Aerosol Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uast20

Solid Particle Collection Characteristics on Impaction Surfaces of Different Designs

Chuen-Jinn Tsai [a] & Yu-Hsiang Cheng [a]
[a] Institute of Environmental Engineering, National Chiao Tung University , No. 75 Poai St., R.O.C., Hsin Chu, Taiwan
Published online: 12 Jun 2007.

Solid Particle Collection Characteristics on Impaction Surfaces of Different Designs

Chuen-Jinn Tsai* and Yu-Hsiang Cheng
Institute of Environmental Engineering,
National Chiao Tung University,
No. 75 Poai St., Hsin Chu,
Taiwan, R.O.C.

The effect of solid particle loading on the collection efficiency of a single-stage impactor with different impaction surface designs has been investigated. Experimental results show that the time-varying collection efficiency depends on the surface coating condition, thickness of particle deposit, and impaction surface design. Deposited particles change the surface condition such that the particle collection efficiency decreases with time for the coated impaction surface while it increases with time for the uncoated impaction surface. However, after heavy loading, the collection efficiency eventually approaches nearly the same asymptotic value whether the impaction surface is coated or not. The impaction surface with an inverted conical cavity and an orifice plate alleviates particle bounce and reentrainment problems during particle collection process, resulting in a much greater collection efficiency than the conventional design, which uses flat impaction surface.

INTRODUCTION

Inertial impactors have been used extensively to measure aerosol size distribution and to collect samples for further chemical analysis. Inherent problems that introduce errors in size distribution measurement are particle bounce and reentrainment (Dzubay et al., 1976; Markowski 1984). These problems are related to the nature of collection surfaces, the type and thickness of coating materials, the type of particle materials, the amount of impaction surface loading and even environmental conditions (Rao and Whitby 1978a and 1978b; Reischl and John 1978; Cheng and Yeh 1979; Hinds 1985; Turner and Hering 1987; Wang and John 1987; Newton et al. 1990; Pak et al. 1992).

*Corresponding author.

Usually in an impactor, particle bounce and reentrainment problems occur only when collecting solid particles. Surface coating on the collection substrate is often used to reduce solid particle bounce. However, for greased coatings, the collection efficiency drops rapidly with respect to particle loading since incoming particles bounce off previously deposited particles (Reischl and John 1978; Turner and Hering 1987; Pak et al. 1992). To prevent particle bounce from heavily loaded greased coatings, Reischl and John (1978) used an oil-soaked sintered metal disk as an impaction surface and showed that the collection efficiency was nearly 100%, independent of particle loading. The improvement is due to the fact that the pores of the metal serve as oil reservoirs and prevent the oil from being blown away from the impaction area. Using a similar idea, Turner and Hering (1987) proposed

0278-6826/95/$9.50
SSDI 0278-6826(94)00060-F

Published by Elsevier Science Inc.

to use oil-coated 10-μm Teflon membrane filter to collect solid particles to facilitate chemical and elemental analysis. Their experimental data showed that the collection efficiency indeed did not decrease with substrate loading.

However, almost all of previous investigations are restricted to traditional flat impaction surfaces, and some (for example, Pak et al. 1992) consider light loading condition only. It is of great importance to investigate the effect of heavy particle loading on the collection efficiency of different impaction surface designs, which are not traditional flat surface. For practical purposes, it is necessary to consider heavy loading condition since many layers of particles can be loaded on impactor stages during ambient aerosol sampling. For example, an impactor stage having a single nozzle of 2.4 mm in diameter and a 2.0-μm cutoff aerodynamic diameter will collect roughly 130–260 layers of particles when the typical stage inlet aerosol mass concentration is 10–20 $\mu g/m^3$ during a 24-h sampling at 5.0 slpm flow rate. Total loaded particle mass is about 0.07–0.14 mg. The estimated number of layers of deposited particles will be even greater when the aerosol concentration is higher. In the estimation, it is assumed that particles are uniformly distributed within a circle of 7.2 mm in diameter. Even with the rotating stage design such as the microorifice uniform deposit impactor (MOUDI) (Marple et al. 1991), it is expected that several tens of layers of deposited particles will appear on the aforementioned stage under the same conditions.

It is desirable to have an inertial impactor that uses uncoated substrates such that the chemical analysis of collected samples free from interference by coating materials can be realized. Uncoated substrates are also more practical in high temperature sampling conditions (Biswas and Flagan 1988). A virtual impactor has been designed to eliminate problems of bounce and reentrainment to allow the collection of a larger particulate mass (Marple and Chien 1980; Chen et al. 1986; Chen and Yeh 1987). The problem of the virtual impactor is the nonzero collection efficiency at small particle sizes since a small secondary flow is required. In some cases, wall losses were found to be excessive (Chen et al. 1986).

Extending the concept of Schott and Ranz (1976), Biswas and Flagan (1988) developed a particle trap impactor, which is a virtual impactor without the secondary flow through the impaction orifice. The particles were collected in an uncoated cavity with 85%–90% collection efficiency at high Stokes numbers. However, possible wall losses and the time-varying collection characteristics were not explicitly shown in the paper. It has been pointed out that in an impactor with uncoated substrates, the collection efficiency will increase with particle loading, since particle–particle collisions may cause loss of energy and change of direction of impacting particles (Wang and John 1987).

This study is to examine heavy solid particle loading effect on the collection efficiency of different impaction surface designs. The basic design is an inverted conical cavity in the collection plate, which is expected to accommodate more particulate mass compared with the conventional flat surface design and to alleviate particle bounce and reentrainment problems. Both coated and uncoated substrates were tested in the laboratory.

IMPACTOR DESIGN

In this study, the impactor was designed based on Marple and Willeke (1976) as shown in Fig. 1. The cutoff size was designed to be 2.0 μm in aerodynamic diameter, Reynolds number was chosen as 3000 and the diameter of the single round nozzle was calculated to be 2.4 mm. The aerosol flow rate, 5 slpm, was chosen to

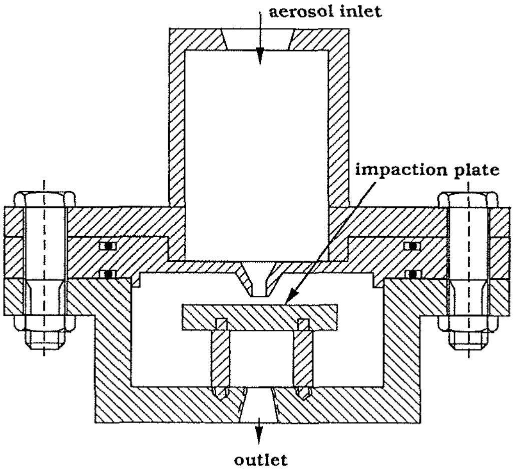

FIGURE 1. A schematic drawing of the present impactor.

be same as the sampling flow rate of the TSI Model 3310A aerodynamic particle sizer used in the current study for collection efficiency measurement. The throat length was one jet diameter and had a 60% conical entrance. The impactor plate was supported by three exchangeable pins. The jet-to-plate distance was adjusted by replacing pins of different length. In this study, the jet to plate distance, which refers to the distance between the nozzle and the top of the cavity, was kept to be the same as the nozzle diameter, 2.4 mm.

Four different collection surfaces shown in Figs. 2a–2d were used in this study. In design No. 1, the collection surface is a traditional flat surface. In design No. 2, the collection surface has an open, inverted conical cavity. The diameter at the top of the conical cavity, 19.2 mm, is eight times that of nozzle diameter, as shown in Fig. 2b with other dimensions. Design No. 3 is similar to design No. 2 except that the bottom of the cavity is a flat circular surface of 3.6 mm in diameter.

Design No. 4 is similar to design No. 3 except that an orifice plate is used to cover the cavity. Four diameters of cavity opening (symbol "D" in Fig. 2d), namely 3.6, 4.8, 6, and 9.6, were tested initially to

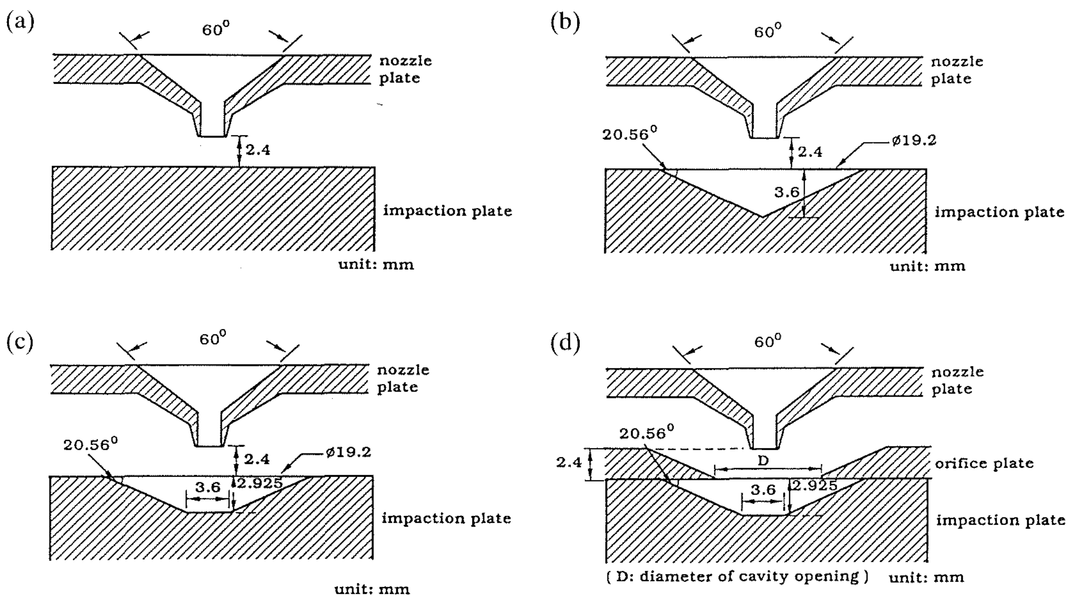

FIGURE 2. Various impaction surface designs. (a) Design No. 1. (b) Design No. 2. (c) Design No. 3. (d) Design No. 4.

find an optimum diameter. Design No. 4 makes the impactor look similar to Biswa and Flagan's particle trap impactor. However, when including the depth of the cavity, the jet-to-plate distance is Biswas and Flagans' impactor is much larger than the current design. Their jet-to-plate distance is about 8.7 times while the current design is only 2.2–2.5 times that of the nozzle diameter.

EXPERIMENTAL METHOD

The experimental setup is shown in Fig. 3. Monodisperse solid ammonium fluorescein particles were generated by the TSI Model 3450 vibrating orifice monodisperse aerosol generator, using the techniques of Vanderpool and Rubow (1988). The aerosols were neutralized using a TSI Model 3054 Kr-85 charge neutralizer and dried in a silica gel diffusion drier before being introduced into the impactor. The TSI Model 3310A aerodynamic particle sizer was used to measure the inlet and outlet number concentrations of the impactor to determine the collection efficiency.

The collection efficiency at every minute was calculated as $E = 1 - C_{out}/C_{in}$, where C_{out} was the outlet number concentration of the aerosol during every minute and C_{in} was the inlet number concentration of the aerosol. The inlet number concentration was the average of several measurements, the variation of which was small, typically within $\pm 5\%$. The impactor was mounted on the top of the aerodynamic particle sizer to minimize transport losses that could lead to errors in the measurement.

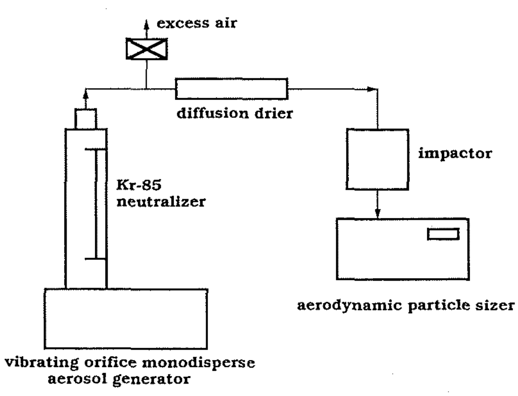

FIGURE 3. Schematic diagram of the present experimental setup.

Both coated and uncoated collection surfaces were used. For measurements involving coated surfaces, surfaces were coated with a thin layer of silicon oil spray (Cling-Surface Co., Angola, NY).

In case that loading test was conducted, a test aerosol of high number concentration about 60–80 $\#/cm^3$ was used. The amount of particle loading on the impaction surface is characterized by a dimensionless number, N_m, which can be calculated as (Turner and Hering, 1987):

$$N_m = \sum_{i=1}^{n} N \cdot E_i \cdot d_p^2 / W^2, \qquad (1)$$

where N is the inlet particle number, d_p is particle diameter, W is the jet diameter, and E_i is the collection efficiency of the impactor at the ith minute. N_m is directly proportional to the number of layers of deposited particles. The loading characteristic can be expressed as the mass of deposited particles, M, as follows:

$$M = \sum_{i=1}^{n} N \cdot E_i \cdot \pi \cdot d_p^3 \cdot \rho_p / 6, \qquad (2)$$

where ρ_p is the density of the particle.

For the determination of wall loss, fluorometric technique was used (Pui et al. 1991). The wall loss was calculated by dividing the amount of particles within the impactor, excluding those on the collection surface, by the total particle mass.

RESULTS AND DISCUSSIONS

Diameter of Cavity Opening in the Design No. 4

Since design No. 4 has an orifice plate on top of the cavity, the diameter of the

TABLE 1. Comparison of Wall Loss Between Designs No. 3 and No. 4 for Light Loading and Coated Surfaces

Impaction Surface Design	No. 3		No. 4							
D (diameter of cavity opening)	—		33.6		4.8		6		9.6	
D/W	—		1.5		2		2.5		4	
D_{pa} (μm)	3.39	5.22	3.44	5.25	3.35	5.25	3.43	5.26	3.45	5.25
$\sqrt{\text{Stk}}$	0.75	1.14	0.76	1.15	0.74	1.15	0.76	1.15	0.77	1.15
Collection efficiency (%)[a]	99.8	99.9	22.8	62.3	86.2	90.6	95.3	97.7	99.8	99.8
Wall loss, %	0.1	0.1	14.2	20.7	8.9	4.5	2.4	1.6	0.1	0.1

[a]Values include wall loss.

cavity opening, D, has to be determined. This was done by comparing efficiency and wall loss of design No. 4 with different diameters of cavity opening. Design No. 3, which is the limiting case of design No. 4 with a very large cavity opening, was also included in the test. The test involved both light loading and heaving loading conditions and all substrates were coated. The collection efficiency was determined by the aerodynamic particle sizer and the wall loss was determined by the fluorometric technique as described before.

Table 1 shows the collection efficiency and wall loss at light loading condition when the experiment was run for about 5 min only and the aerosol number concentration was low in the range of 10–20 #/cm^3. The collection efficiency of design No. 3 is nearly 100% when $\sqrt{\text{Stk}}$ is equal to 0.75 or 1.14. For design No. 4 with $D = 9.6$ mm, the collection efficiency also reaches nearly 100% at high Stokes numbers. But when D decreases, the collection efficiency also decreases. When D equals to 3.6 mm, the collection efficiency is only 22.8% and 62.3% for $\sqrt{\text{Stk}}$ of 0.76 and 1.15, respectively. The low collection efficiency for a small diameter of cavity opening in design No. 4 is probably caused by quiescent air in the cavity that stops the impacting particles effectively.

Not only the collection efficiency is low for a small diameter of cavity opening in design No. 4, the wall loss is severe too. Table 1 shows that when D is 3.6 mm, the wall loss is 14.2% and 20.7% and 20.7% for $\sqrt{\text{Stk}}$ of 0.76 and 1.15, respectively. It was found that most wall loss occurred at the outer wall of the nozzle, indicating that the existing flow from the cavity has a tendency to curl upward, resulting in particle impaction on the outer surface of the nozzle. When the diameter of the cavity opening increases, the exiting jet flow will have a smaller vertical component, which is expected to reduce the wall loss. This is indeed the case, as seen in Table 1. When D is 9.6 mm in design No. 4, the wall loss is only 0.1% at high Stokes numbers. Design No. 3, which is the limiting case of design No. 4 with a very large cavity opening, also has very little wall loss at high Stokes numbers, as expected.

From the above discussion, it is suspected that the wall loss in the particle trap impactor by Biswas and Flagan (1988) may be severe considering that their diameter of cavity opening is only 1.9 mm. But this remains to be checked.

Table 2 shows the results of collection efficiency and wall loss for designs No. 3 and No. 4 ($D = 9.6$ mm) after heavy loading lasting for about 2 h. Total loaded particle mass was about 1.0 mg. Detailed time varying collection efficiency will be discussed later. Table 2 shows that for the design No. 3, the wall loss due to particle reentrainment can be severe at $\sqrt{\text{Stk}}$ of 0.49. It was observed that particle aggre-

TABLE 2. Comparison of Wall Loss between Designs No. 3 and No. 4 ($D = 9.6$ mm) for Heavy Loading and Coated Surfaces

Impaction surface design		No. 3			No. 4	
D_{pa} (μm)	2.21	3.43	5.12	2.23	3.44	5.25
$\sqrt{Stk}$	0.49	0.76	1.12	0.5	0.76	1.15
Collection efficiency, %[a]	74.1	86.5	84.7	76.5	94.0	84.5
Wall loss, %	19.2	5.3	4.7	3.1	6.7	8.5

[a]Values include wall loss.

gates were blown away from the cavity resulting in the severe wall loss at this Stokes number. At higher Stokes numbers, deposited particles were found to pack more tightly, resulting in less particle loss due to reentrainment.

For design No. 4, the wall loss is not severe. The reentrainment problem that occurs at $\sqrt{Stk}$ of 0.5 is now diminished. The wall loss is only 3.1%. At higher Stokes numbers, the reentrainment was not observed but found some particles deposited on the outer wall of the nozzle because of particle bounce from the cavity. However, this loss was several percent only.

Therefore for design No. 4, when D is too small, severe wall loss due to unfavorable exiting flow direction can occur. When D is too large, the reentrainment of deposited particles can occur, which also results in severe wall loss. In the subsequent test, it was decided to use 9.6 mm as the diameter of cavity opening in design No. 4. That is, in the current design No. 4, the diameter of cavity opening is about four times of the nozzle diameter.

Particle Collection Characteristics on Coated Substrates

Silicone oil coated substrates were used to determine the loading effect of solid particles on the collection efficiency of different impaction surfaces. Monodisperse particles of 3.4 ± 0.05 μm in the aerodynamic diameter was used in the 2-h test. The total loaded particle mass was 0.7–0.94 mg. From Fig. 4, it is seen that

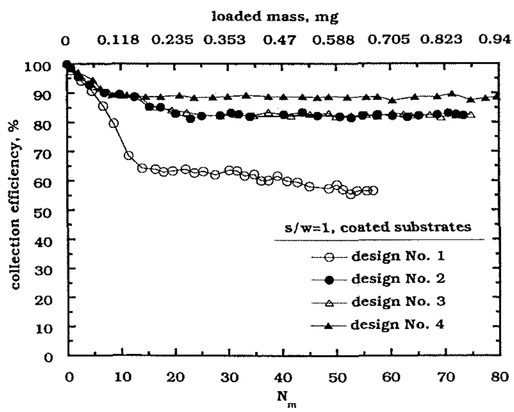

FIGURE 4. Collection efficiency versus N_m and loaded particle mass for coated impaction surfaces. $D_{pa} = 3.4 \pm 0.05$ μm; total running time = 120 min.

particle loading on the impaction surface influences the solid particle collection efficiency to a great extent. For every design, the collection efficiency starts to drop from the initial 100% as the particle loading increases. The collection efficiency of the normal design No. 1 drops most sharply to 63% at $N_m = 13$, and remains more or less steady afterwards.

The collection efficiencies of the other design do not drop as sharply as the design No. 1. After N_m becomes 15–20, the steady-state collection efficiencies are 82%, 82%, and 88% for designs No. 2, 3, and 4, respectively.

The drop in collection efficiency right from the beginning indicates that the capillary action of silicone oil may not be very effective and impacting particles bounce easily away from the previously deposited particles. For design No. 1, bounced particles are carried away from the collection surface because of large radial flow velocity component. Recapture of bounced particles does not happen. For other designs that use conical cavity, the air flow direction changes in a way that reduces its radial component and favors redeposition of bouncing particles within the cavity.

The particle collection characteristic of the design No. 2 is similar to design No. 3. The steady-state particle collection efficiency of design No. 4 is greater than both designs No. 2 and No. 3. This is due to the more efficient recapturing of bounced particles within the cavity. It was observed a substantial amount of particles was recaptured near the top corner of the cavity where flow makes a turn to exit from the orifice. Also as explained before, the reentrainment of deposited particles in the form of aggregates is minimized in design No. 4.

After particle loading for 2 h, the entire curve of collection efficiency versus particle aerodynamic diameter was then obtained without cleaning the impaction surface. Experiment for each particle size only lasted for 1 min to avoid adding more particle loading on the impaction surface. The experimental collection efficiency curves are designated as "heavy loading" in Figs. 5a–5d for four different impaction surface designs. Also included in Fig. 5 are the collection efficiency curves under

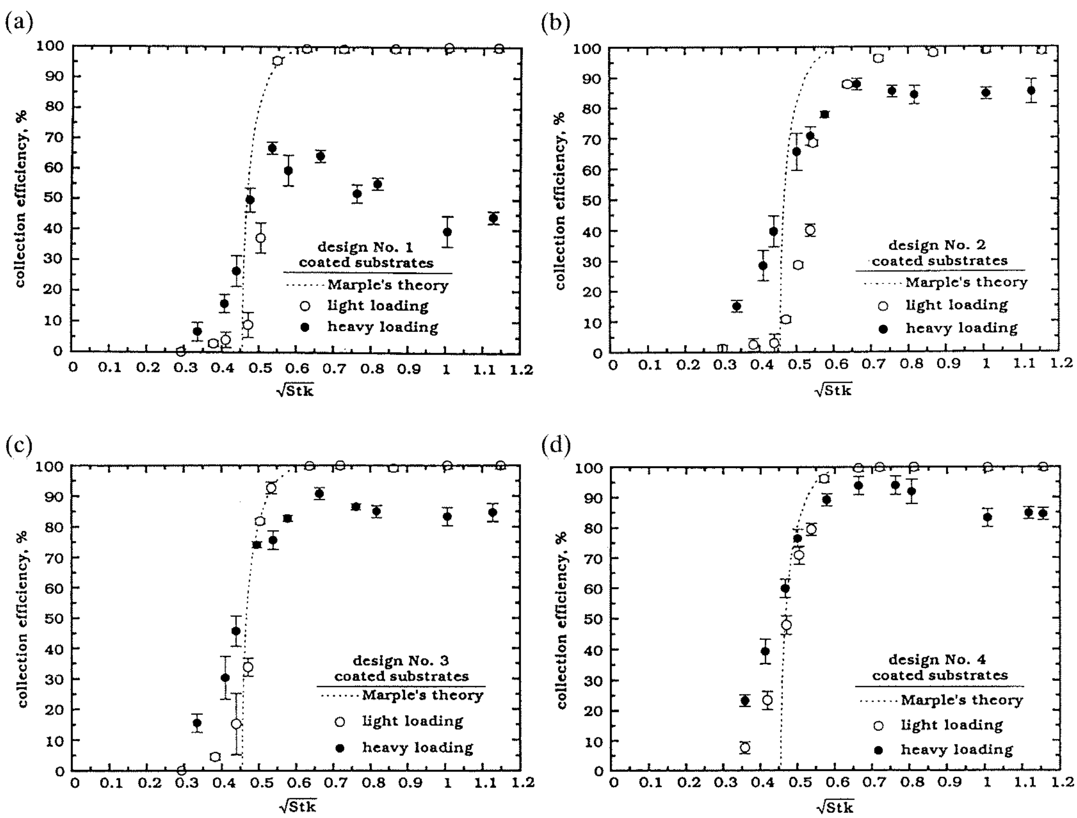

FIGURE 5. Collection efficiency versus particle aerodynamic diameter for coated impaction surfaces. (a) Design No. 1. (b) Design No. 2. (c) Design No. 3. (d) Design No. 4.

light loading condition, which was obtained when the experiment involving a clean impactor only lasted for 1 min.

As expected, when the particle loading is light, all four different designs have similar collection efficiency curves. Collection efficiency curves are in close agreement with Marple's theoretical curves except the design No. 2. When particle loading is heavy, Fig. 5a shows that collection efficiency begins to drop after reaching 70% at $\sqrt{\text{Stk}}$ of 0.53 for the design No. 1. Particle bounce from previously deposited particles becomes more severe as the Stokes number gets higher, resulting in even lower collection efficiency at high Stokes numbers. For example, the collection efficiency is only 45% when $\sqrt{\text{Stk}}$ is equal to 1.13. There appears to have no particle rebound when $\sqrt{\text{Stk}}$ is less than 0.53. The collection efficiency curve of the design No. 1 with a coated impaction surface is very similar to the previous experimental data by Rao and Whitby (1978a) for an uncoated impaction surface.

Under heavy loading condition, designs No. 2, 3, and 4 have much better collection efficiency curves than design No. 1. At high Stokes numbers, collection efficiencies of these three designs remain nearly constant at 85%. In design No. 4, a drop in the collection efficiency for $\sqrt{\text{Stk}}$ ranging from 0.5 to 0.8 is small. It remains greater than 90%. But as the Stokes number increases, the collection efficiency again drops to 85% due to particle bounce. The advantage of design No. 4 over the other designs is the prevention of reentrainment of deposited particles, as explained in the previous section.

Particle Collection Characteristics on Uncoated Substrates

It is of great interest to see if the superior particle collection characteristics of designs No. 2, 3, and 4 persists for uncoated substrates when compared with design No. 1. At first, highly concentrated monodisperse particles of 3.2 ± 0.05 μm in aerodynamic diameter were sampled for 90 min through the impactor with initially clean substrate. The total loaded particle mass was 0.16–0.32 mg. The resulting collection efficiency versus N_m and the loaded particle mass for four different designs are plotted in Fig. 6. It is seen that the initial collection efficiency are very low for every surface design. It is only 10–20% for design No. 1 and 25%–35% for the other designs. But right from the beginning of the test, the collection efficiency increases with respect to particle loading. For designs 2, 3, and 4, the slope of the increase in the collection efficiency is very steep initially, then the efficiency becomes steady at about five layers of deposited particles. The steady-state collection efficiencies are 80%, 80% and 84% for designs No. 2, 3, and 4, respectively. The increase in the collection efficiency is relatively slow for the design No. 1. After eight layers of deposited particles, the collection efficiency remains fixed at about 55%.

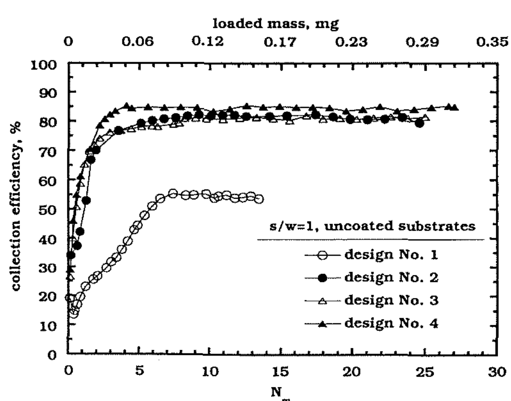

FIGURE 6. Collection efficiency versus N_m and loaded particle mass for uncoated impaction surfaces. $D_{pa} = 3.2 \pm 0.04$ μm; total running time = 90 min.

The above particle loading phenomena have never been explored before in the open literature. The increase in the collection efficiency as particles load up is because of the change in impaction surface characteristics. Initially, the uncoated impaction surface is smooth and hard, solid particles bounce easily upon impaction with the substrate. The relatively large radial flow component in design No. 1 carries away bouncing particles easily resulting in the smallest initial collection efficiency among all designs. A small amount of impacting particles will be collected on the substrate with asperities on the surface. Loss of kinetic energy occurs due to adhesion energy as well as plastic deformation (Wall et al. 1990; Tsai et al. 1990; Xu and Willeke 1993), resulting in possible particle collection or recapturing of bounced particles by the substrate.

As the amount of deposited particles gradually increases, more incident particles will impact on previously deposited particles. Part of the incident kinetic energy is probably spent to move deposited particles away from their initial positions. This increases the likelihood of particle collection upon impaction. Also the particle rebound velocity will more likely have a downward component when particle-to-particle collision occurs, which also increases the possibility of particle collection. When deposited particles get thick enough under the nozzle, the incident particles always impact on the same particle bed. Then there will be no further change in the collection efficiency unless the particle mound becomes too high to get reentrained.

For designs other than No. 1, particles still bounce away from the conical cavity initially. But because of the conical tip, more deposited particles are concentrated around the tip initially and the initial particle to particle collision occurs more frequently resulting in a steep increase in the collection efficiency. The steady-state collection efficiency is also reached much faster than design No. 1 because a thick layer of particle deposits is built up more quickly near the tip of the cavity.

After particle loading for $1\frac{1}{2}$ h, the curve of collection efficiency versus particle aerodynamic diameter was then obtained again without cleaning the impactor. Entire collection efficiency curves for four designs at light and heavy particle loading conditions were obtained and plotted in Figs. 7a–7d, in the same way as Figs. 5a–5d. For design No. 1, at light particle loading, the collection efficiency curve of the impactor degrades very substantially when the Stokes number is greater than Stk_{50}. The collection efficiency is only 10%–20% when $\sqrt{Stk}$ is greater than 0.7. At heavy particle loading, particle bounce is reduced somewhat near Stk_{50}, but it remains a serious problem for $\sqrt{Stk}$ greater than 0.7 when the collection efficiency starts to drop sharply again to 10%–20% range at high Stokes numbers.

For design No. 2, the collection efficiency at light condition is improved but remains low in the 20%–50% range for $\sqrt{Stk}$ greater than 0.7. Similar characteristics exist for designs No. 3 and 4. However, at heavy particle loading, the collection efficiency of these three designs are greatly improved. For design No. 2, the collection efficiency can reach 85% at $\sqrt{Stk}$ of 0.62, and gradually drops to 75% at $\sqrt{Stk}$ of 1.15. The design No. 3 has a similar characteristics but the efficiency now drops to 60% when $\sqrt{Stk}$ is greater than 1.0. Design No. 4 has the best collection efficiency near Stk_{50}, reaching about 90% at a $\sqrt{Stk}$ of 0.62. The collection efficiency gradually drops to 65%–75% as $\sqrt{Stk}$ becomes greater than 0.9.

From the above discussion, design No. 2 seems to have a better particle collection characteristics than design No. 4. But the experimental observation indicates that the wall loss due to reentrainment in design No. 2 is still very severe near Stk_{50} for the uncoated substrate. Design No. 4

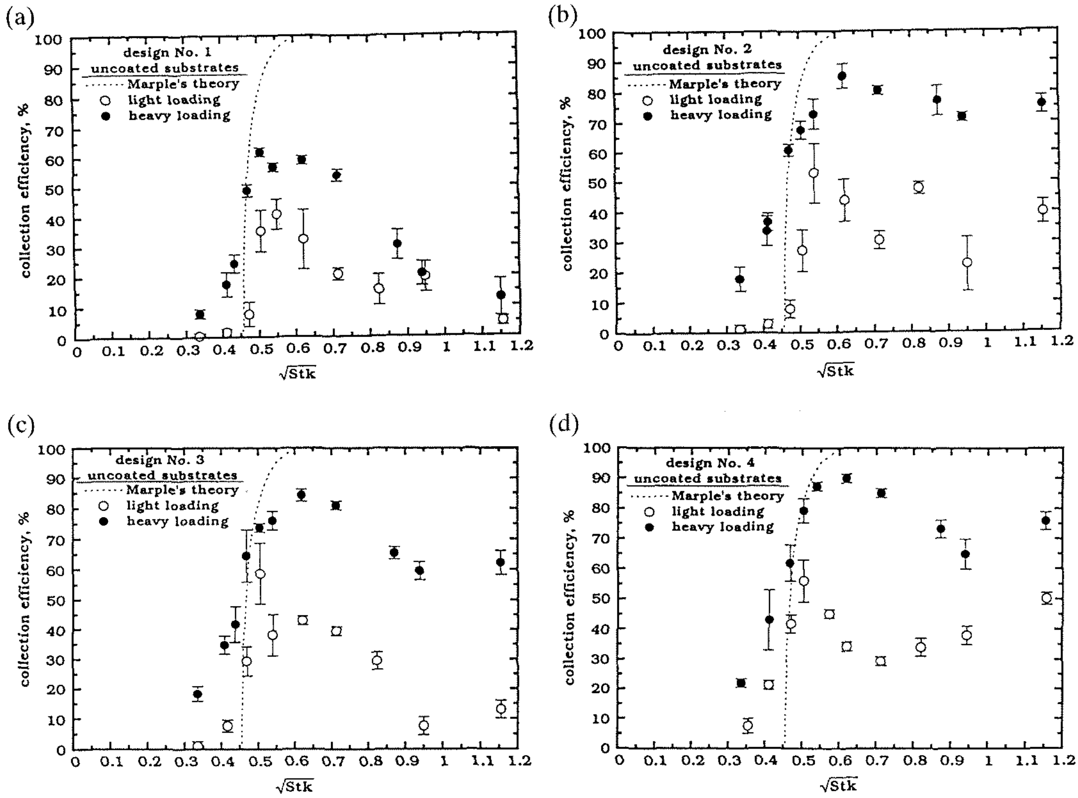

FIGURE 7. Collection efficiency versus particle aerodynamic diameter for uncoated impaction surfaces. (a) Design No. 1. (b) Design No. 2. (c) Design No. 3. (d) Design No. 4.

has very little particle reentrainment problem. The reason that under heavy particle loading conditions, the particle collection efficiency for all designs is lower for the uncoated substrate than the coated substrate can be explained. This is because the increase in the collection efficiency is mainly due to the recapture of the rebounding particles as particle-to-particle collision occurs, and the coated substrate is more effective in collecting rebounded particles than the uncoated substrate.

CONCLUSIONS

Previous theoretical and experimental work about solid particle loading effect on the impactor collection efficiency is restricted to flat impaction surface only. This study has extended the work to heavy particle loading conditions using different impaction surface designs.

It has been found that particle loading on the impaction substrate changes the surface characteristics substantially. For coated substrates, the particle collection efficiency drops very severely with respect to particle loading for conventional flat impaction surface design. When the impaction surface is loaded with several tens of particle layers, the particle collection efficiency curve looks very similar to that of uncoated substrate. With an inverted conical cavity, the adverse effect of particle loading on the collection efficiency may be minimized to a great extent. To prevent wall loss due to particle bounce and reentrainment, an orifice plate having an opening diameter about four times that of the nozzle diameter has been shown to be very effective.

For the uncoated substrate, the particle loading on the substrate changes the surface characteristics that favors incident particle collection and recapturing of bounced particles. The collection efficiency is shown to increase from the very beginning of particle sampling. After heavy particle loading of several tens of particle layers, the collection efficiency is shown to reach a steady-state value that is very close to that of coated substrate for all design. However, for the conventional flat impaction surface designs, the increase in the collection efficiency after heavy particle loading is not very substantial. With a conical cavity on the uncoated impaction substrate, heavy particle loading results in a collection efficiency curve that is high and of great potential application, such as particle sampling in high temperature exhaust gas from a stack.

The authors would like to acknowledge the support of the National Science Council, Taiwan, Republic of China, under a contract number NSC 82-0410-E-009-278.

REFERENCES

Biswas, P., and Flagan, R.C. (1988), *J. Aerosol Sci.* 19:113–121.

Chen, B. T., Yeh, H. C., and Cheng, Y. S. (1986). *Aerosol Sci. Technol.* 5:369–376.

Chen, B. T., and Yeh, H.C. (1987). *J. Aerosol Sci.* 18:203–214.

Cheng, Y. S., and Yeh, H. C. (1979). *Environ. Sci. Technol.* 13:1392–1396.

Dzubay, T. H., Hines, L. E., and Stevens, R. K. (1976). *Atmos. Environ.* 10:229–234.

Hinds, W. C., Liu, W. V., and Froines, J. R. (1985). *Am. Ind. Hyg. Assoc. J.* 46:517–523.

Markowski, G. R. (1984). *Aerosol Sci. Technol.* 3:431–439.

Marple, V. A. and Chien, C. M. (1980). *Environ. Sci. Technol* 14:976–984.

Marple, V. A., and Willeke, K. (1976). *Atmos. Environ.* 10:891–896.

Marple, V. A., Rubow, K. L., and Behm, S. M. (1991). *Aerosol Sci. Technol.* 14:434–446.

Newton, G. J., Cheng, Y. S., Barr, E. B., and Yeh, H. C. (1990). *J. Aerosol Sci.* 21:467–470.

Pak, S. S., Liu, B. Y. H., and Rubow, K. L. (1992). *Aerosol Sci. Technol.* 16:141–150.

Pui, D. Y. H., Lewis, C. W., Tsai, C. J., and Liu, B. Y. H. (1990). *Environ. Sci. Technol.* 234:307–312.

Rao, A. K., and Whitby, K. T. (1978a). *J. Aerosol Sci.* 9:77–86.

Rao, A. K., and Whitby, K. T. (1978b). *J. Aerosol Sci.* 9:87–100.

Reischl, G. P., and John, W. (1978). *Staub. Reinhalt. Luft.* 38:55.

Schott, J. H., and Ranz, W. E. 1976). *Environ. Sci. Technol.* 10:1250–1256.

Tsai, C.-J., Pui, D. Y. H., and Liu, B. Y. H. (1990). *Aerosol Sci. Technol.* 12:497–507.

Turner, J. R., and Hering, S. V. (1987). *J. Aerosol. Sci.* 18:215–224.

Walls, S., John, W., Wang, H.C., and Goren, S. (1990). *Aerosol Sci. Technol.* 12:926–946.

Wang, H. C., and John, W. (1987). *Aerosol Sci. Technol.* 7:285–299.

Xu, M., Willeke, K., Biswas, P., and Pratsinis, S. E. (1993). *Aerosol Sci. Technol.* 18:143–155.

Vanderpool, R. W., and Rubow, K. L. (1988). *Aerosol Sci. Technol.* 9:65–69.

Received July 25, 1994; revised October 28, 1994.