Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/lsst20

Particle Collection Efficiency of Different Impactor Designs

CHUEN-JINN TSAI [a] & TSAI-YIN LIN [a]

[a] INSTITUTE OF ENVIRONMENTAL ENGINEERING, NATIONAL CHIAO TUNG UNIVERSITY , NO. 75 POAI STREET, HSIN CHU , 300 , TAIWAN

Published online: 15 Feb 2007.

To cite this article: CHUEN-JINN TSAI & TSAI-YIN LIN (2000) Particle Collection Efficiency of Different Impactor Designs, Separation Science and Technology, 35:16, 2639-2650, DOI: 10.1081/SS-100102360

To link to this article: http://dx.doi.org/10.1081/SS-100102360

SEPARATION SCIENCE AND TECHNOLOGY, **35**(16), pp. 2639–2650, 2000

Particle Collection Efficiency of Different Impactor Designs

CHUEN-JINN TSAI* and TSAI-YIN LIN
INSTITUTE OF ENVIRONMENTAL ENGINEERING
NATIONAL CHIAO TUNG UNIVERSITY
NO. 75 POAI STREET
300 HSIN CHU
TAIWAN

ABSTRACT

In this study, three different impactor designs were used to investigate the effect of solid particle bounce on the collection efficiency. Design no. 1 is a common impactor with a flat impaction surface surrounded by a retainer ring. Design no. 2 is similar to a particle trap impactor but has a shallower cylindrical cavity, whereas design no. 3 is a regular particle trap impactor. In some cases, a minor flow at 10% of the total flow rate was drawn under the filter substrate to improve the collection efficiency. The experimental data of solid particles show that for design no. 1 without minor flow, the particle collection efficiency increases with Stokes number (Stk) and peaks at 75% at $\sqrt{\text{Stk}}$ of 0.50 (when jet-to-plate distance $S/W = 1$) or 70% at $\sqrt{\text{Stk}}$ of 0.60 ($S/W = 4$). The collection efficiency drops thereafter with increasing Stokes number because of particle bounce. The minor flow increases the collection efficiency by 10–20%. The solid particle collection efficiency of design no. 2 is lower than that of design no. 1 except when $\sqrt{\text{Stk}}$ is close to 1.0. The collection efficiency of design no. 2 increases from 30 to 50% when $\sqrt{\text{Stk}}$ is increased from 0.5 to 1.1. The effect of the minor flow on the increase of the collection efficiency, which is 20–30%, is more pronounced than for design no. 1. For design no. 3 without minor flow, the solid particle collection efficiency is found to increase with increasing Stokes number, and the shape of the collection efficiency curve is quite different from the other two designs. The collection efficiency increases monotonically from 10 to 70% when $\sqrt{\text{Stk}}$ is increased from 0.4 to 1.7.

Key Words. Impactor; Particle aerodynamic diameter; Aerosol instrument

* To whom correspondence should be addressed.

INTRODUCTION

Inertial impactors are widely used in ambient and workplace aerosol sampling to determine the size distribution of particles. Particles collected on the impactor substrates can be weighed and analyzed further for chemical composition. Liquid particles are collected easily because they stick to the impactor plate upon impaction. However, for collection of solid particles, particle bounce may occur, which significantly affects the measured size distribution. Surface coating in the collection substrates is widely used to reduce solid particle bounce (1, 2). However, surface coating becomes less effective when the particle loading is heavy and it also interferes with chemical analysis of the collected particle samples.

Different impactor designs have been investigated to eliminate the above-described problems (2–5). Some designs claim to be successful, but sample retrieval from the impactors with specially designed impaction surfaces becomes difficult, especially when filter weighing and subsequent chemical analysis are necessary.

This study examines the particle collection efficiency of different impactor designs in order to determine a better design for solid particle collection. In some of the experiments, the effect of minor flow through the substrate on the reduction of solid particle bounce was also examined.

DESIGN CONCEPT

Three different impactor designs, shown in Figs. 1a–1c, were used in the study. Design no. 1 is a popular impactor with a flat impaction surface surrounded by a 2-mm-deep retainer ring of 16 mm inner diameter. The retainer ring helps collect particles if they bounce from the impactor substrate. Design no. 2 has an enclosed cylindrical cavity of 3.6 mm in depth and 18 mm inner diameter, and has an orifice of 5 mm diameter at the top. This design is similar to that used in Tsai and Cheng (2) except that the impactor substrate of design no. 2 is flat. Design no. 3 is similar to design no. 2 except that the cylindrical cavity depth, 14 mm, is much deeper. The design parameters of design no. 3 were based on the particle trap impactor of Biswas and Flagan (3). Filter substrates supported by porous metal disks were used to collect particles. Minor flow can be drawn under the porous metal disk to reduce particle bounce and increase the solid particle collection efficiency.

The impactors are single-stage design with cutoff aerodynamic diameter of 2.0 μm. The diameter of the single round nozzle is 2.4 mm and the flow rate was 5 L/min. Three exchangeable pins support the impaction plate. The jet-to-plate distance (S), which refers to the distance between the nozzle and the top of the impaction plate, was adjusted to 2.4 or 9.6 mm (or one time or four times the nozzle diameter).

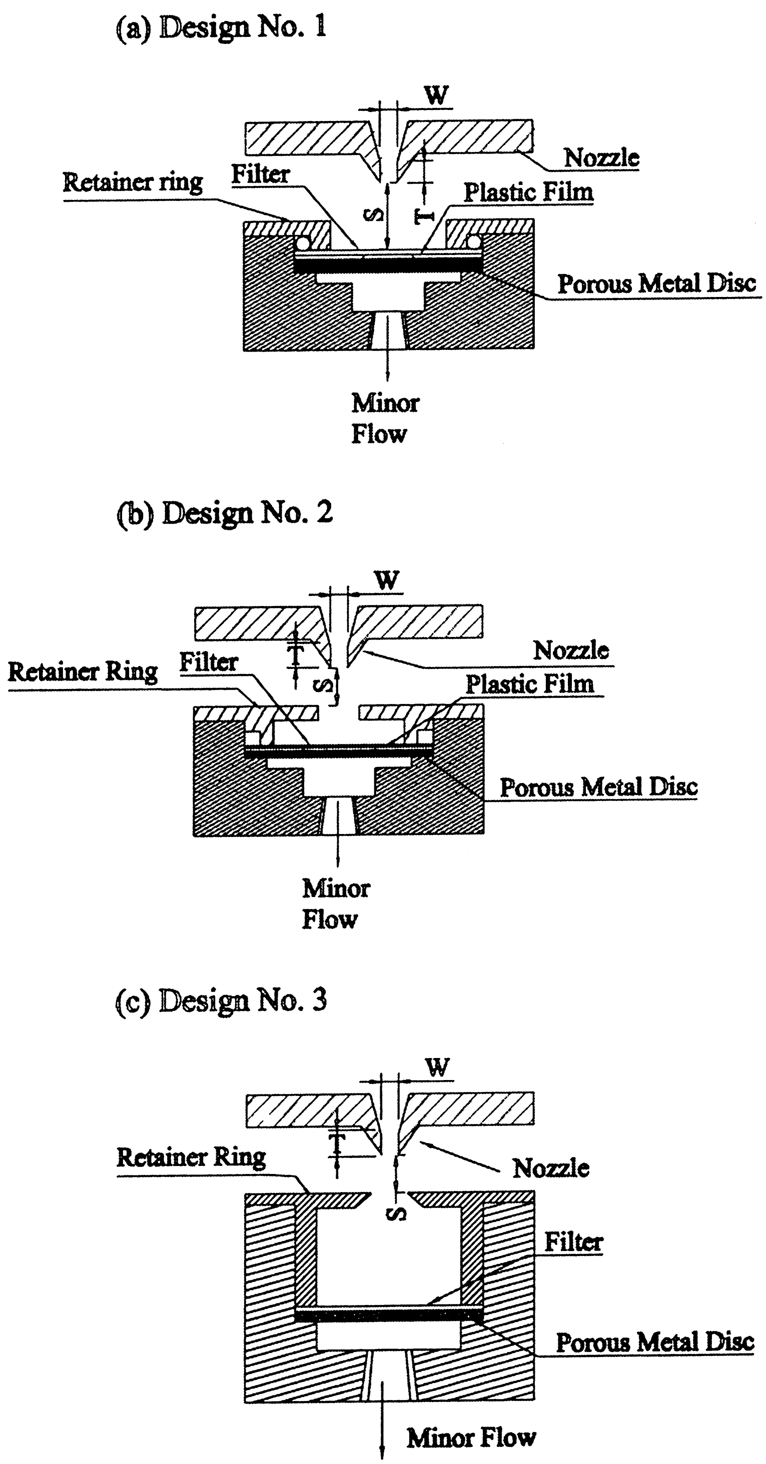

FIG. 1 Three different impactor designs.

EXPERIMENTAL METHODS

The experimental setup is shown in Fig. 2. Monodisperse liquid oleic acid and solid ammonium fluorescein particles were generated by the model 3450 vibrating orifice monodisperse aerosol generator (TSI Inc., St. Paul, MN). The aerosols were then neutralized using a model 3054 Kr-85 charge neutralizer (TSI). The model 3310A aerodynamic particle sizer (TSI) was used to measure the particle aerodynamic size and concentration.

At the end of each sampling experiment, particles on the collection filter, the retainer ring, the inner wall, the outer nozzle, and the downstream filter were extracted by using 0.001 N NaOH (for liquid particles) or 0.1 N NH_4OH solution (for solid particles). Particles collected on the inner wall and outer nozzle were considered as particle loss at the wall, which is also called wall

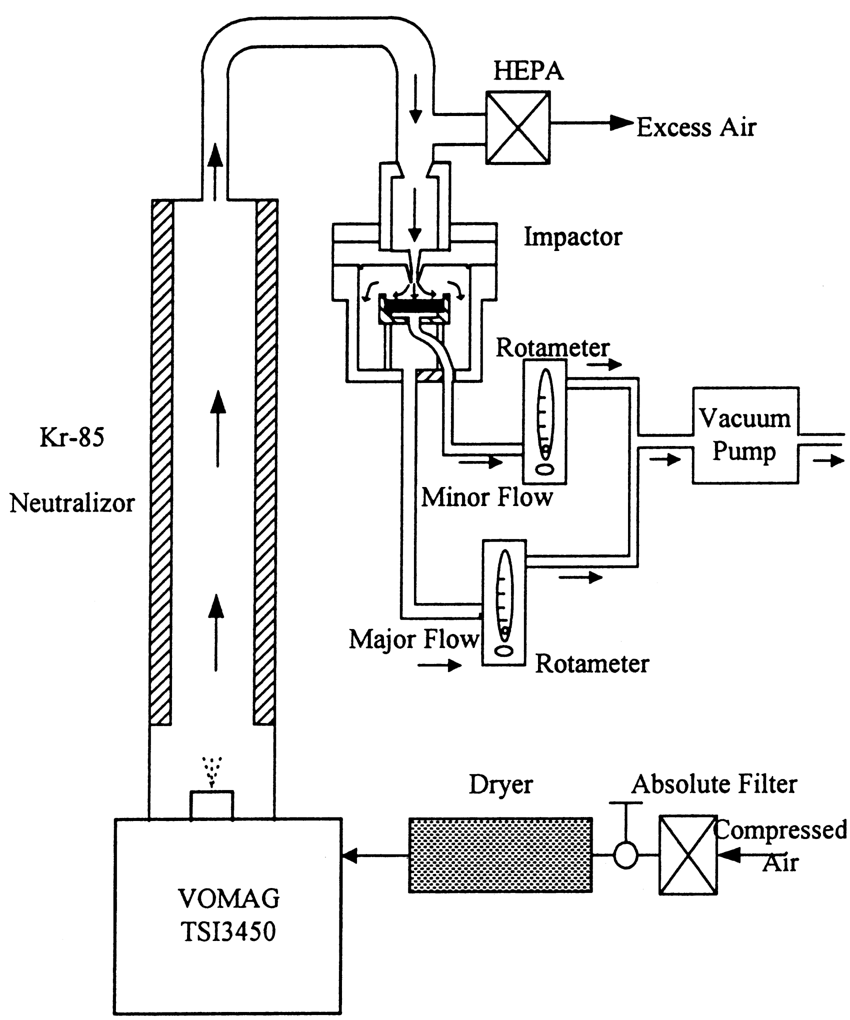

FIG. 2 The experimental setup.

loss. A fluorometer (model 10-AU, Tuner Designs, CA) was used to measure the collection efficiency and wall loss of the impactors. The particle collection efficiency, η (%), and the wall loss of the impactor, loss (%), were determined as follows:

$$\eta(\%) = \frac{M_f + M_r}{M_f + M_r + M_w + M_{df} + M_n} \times 100(\%) \quad (1)$$

$$\text{Loss}(\%) = \frac{M_w + M_n}{M_f + M_r + M_w + M_{df} + M_n} \times 100(\%) \quad (2)$$

where M_f and M_r are the masses of fluorescein for the collection filter and the retainer, respectively, which were determined with the fluorometer. The M_w, M_n, and M_{df} values are the masses of fluorescein on the inner wall, nozzle, and downstream filter, respectively. In the following, the particle collection efficiency is reported based on the Stokes number, Stk, which is defined as

$$\text{Stk} = \frac{\rho_p D_p^2 C U}{9 \mu W} \quad (3)$$

where ρ_p is the particle density, D_p is the particle diameter, C is the slip correction factor, U is the average flow velocity at the impactor nozzle, μ is the air viscosity, and W is the diameter of the impactor nozzle. Stk_{50} is defined as the Stokes number when the collection efficiency is 50%. The square root of Stokes number, $\sqrt{\text{Stk}}$, represents the dimensionless particle diameter.

RESULTS AND DISCUSSION

Design No. 1 Impactor

Design no. 1 was first tested using liquid oleic acid particles. Glass fiber (model EPM-2000, Whatman Inc., NJ,) and polycarbonate (PC, model N020, 0.2 μm pore, Nuclepore Corp., CA) filters were used as substrates for comparing the difference in the collection efficiency. The filters were 25 mm in diameter. For liquid oleic acid particles, the collection efficiency curve of the glass fiber filter was found to be different from that of the PC filter and the theoretical result (6, 7). The $\sqrt{\text{Stk}_{50}}$ of the glass fiber filter is 0.40, which is different from 0.47 for the PC filter. In addition, the collection efficiency of the glass fiber filter is higher than that of the PC filter at low Stokes number, similar to results found by Rao and Whitby (8). This increase in efficiency is attributed to the additional filtration by the rough surface of the glass fiber filter (8). For the subsequent experiments, glass fiber filters were used because they are less bouncy than PC filters.

To reduce solid particle bounce, a minor flow controlled at 0.5 L/min (10% of the total flow rate) was used. The observation by Sethi and John (9) revealed that the diameter of the particle deposition spots is about twice that of the nozzle diameter. The same observation was found in our experiment. Therefore, when the minor flow rate was used to control solid particle bounce, the suction flow area was restricted within a 5-mm diameter area under the filter substrate to increase the suction flow velocity and hopefully the effectiveness of particle bounce prevention. This was achieved by inserting a plastic film with a 5-mm diameter central hole between the porous metal disk and filter substrate.

Figure 3 shows the collection efficiency curves of solid and liquid particles of design no. 1 with the glass fiber filter while the *S*/*W* value equals 1. Compared to liquid particles, the collection efficiency curve of the solid particle drops sharply at higher Stokes numbers. When $\sqrt{\mathrm{Stk}}$ is increased from 0.5 to 1.0, the solid particle collection efficiency drops from 75 to 50%. Use of the minor flow increases the collection efficiency by 10–20%; the maximum efficiency peaks at 85% when $\sqrt{\mathrm{Stk}} = 0.4$ and gradually drops to 65% at $\sqrt{\mathrm{Stk}} = 1.0$.

When *S*/*W* is increased to 4.0, the collection efficiency curve for solid particles does not change appreciably, as shown in Fig. 4. The peak collection efficiency does not change very much, but it now occurs at $\sqrt{\mathrm{Stk}} = 0.6$ for the cases with minor flow and without minor flow. The gradual decrease of the collection efficiency with $\sqrt{\mathrm{Stk}}$ still occurs because of particle bounce, whether or not the minor flow is used.

Wall loss of design no. 1 is not excessive, as shown in Fig. 5, when $\sqrt{\mathrm{Stk}}$ is less than 1.1. In general, wall loss increases with an increasing $\sqrt{\mathrm{Stk}}$ and the maximum loss is less than 7%. Although the minor flow increases the solid particle collection efficiency, it does not affect wall loss.

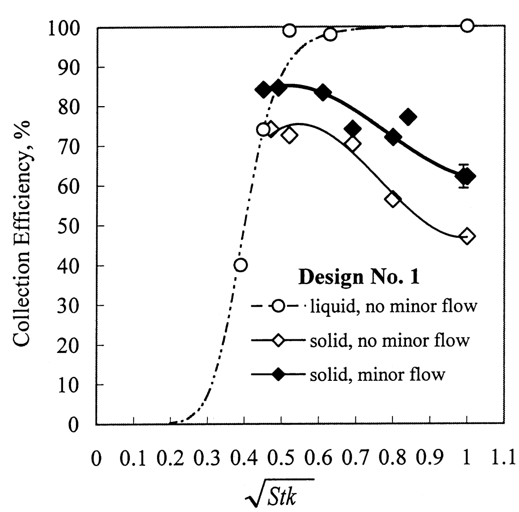

FIG. 3 Particle collection efficiency curve, design no. 1, *S*/*W* = 1.0.

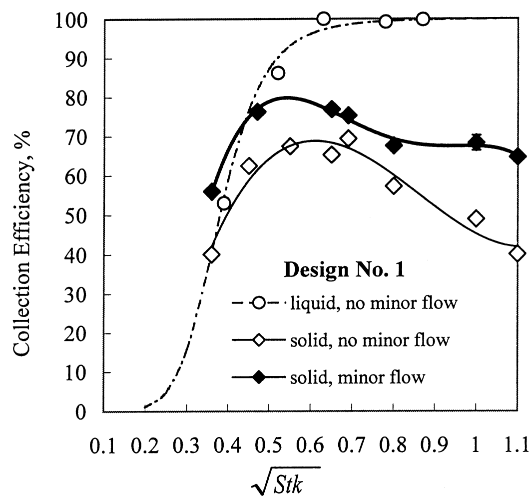

FIG. 4 Particle collection efficiency curve, design no. 1, $S/W = 4.0$.

Design No. 1 is similar to the impactor used by Sioutas et al. (5), except that the collection surface of design no. 1 is glass fiber filter instead of aluminum. Because the glass fiber filter exhibits less bouncy characteristics than those of aluminum, the collection efficiency of the current design is higher than that shown by Sioutas et al. (5). Rao and Whitby (8) also showed that the solid particle collection efficiency of the glass fiber filter is higher than that of stainless steel substrates.

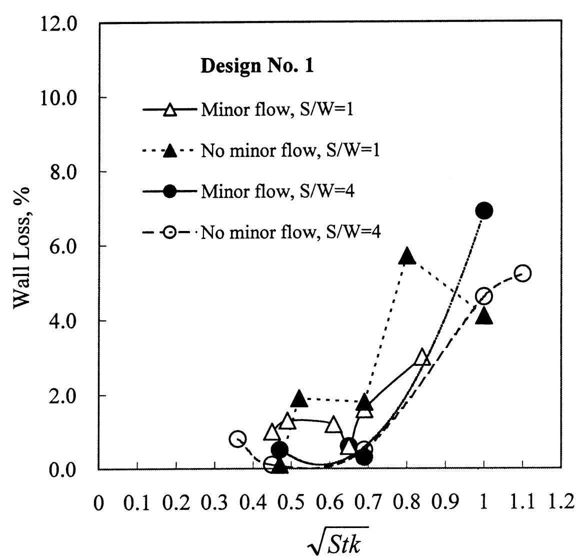

FIG. 5 Particle wall loss, design no. 1.

Design No. 2 Impactor

For *S*/*W* = 1, Fig. 6 shows that the collection efficiency of liquid particles is not as high as that for design no. 1. In general, the collection efficiency of solid particles of design no. 2 is lower than that of design no. 1, except when $\sqrt{\text{Stk}}$ is close to 1.0. Without the minor flow, the maximum collection efficiency is only 50% and does not change very much with $\sqrt{\text{Stk}}$. Addition of the minor flow increases the collection efficiency by 20–30%, with a maximum efficiency of 70%. When S/W is increased to 4.0, the solid particle efficiency curve changes slightly, as shown in Fig. 7. The peak collection efficiency values are similar to those shown in Fig. 6, but they occur at $\sqrt{\text{Stk}} = 0.9$ and 1.1 for the cases with minor flow and without minor flow, respectively. That is, when *S*/*W* = 4, particles must have higher inertia in order to be impacted on the substrate.

Observation of particle deposition spots shows us that the deposition diameter is larger than the theoretical prediction by Marple (7) and the empirical observation by Sethi and John (9). In addition to this observation, the fact that the collection efficiency of solid particles for design no. 1 is lower that of design no. 2 suggests that quiescent air in the cylindrical cavity of design no. 2 prevents some solid particles from impacting on the substrates effectively. Therefore, the peak collection efficiency is not as high as that of design no. 1. When *S*/*W* is increased to 4.0, the corresponding $\sqrt{\text{Stk}}$ must be higher in order to have the same collection efficiency value as when *S*/*W* = 1.0.

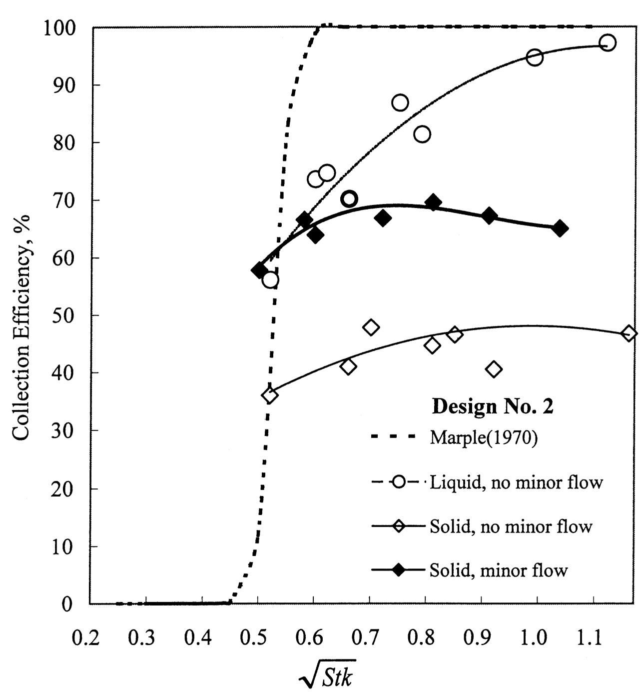

FIG. 6 Particle collection efficiency curve, design no. 2, *S*/*W* = 1.0.

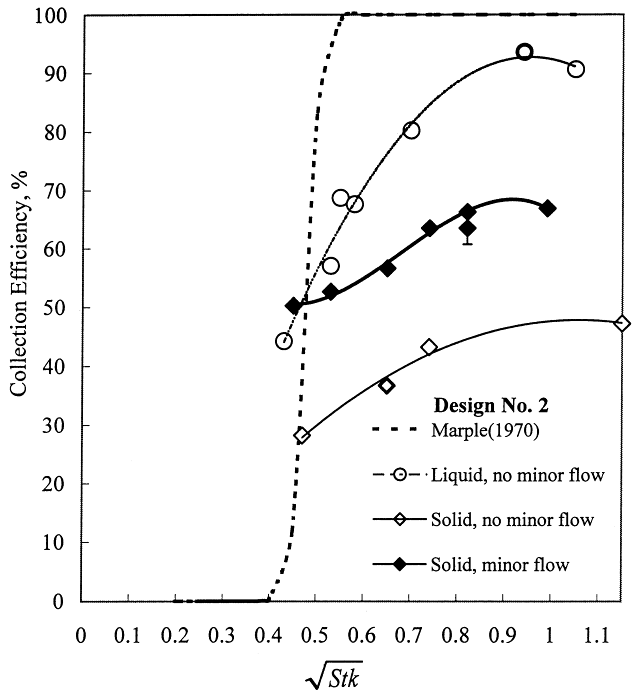

FIG. 7 Particle collection efficiency curve, design no. 2, $S/W = 4.0$.

For either case of $S/W = 1$ or 4, the amount of particles deposited on the retainer ring increases with an increasing $\sqrt{\text{Stk}}$ for solid particles. However, the amount decreases with an increasing $\sqrt{\text{Stk}}$. This suggests that solid particle bounce still occurs in design no. 2 and the extent of particle bounce increases with an increasing $\sqrt{\text{Stk}}$.

Wall loss of design no. 2 is slightly higher than that of design no. 1, as shown in Fig. 8. In general it increases with an increasing $\sqrt{\text{Stk}}$ and the maximum loss is less than 13%. Unlike design no. 1, the minor flow not only increases the solid particle collection efficiency, but also decreases the wall loss. When $S/W = 4$, wall loss is more excessive than when $S/W = 1.0$.

Design No. 3 Impactor

Biswas and Flagan (3) showed that the particle trap impactor reduces solid particle bounce effectively. Design no. 3 is based on the same geometry of Biswas and Flagan (3). The experimental data of solid particle collection efficiency, shown in Fig. 9, show that the collection efficiency is low when $\sqrt{\text{Stk}}$ is less than 0.8. It gradually increases from 10 to 70% as $\sqrt{\text{Stk}}$ is increased from 0.4 to as high as 1.7. That is, at the same $\sqrt{\text{Stk}}$, design no. 3 has lower collection efficiency than either design no. 1 or 2. This result is reasonable because design no. 3 has a much deeper cavity than design no. 2. Quiescent air

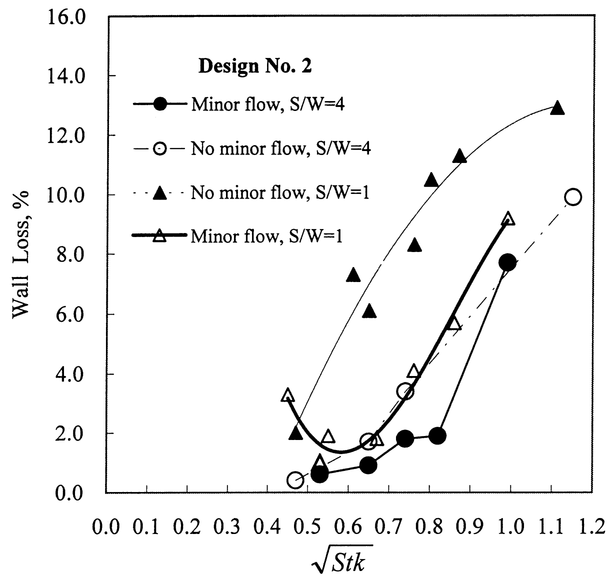

FIG. 8 Particle wall loss, design no. 2.

in design no. 3 stops particles effectively from impacting on the substrate unless particle inertia is very high. This finding contradicts results found by Biswas and Flagan (3). It is speculated that particle loss in their study was not well quantified, which might contribute to errors in measurement.

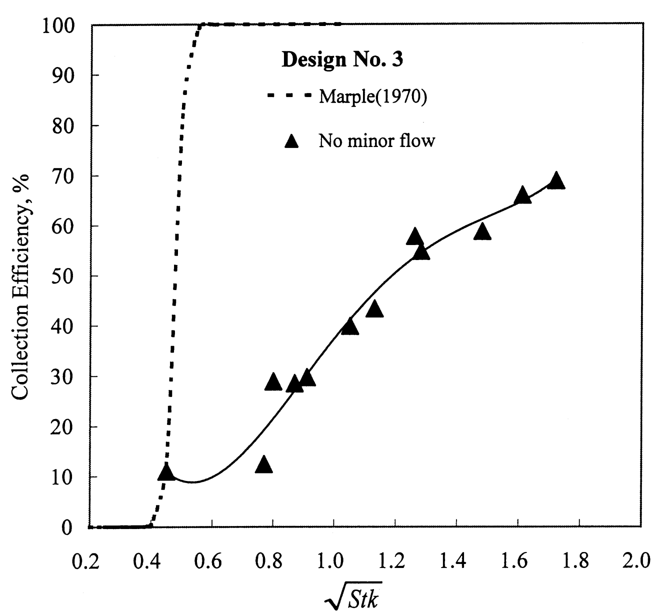

FIG. 9 Particle collection efficiency curve, design no. 3.

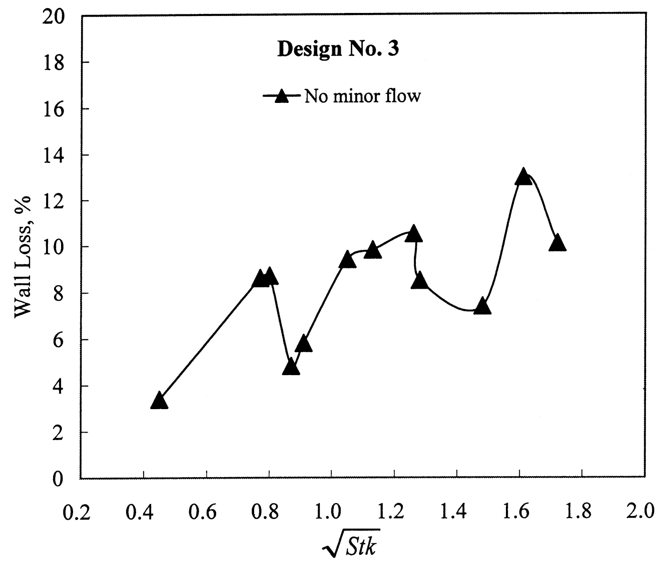

FIG. 10 Particle wall loss, design no. 3.

Particle wall loss is shown in Fig. 10. The relationship of wall loss with $\sqrt{\text{Stk}}$ is similar to that of design no. 2. Wall loss increases with an increasing $\sqrt{\text{Stk}}$ and the maximum is about 14% in the range of Stokes numbers tested.

CONCLUSION

In this study, glass fiber filters were found to prevent solid particle bounce, resulting in higher collection efficiency than that of PC filters. When glass fiber filters were used as substrates, three different impactor designs were investigated for solid particle collection efficiency.

Results show that traditional inertial impactor, such as design no. 1, has the highest collection efficiency among the three designs except when $\sqrt{\text{Stk}}$ is close to 1.0. Particle trap impactors, such as designs no. 2 and 3, do not eliminate particle bounce problems completely. A deeper cylindrical cavity in the trap only results in lower collection efficiency at the same $\sqrt{\text{Stk}}$.

The minor flow eliminates some particle bounce problems and increases the solid particle collection efficiency of design no. 1 by 10–20% and design no. 2 by 20–30%. For example, when $\sqrt{\text{Stk}}$ is less than 0.6 for design no. 1 with minor flow, the collection efficiency for solid particles can be as high as 85%. It is conceivable that impactor substrates are very important and should be investigated further to prevent particle bounce.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the Taiwan National Science Council of the Republic of China under Grant NSC 88-2211-E-009-029.

REFERENCES

1. S. S. Pak, B. Y. H. Liu, and K. L. Rubow, "The Effect of Coating Thickness on Particle Bounce in Inertial Impactors," *Aerosol Sci. Technol.*, *16*, 141 (1992).
2. C. J. Tsai and Y. H. Cheng, "Solid Particle Collection Characteristics on Impactor Surfaces of Different Designs," *Ibid.*, *14*, 96 (1995).
3. P. Biswas and R. C. Flagan, "The Particle Trap Impactor," *J. Aerosol Sci.*, *19*, 113 (1988).
4. H. T. Kim, Y. J. Kim, and K. W. Lee, "New PM_{10} Inlet and Evaluation," *Aerosol Sci. Technol.*, *29*, 350 (1998).
5. C. Sioutas, M. C. Chang, S. Kim, P. Koutrakis, and S. T. Ferguson, "Design and Experimental Characterization of a PM_1 and $PM_{2.5}$ Personal Sampler," *J. Aerosol Sci.*, *30*, 693 (1999).
6. V. A. Marple and K. Willeke, "Impactor Design," *Atmos. Environ.*, *10*, 891 (1976).
7. V. A. Marple, *A Fundamental Study of Inertial Impactors*, Ph.D. Thesis, Mechanical Engineering Department, University of Minnesota, Minneapolis, MN, 1970.
8. A. K. Rao and K. T. Whitby, "Non-Ideal Collection Characteristics of Inertial Impactors-I. Single-Stage Impactors and Solid Particles," *J. Aerosol Sci.*, *9*, 77 (1978).
9. V. Sethi and W. John, "Particle Impaction Patterns from a Circular Jet," *Aerosol Sci. Technol.*, *18*, 1 (1993).

Received by editor December 6, 1999
Revision received April 2000