor6). All of the impactors tested are of the round jet type.

The round jet virtual impactor, however, has an inherent disadvantage in that it cannot be scaled-up while maintaining constant classification performance parameters. Consequently, the quantity being treated cannot be increased. In this study, a rectangular jet impactor was constructed and its classification performance was investigated both theoretically and experimentally using mono-disperse aerosol particles.

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2. Impactor configuration and theoretical calculation

2.1 Impactor configuration, and separation efficiency when introducing clean air

Figure 1 shows the outline of the constructed rectangular jet impactor. The total length of the brass-made impactor is approx. 20 cm. The jet (4) (width: 1 mm, length: 10 mm) is positioned facing the nozzle (5) in the slit, and particles are classified there. The impactor is designed so that aerosol is introduced through (1) and clean air through (2) and (3). The aerosol and air are then accelerated by the jet (4). Particles are classified according to their aerodynamic diameters, as coarser aerosol having larger inertia discharges through (7) and finer aerosol having smaller inertia discharges through (6). The slit gap between the acceleration jet (4) and the collection nozzle (5) can be adjusted using the adjustment screw (8) and the spacer (10). Two flow laminators are positioned in the laminator (9), each with six 3 mm inner diameter holes, which streamline the clean air flow.

Figure 2 illustrates a schematic diagram of the aerosol classification mechanism of the rectangular jet impactor when clean air is introduced. Mono-disperse aerosol particles accelerated by the jet are separated to the right and left of the critical particle trajectory illustrated by the broken line. The separation efficiency $\eta$ is given as follows:

$$
\eta = \frac{\int_{B_a}^{B_c} l \cdot u \cdot n \cdot dx}{\int_{0}^{B} l \cdot u \cdot n \cdot dx} \tag{1}
$$

If the number concentration of aerosol particles $n(x)$ satisfies the following equation in the $x$ direction of the jet width:

$$
n(x) = \begin{cases} 
0 & : 0 \leq x < B_a \\
n = \text{const} & : B_a \leq x \leq B_b \\
0 & : B_b < x \leq B
\end{cases} \tag{2}
$$

When the critical particle trajectory is within the right or left of the clean air flow, the first and third equations of Eq. (2) give the separation efficiency as follows;
\[ \eta = 0 \quad \text{for} \quad 0 \leq B_t < B_a \quad (3) \\
\eta = 1 \quad \text{for} \quad B_b < B_c \leq B \quad (4) \\
\]

On the other hand, when the critical particle trajectory is within the aerosol flow as shown in Fig. 2, the second equation of Eq. (2) gives,

\[ \eta = \frac{\int_{B_a}^{B_c} u \, dx}{\int_{B_a}^{B_b} u \, dx} \quad \text{for} \quad B_a \leq B_c \leq B \quad (5) \]

assuming that \( n(x) \) does not change in the direction of the jet length \( l \). Eq. (5) is rewritten as follows:

\[
\eta = \frac{\int_{0}^{B_c} u \, dx}{\int_{0}^{B_b} u \, dx} \cdot \frac{\int_{B_a}^{B_c} u \, dx}{\int_{B_a}^{B_b} u \, dx}
\]

\[
= \frac{\int_{0}^{B} u \, dx}{\int_{0}^{B_a} u \, dx} \cdot \frac{\int_{B_a}^{B_c} u \, dx}{\int_{B_a}^{B_b} u \, dx}
\]

where

\[
I \cdot \int_{0}^{B} u \, dx = Q_t, \quad I \cdot \int_{B_a}^{B_b} u \, dx = Q_p, \quad I \cdot \int_{0}^{B_a} u \, dx = Q_e
\]

The number of particles that flow on the left side of the critical particle trajectory are collected in the collection nozzle. If the flow rate is denoted by \( Q_x \), Eq. (6) is represented by:

\[ \eta = \frac{Q_t}{Q_p} \cdot \frac{Q_x}{Q_t} - \frac{Q_c}{Q_p} \quad (7) \]

where \( Q_x/Q_t \) is the separation efficiency \( \eta_0 \) when clean air is not introduced. When flow rate ratios \( \alpha \) and \( \beta \) are defined by the following equations,

\[ \alpha = \frac{Q_t}{Q_p}, \quad \beta = \frac{Q_c}{Q_p} \quad (8) \]

Eq. (7) reads:

\[ \eta = \alpha \eta_0 - \beta \quad (9) \]

Eq. (9) suggests that the impactor may have a sharp classification performance by selecting appropriate flow rate ratios \( \alpha \) and \( \beta \).

2. 2 Numerical analysis of separation efficiency \( \eta_0 \)

This section describes separation efficiency \( \eta_0 \) when clean air is not introduced. Using the finite difference method described in the previous report, separation efficiency was obtained by assuming that the air flow was represented by a potential flow. The flow in the impactor is, however, two-dimensional and therefore, the dimensionless stream function \( \varphi \) shown below was used:

\[ \frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} = 0 \quad (10) \]

The dimensionless velocity components in the \( x \) direction (right angle to the flow direction) and in the \( y \) direction (flow direction) are given by:

\[ u_x = \frac{\partial \varphi}{\partial y}, \quad u_y = -\frac{\partial \varphi}{\partial x} \quad (11) \]

The area including the jet acceleration zone was divided into 1180 triangular elements (number of nodes: 660) and was numerically calculated by the finite element method. (Details of the calculation are omitted.) The approximation analysis, obtained by using the same method as in a previous report, and the numerical analysis of the acceleration jet effect satisfactorily coincided. This coincidence suggests that the effect of the acceleration jet deflects the particles toward the center line. This effect is caused by particle inertia at the converging zone where the particles enter from the inversed triangle acceleration zone to the straight flow channel. The inversed triangle acceleration zone and straight flow channel are smoothly connected by a curvature radius of 10 mm. If it is assumed that the mean air velocity in the jet is \( u_c \), the deviation \( \delta \) of the particle trajectory at the jet inlet can be approximated using the following equation:

\[ \delta = \tau u_c \tan \theta \quad (12) \]

where \( \tau \) is the particle relaxation time, and \( \theta \) is the half angle (20 deg.) of the converging zone of acceleration jet. The air flow on both sides \( \delta \), given by Eq. (12) in the straight flow channel (width \( B \)), does not include aerosol particles. Therefore, by permitting the separation
efficiency to be \( \eta_0' \) when not affected by the acceleration jet, and to be \( \eta_0 \) where there is acceleration jet, the following equation is obtained:

\[
\eta_0 = \frac{B_0 - \delta}{B - 2\delta} = \frac{\eta_0' - \delta}{1 - 2\delta}
\]  

(13)

where \( \delta \) is a dimensionless deviation defined by:

\[
\delta = \frac{\delta}{B} = \frac{u_c}{u_0} \psi \tan \theta
\]  

(14)

\( \psi \) is the particle inertia parameter. Since the flow separates from the lower edge of the jet when the flow enters from the jet to the slit\(^2\), this effect should be considered. In this study, the flow separation effect using an enlarged transparent model was observed, and a numerical analysis was done assuming the interface to be a rigid wall. However, since the flow separation effect can be ignored when the slit width ratio is 0.25, the calculation, taking into account the separation effect, was done when the slit width ratio was 0.5 and 1.0. Figure 3 summarizes the results of these analyses\(^*\).

3. The apparatus of the experiment and the method used

Figure 4 outlines the apparatus of the experiment. In this study, latex suspension was appropriately diluted, and the aerosol for testing was generated by spraying the suspension with a nebulizer. The generated aerosol was fed into the impactor via the ribbon heater and diffusion dryer. The flow rate at each location was measured using rotameters calibrated in advance with a gas meter. Ambient air was filtered with a glassfiber filter (GB-100R produced by TOYO ROSHI Corp.) and introduced into the impactor as clean air. Aerosol particles classified with the impactor were collected using Sartorius-Membrance filter F1 or F2 and were subjected to the process described in the previous report\(^6\). They were then observed and counted by means of a microscope.

Table 1 lists the conditions of the experiment. Experiments were carried out for slit width ratios \( S_l \) of 0.25, 0.5, and 1.0, and a flow rate ratio \( Q_r = (Q_u/Q_t) \) of 0.1. All experiments done by introducing clean air were conducted by fixing the slit width ratio at 0.5. The pressure at the slit exit and the ambient pressure were measured using a vacuum gauge, and Cunningham’s slip correction was carried out.

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\* The square root of the inertia parameter was used as the abscissa of the figure in order to make it easy to understand the correspondence between the separation efficiency and particle size. In the following description, \( \sqrt{\psi} \) is also designated as an inertia parameter to simplify the description. To avoid confusion, the symbol \( \sqrt{\psi} \) has also been included.
Table 1 Conditions of the experiment

| Aerosol  | PSL ($\rho_p = 1.05 \times 10^3$ kg/m$^3$)  
|          | $D_p = 0.804, 1.091 \mu$m)  
|          | PVT ($\rho_p = 1.03 \times 10^3$ kg/m$^3$)  
|          | $D_p = 2.020 \mu$m)  
| Number concentration of aerosol | 31 - 1590 $\times 10^6$ [particles/m$^3$]  
| Total flow rate | $Q_t = 8 - 104$ [l/min]  
| Mean air velocity in jet | $u_0 = 12 - 166$ [m/s]  
| Mean air velocity in slit | $u_{fl} = 19 - 288$ [m/s]  
| Inertial parameter | $\sqrt{\psi_{50}} = 0.2 - 1.5$ [-]  
| Flow Reynolds number | $R_e = 1500 - 19700$ [-]  
| Jet dimmension | $B = 0.102$ [cm], $l = 1.022$ [cm]  
| Slit width ratio | $S_t = 0.25, 0.5, 1.0$  
| Flow rate ratio | $Q_r = 1/10$  

* PSL = Polystyrene Latex  
PVT = Polyvinyltoluene

4. Results of the experiment and discussion

Figure 5 shows the relationship obtained between the inertia parameter and separation efficiency when no clean air flowed into the jet. The figure shows that the smaller the slit width ratio $S_t$ is, the smaller the inertia parameter $\sqrt{\psi_{50}}$ is in order to obtain 50% separation efficiency. The separation efficiency curves of slit width ratios of 0.25, 0.5, and 1.0 are almost parallel. That is, the sharpness of the classification performance does not depend on

Fig. 5 Comparison between calculation and experimental separation efficiencies

Fig. 6 Separation characteristics of the rectangular jet impactor compared with those of the round jet impactor.

Fig. 7 Interia parameters as a function of the ratio of slit gap to jet breadth

the slit width ratio. Solid lines in Fig. 5 represent the numerical-analysis results shown in Fig. 3, wherein the calculation results, in which the air flow is assumed as a potential flow, are modified based on the effects of the acceleration jet and the flow separation at the slit. The
Figure 6 shows the relationship between the inertia parameter $\sqrt{\psi}$ and separation efficiency $\eta_0$ of rectangular- and round-jet-impacters having the same slit width ratio. The solid and broken lines represent the results of the experiment using rectangular and round jet impacters. Only the data of $S_l = 0.5$ was plotted to obtain a clear figure. The data on the round impactor were quoted from the previous report\(^\text{(69)}\). The figure shows that the round jet impactor can obtain sharper classification performance and that its inertia parameter $\sqrt{\psi_{50}}$ for obtaining 50% separation efficiency varies depending on the slit width ratio. The smallest particle that the present impactor can classify without using clean air is discussed next.

Figure 7 illustrates the dependencies of both the calculated maximum inertia parameter $\sqrt{\psi_{\text{max}}}$ limited by the sound velocity (described below), and the experimentally obtained inertia parameter $\sqrt{\psi_{50}}$, to obtain 50% separation efficiency, in which the slit width ratio of an impactor has a jet width of $B = 1$ mm.

The maximum inertia parameter limited by the sound velocity represents an inertia parameter for the mean air velocity in jet $u_0$ when either the jet velocity or slit velocity reaches acoustic velocity. In this experiment, since the slit width ratio $S_l$ is smaller than 1, the critical condition is obtained when the slit velocity reaches the acoustic velocity. However, since flow separation occurs at the slit as described above, the effects of the flow separation should be corrected. In this study, $S_l' \times (\text{sound velocity})/0.9$ was entered into the mean air velocity in jet $u_0$ using the theoretical calculation result reported by Forney et al.\(^\text{(19)}\), where the correction coefficient 0.9 means that 90% of the total flow rate $Q_t$ was drawn into the slit side ($Q_r = 0.1$). $S_l'$ is the value of the slit width ratio corrected for flow separation. ($S_l' = 0.128, 0.248, 0.339, 0.400, 0.455$ correspond to $S_l = 0.2, 0.4, 0.6, 0.8, 1.0$. The ratio $S_l'/S_l$ is 0.640, 0.620, 0.563, 0.500, 0.455.) The results reported by Forney et al. agree with the observed results of flow separation using the enlarged transparent model.

If the curve of the maximum inertia parameter $\sqrt{\psi_{\text{max}}}$ limited by the sound velocity of a specific particle size is below the curve of inertia parameter $\sqrt{\psi_{50}}$ for obtaining 50% separation, it is impossible for more than 50% of the particles of a specific size to move directly into the coarser particle zone. Accordingly, it can be understood that the present impactor can classify particles of an aerodynamic diameter of 1 micron, but it cannot classify particles of aerodynamic diameter of 0.8 micron or less, irrespective of the slit width ratio. The curve of $\sqrt{\psi_{50}}$ varies parallel to the curve of $\sqrt{\psi_{\text{max}}}$, as shown in Fig. 7. Therefore, the minimum particle diameter able to be classified at the maximum suction rate, when the mean air velocity in the slit reaches acoustic velocity, does not depend on the slit width ratio.

Figures 8 and 9 show the relationships between the inertia parameter $\sqrt{\psi}$ and the separation efficiency $\eta$ when clean air is introduced into the jet. These experiments were carried out under the following conditions: the slit width ratio $S_l$ was 0.5, and flow rate ratio $Q_r$ was 1/10, where $\alpha = 2$, and $\beta = 0.5$ represents that the sectional mean velocity ratio of clean air introduced from (2) to aerosol flow introduced from (1) to the clean air flow from (3) at the converging zone of the jet which is 1:1:1. $\alpha = 2$, and $\beta = 0$ represents 0:1:2, and $\alpha = 2$, and $\beta = 1$ represents 2:1:0. The solid lines represent the separation efficiency $\eta_0$ when clean air was not introduced, and the chain lines represent the calculated separation efficiency.
when clean air was introduced, obtained by substituting $\eta_0$ represented by the solid line into Eq. (9). The broken line represents a calculation result assuming that the aerosol flow and clean air flow are not completely separated into three layers in the jet, and that they are mixed at both ends of the jet in the lengthwise direction. That is, by assuming they are completely mixed in the length $\gamma$ times the jet width $B$, separation efficiency $\eta_e$ is given by:

$$\eta_e = \frac{2\gamma}{l} \eta_0 + \frac{l - 2\gamma}{l} \eta$$

(15)

where $l$ is the length of the rectangular jet.

The broken line represents the separation efficiency obtained by substituting $\gamma = 2B$ into the above equation. When $\alpha = 2$, $\beta = 0.5$ (Fig. 8), that is, the aerosol flow and clean air flow are introduced at the same velocities, the sharpness of the classification performance is improved more than when clean air is not introduced, showing that the separation efficiency of finer particles (in the lower inertia region) decreases below the undeflected flow rate. These results are satisfactorily represented by the broken lines wherein the end effect is considered. When $\alpha = 2$, $\beta = 0$ (Fig. 9), that is, clean air flow at the opposite side of the slit is not introduced, the inertia parameter for obtaining 50% separation can be reduced without reducing the slit width ratio, however, the separation efficiency in the lower inertia region becomes less sharp. These results are also satisfactorily represented by the broken lines wherein the end effect is considered. When $\alpha = 2$, $\beta = 1$, that is, clean air flow at the slit side is not introduced, and the separation efficiency curve moves toward the right. These results are also satisfactorily represented by the broken lines wherein the end effect is considered.

The following empirical equation was obtained by measuring the differential pressure $\Delta P$ between the static pressure at the exit of the present impactor and the atmospheric pressure. This was done by changing the mean air velocity in jet $u_0$ and slit width ratio $S_l$, and by making a linear approximation on the double logarithm graph using the least squares method.

$$\Delta P = 2.82 S_l^{-0.84} \cdot \rho_i u_0^{-2.00} \text{ [Pa]}$$

(16)

where $\rho_i$ is air density at the impactor inlet.

The 68 items of data are obtained for the slit width ratios 0.25, 0.5, and 1.0, and the standard deviation of the estimated value in the above equation is $1.8 \times 10^3$ Pa.

5. Conclusion

A rectangular jet virtual impactor was constructed to study aerosol classification performance both theoretically and experimentally, and the following results were obtained:

1) The separation efficiency curves (without introducing clean air) obtained by potential flow calculation with modifications of the effects of the acceleration jet and the flow separation at the slit, satisfactorily agree with the experimentally obtained results.

2) The sharpness of classification was not as good as that of a round jet impactor, and the variable range of the cut size was smaller.

3) The mean air velocity at the slit reaches the sound velocity earlier than at the jet in the present impactor. This differs from the round jet impactor. Therefore, the width and length of the jet should be determined with respect to this consideration. The minimum cut size at the maximum flow rate reaching the sound velocity does not depend on the slit width ratio.

4) Higher degrees of classification performance
sharpness were obtained by introducing clean air flows into both sides of the aerosol flow, and the cut size was variable with in a certain range by adjusting the flow rate of the introduced clean air flow.

5) The separation characteristics when clean air was introduced were well explained by assuming perfect mixing between the aerosol flow and the clean air flows at both ends (twice the jet width) of the rectangular jet.

Nomenclature

\( B \) : jet width [m]
\( B_a \) : left end of aerosol flow (Fig. 2) [m]
\( B_b \) : right end of aerosol flow (Fig. 2) [m]
\( B_c \) : critical position (critical trajectory, Fig. 2) [m]
\( C \) : Cunningham's correction factor [-]
\( D_p \) : particle diameter [m]
\( l \) : jet length [m]
\( n \) : number concentration of aerosol particles [particles/m³]
\( \Delta P \) : pressure difference [Pa]
\( Q_e \) : clean air flow rate (Fig. 2) [m³/s]
\( Q_p \) : aerosol sample flow rate [m³/s]
\( Q_t \) : total flow rate [m³/s]
\( Q_u \) : undeflected flow rate through nozzle [m³/s]
\( Q_s \) : flow Reynolds number in jet \( = B u_o p / \mu \) [-]
\( S_t \) : ratio of slit gap to jet width [-]
\( S_f \) : \( S_t \) corrected for flow separation [-]
\( u \) : air velocity [m/s]
\( u_o \) : mean air velocity in jet [m/s]
\( \bar{x} = x / B \) : dimensionless coordinates [-]
\( \gamma \) : parameter in Eq. (15) [-]
\( \delta \) : deviation of particle trajectory at jet inlet [m]
\( \delta / B \) : [-]
\( \eta \) : separation efficiency [-]
\( \eta_0 \) : separation efficiency (without clean air) [-]
\( \eta_e \) : separation efficiency (without acceleration-jet, without clean air) [-]
\( \theta \) : half angle of converging zone of acceleration-jet [rad]
\( \mu \) : air viscosity [kg/m·s]
\( \rho_i \) : air density at impactor inlet [kg/m³]
\( \rho_p \) : particle density [kg/m³]
\( \tau \) : particle relaxation time \( (= D_p^2 / 18 \mu) \) [s]
\( \psi \) : dimensionless stream function [-]
\( \phi \) : inertia parameter \( (= \rho_p D_p^2 u_o C / 18 \mu B) \) [-]

References

1) Conner, W. D.: *J. Air Pollut. Control Assoc.*, 16, 35 (1966).
2) Forney, L. J., D. G. Ravenhall and D. S. Winn: *J. Appl. Phys.*, 49, 2339 (1978).
3) Forney, L. J., D. G. Ravenhall and S. S. Lee: *Environ. Sci. Technol.*, 16, 492 (1982).
4) Marple, V. A. and C. M. Chien: *Environ. Sci. Technol.*, 16, 492 (1982).
5) Masuda, H., D. Hochrainer and W. Stöber: *J. Aerosol Sci.*, 10, 275 (1979).
6) Masuda, H. and T. Motooka: *Kagaku Kogaku Ronbunshu*, 8, 717 (1982).
7) Yoshida, H., K. Fujii, Y. Yonemoto, H. Masuda and K. Iinoya: *Ibid*, 4, 419 (1978).