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Flow Visualization of a Compound Swirl Jet with a Thick Rim

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Abstract : The conventional push-pull type ventilating system has two different functions: collection and ventilation. The entrainment flow of the jet is available for collecting suspended materials such as smoke, vapor and dust. In order to achieve more effective cleaning of dirty air, a compound swirl jet, which is composed of a coaxial annular swirl jet and a round free jet with a thick rim was proposed by the authors. A compound swirl flow has been shown to be very useful for the push-pull type ventilator by selecting the flow ratio of the annular swirl jet to the round free jet. As a fundamental study on the compound swirl flow, flow visualization was carried out using the smoke method to clarify the structure of the flow interaction between the round free jet and the annular swirl jet, respectively. As a result, a most suitable flow ratio for a push flow of the push-pull type ventilator was found to exist.

Keywords : Swirl flow, Entrainment, Push-pull type ventilator, Smoke method.

1. Introduction

The ventilation of dirty air is very important to maintaining the environment of a room, especially kitchens, smoky areas, and factories. Many types of ventilator have been developed thus far. This paper considers a push-pull type ventilating system (e.g., Hayashi, 1973). The conventional push-pull type ventilating system has two different functions: collection of many kinds of suspended particles in the surrounding air and ventilation of the collected particles to the outside. The entrainment flow of the jet is available for collecting the suspended materials as smoke, vapor and dust. As far as the authors are aware, a free jet flow has been used as the push flow of the push-pull ventilator. It can be considered that the swirl flow is to be used as the collecting flow because of it has a stronger entrainment effect than the free jet. However, the swirl jet diffuses rapidly in the downstream direction and it is desirable to the push flow as uniformly as possible, at least until reaching the pull unit (e.g., Hayashi, 1982).

In order to achieve more effective cleaning of dirty air, a compound swirl jet, which is composed of a coaxial annular swirl jet and a round free jet with a thick rim was proposed by the authors (e.g., Nozaki et al., 1998, 2000). It was found previously that a compound swirl flow is very useful for the push-pull type ventilator by selecting the suitable flow ratio of the coaxial annular swirl jet to the round free jet (e.g., Nozaki et al., 2001). However, the smoke was mixed only in the annular swirl jet, and then the flow interaction between the free jet and the annular swirl jet could not be clarified precisely. As a fundamental study on the compound swirl flow, flow visualization was carried out using the smoke method to clarify the structure of the flow for the round free jet and the annular swirl jet, respectively.

2. Experimental apparatus and method

Figure 1 shows the experimental apparatus and the instruments of the compound swirl flow. A compressor is used as the power source for the round free jet, and the centrifugal blower is used for the annular swirl jet. It is difficult to introduce the smoke to the free jet, so a smoke chamber is mounted in the system. It was found previously that the characteristics of the compound swirl jet change with the flow rate ratio of the free jet to the annular swirl jet (e.g., Nozaki et al., 2000). Experiments were carried out for flow rate ratios of Q_s/Q_j=1.1 for the case of inadequate swirl, 2.0 for the case of adequate swirl and 2.7 for the case of too much swirl as the flow rate of the free jet Q_j was held constant at 0.77×10^{-3} m^3/s (mean velocity: 61.3 m/s). The visualized pictures were taken by a CCD camera (SONY, XC-003, Frame rate 1/30 sec, Resolution 768(H)×494(V)) and recorded using a digital video cassette recorder (SONY, DSR-30). The YAG laser (NEW WAVE RESEARCH, Y15-2L, Power 15 mJ/pulse, Wavelength 1/30 sec) was also used as a light source. The laser is placed at a distance of 2 m from the nozzle. The photographs were taken in the r-z section and r-θ section at z/D_{so}=1.

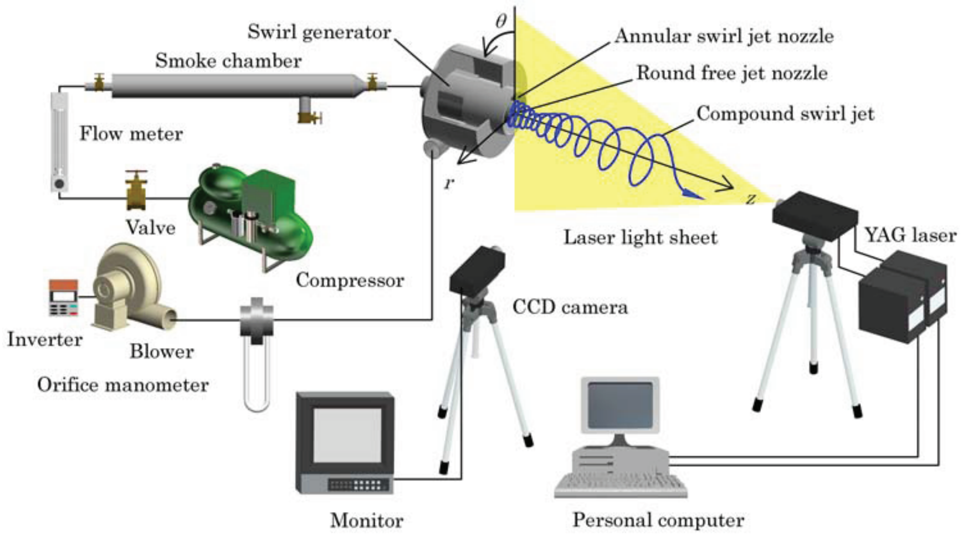


Fig. 1. Experimental apparatus and instruments.

Figure 2 shows the compound swirl generator. The generator consists of a pre-swirl chamber and four swirl vanes. The air from the blower is introduced in the tangential direction to generate the swirl flow, and is then introduced to the coaxial annular pipe through four swirl vanes to increase the swirl component of the flow. In this paper, each dimension was decided considering the actual push-pull ventilator applied for a smoking table, as D_{ps}= 71 mm, D_{so}= 100 mm, D_{si}= 48 mm,

D_j = 4 mm, L_a = 150 mm, L_g = 60 mm, b = 4 mm and T_j = 22 mm. Then, in this case, the free jet is fully developed in the pipe before issuing to the test section.

The swirl number of the annular swirl jet, which indicates the intensity of the swirl flow is given by

$$Sw = \frac{2\pi\rho \int_0^\infty U_z U_\theta r^2 dr}{2\pi\rho R \int_0^\infty U_z^2 r\, dr} ,$$

where U_z and U_θ are the axial and tangential velocity, respectively, R is the jet radius and ρ the density of air. The swirl number is fixed by the configuration of the swirl generator. The swirl number at the nozzle exit is held constant at 1.5 regardless of the flow rate ratio and the geometrical conditions are also held constant throughout this experiment. In order to clarify the flow, flow visualization was carried out using the smoke method to clarify the structure of the flow interaction between the round free jet and the annular swirl jet. The smoke was generated by burning the incense sticks.

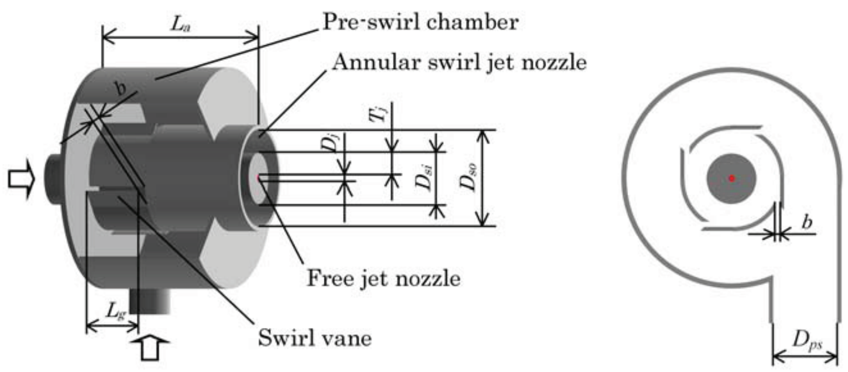


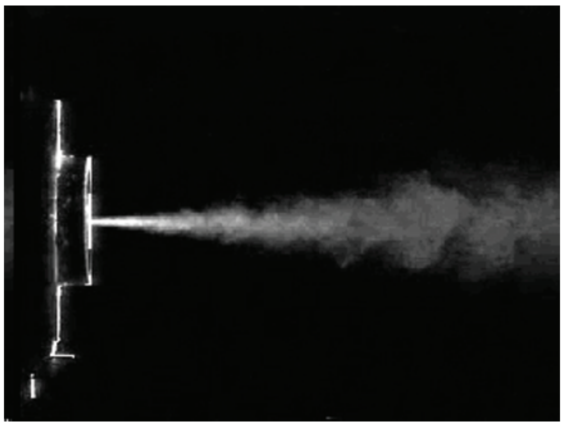
Fig. 2. Compound swirl jet generator.

3. Experimental results and discussion

Figures 3 (a) and (b) show the visualized images of the annular swirl jet and the round free jet, respectively. As shown in Fig. 3 (a), the diffusion progresses very rapidly in the downstream direction, whereas the annular swirl jet shows a very strong entrainment effect, but is restricted to the vicinity of the nozzle and diffuses very widely. A counter flow to the upstream direction is observed in the center region of the flow. Thus, the annular swirl jet itself is unsuitable for the push flow. In the case of the round free jet, as shown in Fig. 3 (b), the jet radius is narrow, but the entrainment flow is weak, and is thus also unsuitable for the push flow. So, by combining the round free jet and the coaxial annular swirl jet, a jet that shows relatively high energy density can be achieved. It was clarified that structure of the compound swirl jet changes based on the flow rate ratio of the annular swirl jet to the round free jet (e.g., Nozaki et al. 1998, 2000).

Figures 4 (a), (b) and (c) show the visualized pictures of Q_s/Q_j = 1.1 for the case of inadequate swirl, 2.0 for the case of adequate swirl and 2.7 for the case of too much swirl, respectively. Both the left- and right-hand side pictures show the same flow. The left-hand side figure shows the case of mixing the smoke in the annular swirl flow, and the right-hand side shows that in the round free jet. In the case of Q_s/Q_j = 1.1(inadequate swirl), as shown in Fig. 4 (a), the influence of the swirl is limited to the vicinity of the exit, as can be seen the smoke cloud. Then, the influence of the free jet

(a) Annular swirl jet



(b) Round free jet

Fig. 3. Flow visualized photographs of annular swirl jet and round free jet.

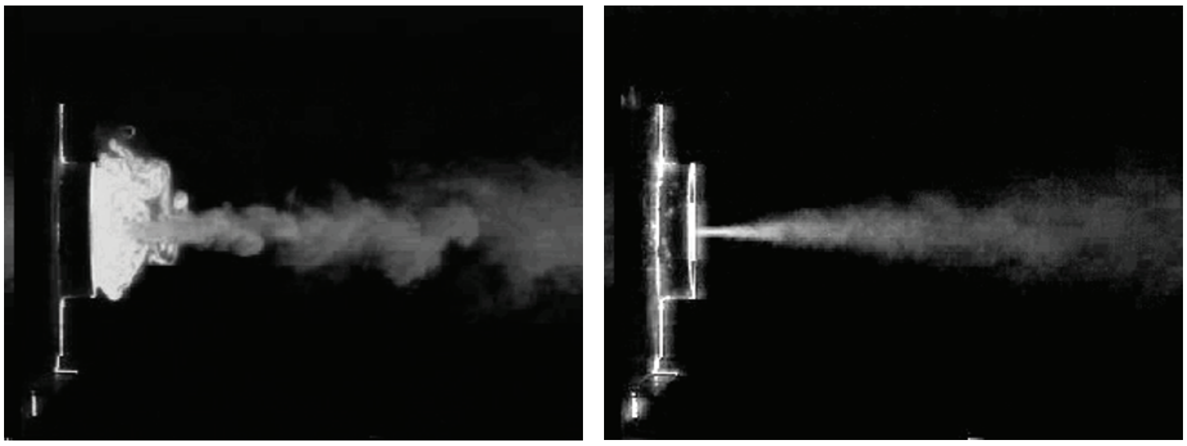
is dominant and is similar to the free jet on the whole. In the case of $Q_s/Q_j = 2.0$ (adequate swirl), as shown in Fig. 4 (b), which has been confirmed to be suitable for the push flow, the flow showing strong entrainment can be obtained by adding the annular swirl jet, whereas the diffusion of the jet increases as a whole. In the vicinity of the nozzle exit, a cloud can be observed, but disappears soon, the influence of the free jet is relatively dominant. In the case of $Q_s/Q_j = 2.7$ (too much swirl), as shown in Fig. 4 (c), the influence of the annular swirl jet becomes dominant and diffusion of the jet increases, whereas the entrainment flow increases. On the other hand, from the observation of the VTR, by adding the annular flow to the free jet, it is clarified that there exists a unique interaction between the two flows. In the case of using the compound swirl jet as the push flow of the push-pull type ventilator, there exists an inverse relation between the entrainment flow and the jet diffusion, i.e. the larger the flow rate ratio, the larger the entrainment and the diffusion. There exists a flow rate ratio which gives adequate swirl and diffusion. Figures 5 (a), (b) and (c) show the visualized pictures of r-θ section at $z/D_{so} = 1$ for $Q_s/Q_j = 1.1$, 2.0 and 2.7, respectively. In the case of $Q_s/Q_j = 1.1$ shown in Fig. 5(a), the annular swirl flow is consumed by the round free jet even in the vicinity of the exit. On the other hand, in the case of $Q_s/Q_j = 2.7$ (Fig. 6 (c)), the free jet diffuses rapidly due to the strong swirl. The counter clockwise swirl can be observed by the time series of pictures. In the case of $Q_s/Q_j = 2.0$ (Fig. 6 (b)), the non-rotational case can be observed in the center region and the swirl can be observed in the outer region of the flow. Then, a suitable flow is established for the push flow of the push–pull type ventilator.

It is very difficult to visualize the flow. Then, by analyzing the time series of the visualized pictures, the illustrations of the compound swirl jet for each flow rate ratio are obtained as shown in Figs. 6(a), (b) and (c). There exists an inverse relations between the entrainment and the diffusion of the jet. With regard to the push flow of the push–pull type ventilator, the suitable flow rate ratio of the annular swirl jet to the free jet is recommended, as shown in Fig. 6 (b).

Figure 7 shows the flow rate increase in the downstream direction for the round free jet, the annular swirl jet and the compound swirl jet, which are obtained by analyzing the velocity component measurement [e.g., Nozaki et al., 2002]. The axial length is normalized by the hydraulic diameter D_m defined by

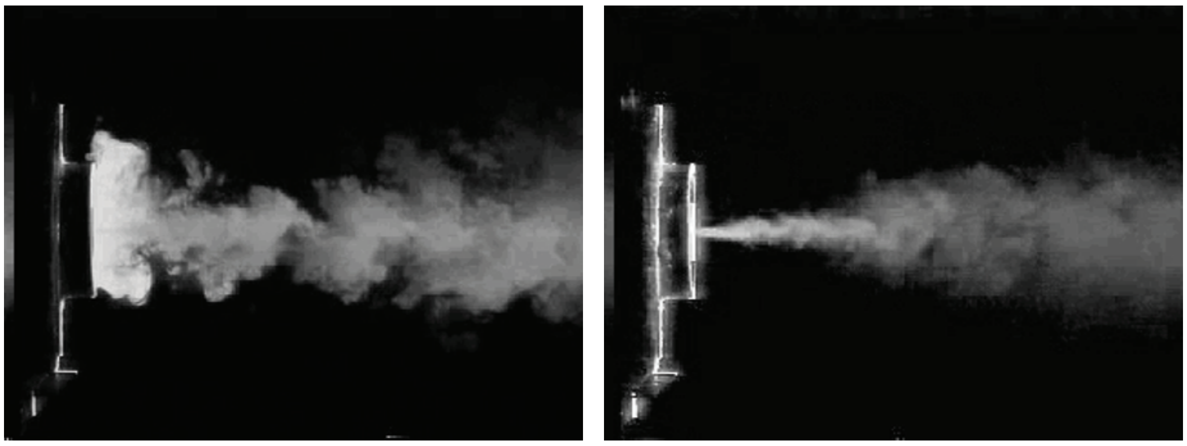
$$D_m = \frac{A}{S},$$

where A is the flow cross sectional area and S is the wetted perimeter. It was reported that the entrainment of the free jet is weaker than that of the annular swirl jet [e.g., Rajaratnam, 1976],



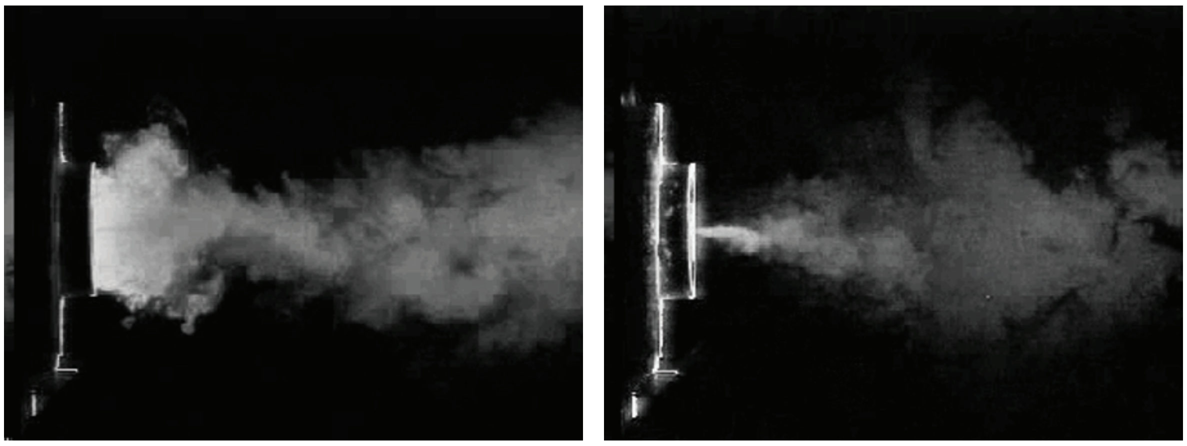
Smoke mixed in annular swirl jet   Smoke mixed in free jet

(a) Q_s/Q_j =1.1 (inadequate swirl)



Smoke mixed in annular swirl jet   Smoke mixed in free jet

(b) Q_s/Q_j =2.0 (adequate swirl)



Smoke mixed in annular swirl jet   Smoke mixed in free jet

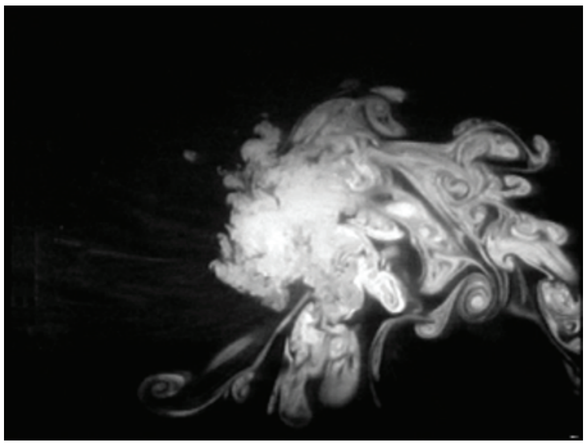
(c) Q_s/Q_j =2.7 (too much swirl)

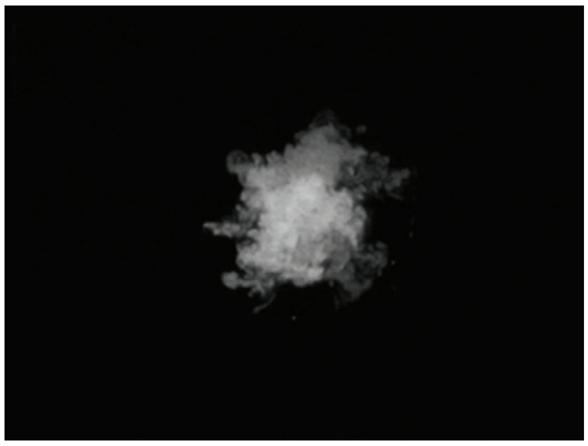
Fig. 4. Flow visualized photographs of compound swirl jet (*r*-*z* plane).


Smoke mixed in annular swirl jet

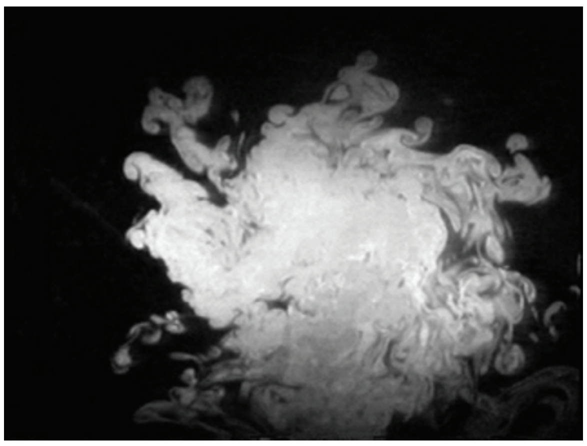

Smoke mixed in free jet

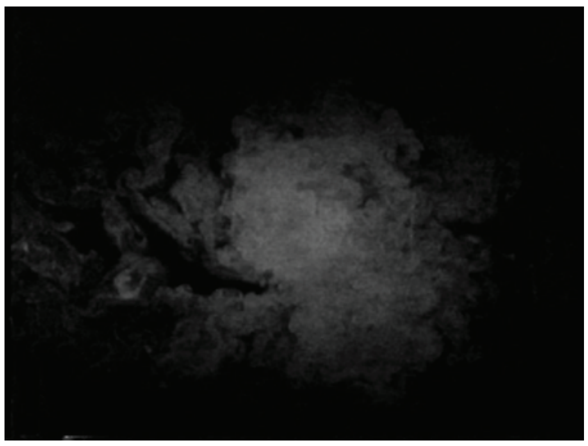
(a) $Q_s/Q_j = 1.1$


Smoke mixed in annular swirl jet


Smoke mixed in free jet

(b) $Q_s/Q_j = 2.0$


Smoke mixed in annular swirl jet


Smoke mixed in free jet

(c) $Q_s/Q_j = 2.7$

Fig. 5. Visualization of compound swirl jet (r-θ plane).

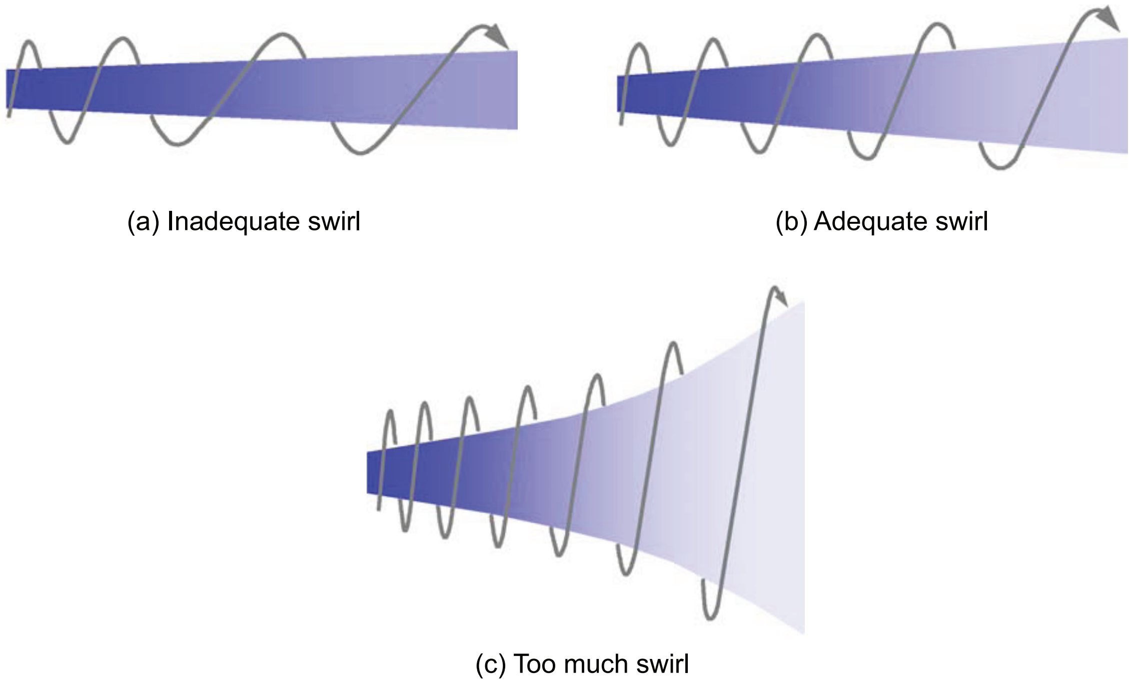


Fig. 6. Illustrations of compound swirl jet (*r*-*z* plane).

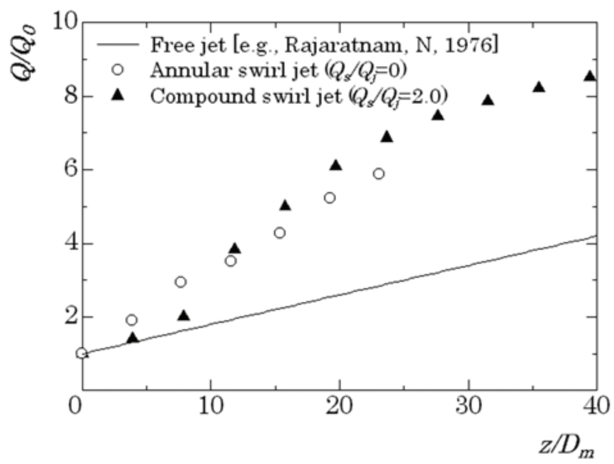


Fig. 7. Increase in flow rate.

then the increase in the flow rate is the slowest. As can be seen from this figure, the flow rate of the annular swirl jet in the downstream direction is large in the vicinity of the exit, but decays rapidly and disappears suddenly at $z/D_m = 23$, which corresponds to $z/D_{so} = 3$, due to diffusion of the jet itself. In the case of the compound swirl jet, the increase in the flow rate is large on the whole. Then, the compound swirl flow is most suitable for the push flow of the push-pull type ventilator.

4. Conclusion

From the experimental results of flow visualization by means of the smoke method involving the compound swirl flow by adding the coaxial annular swirl jet to the round free jet having a thick rim, it was found that the characteristics of the compound swirl jet vary widely with the flow rate ratio of the annular swirl jet to the round free jet. It is considered that the compound swirl jet is a very useful method as the diffusion control of the flow. As one of the practical applications of such flow and for a given configuration of the swirl generator, by selecting the adequate flow rate ratio as 2.0, the compound swirl jet shows the suitable characteristics for the push flow of the push-pull type ventilator of the smoking table.

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