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# Effect of gravity on particle collection efficiency of inertial impactors

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**Abstract**

This study has investigated the effect of gravitational force on particle collection efficiency in inertial impactors numerically and experimentally. In the numerical study, two-dimensional flow field in the inertial impactor was simulated by solving the Navier–Stokes equations with the control volume method. Particle trajectories were then calculated to obtain the collection efficiency at different Reynolds numbers, which are based on nozzle diameter. This study shows that gravitational force increases the particle collection efficiency when the Reynolds number is below about 1500. The numerical results were found to be in good agreement with the experimental data of Marple et al. (*JAPCA*, *37*, 1303) (1987), Rubow et al. (*American Industrial Hygiene Association Journal*, *48*, 532) (1987) and those obtained in the present study. © 2001 Elsevier Science Ltd. All rights reserved.

*Keywords:* Collection efficiency; Cascade impactors; Inertial impactors

## 1. Introduction

Inertial impactors are widely used for size-fractionated sampling of aerosols. Because of their importance, inertial impactors have been studied extensively by many previous investigators, both theoretically and experimentally. Previous theoretical analysis of the inertial impactors predicted the cutoff diameter and the shape of the collection efficiency of the curves reasonably well. The original impactor theories were developed by Ranz and Wong (1952) and Davies and Aylward (1951). The design guidelines of the impactors were developed based on the numerical analysis of the Navier–Stokes equations to obtain the flow field and the subsequent numerical integration of

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particle equations of motion to obtain the particle trajectories and collection efficiency curves (Marple, 1970; Marple & Liu, 1974; Marple & Willeke, 1976; Rader & Marple, 1985). Marple (1970) and Marple and Liu (1974) made a thorough parametric study of inertial impactors and found that the Reynolds number based on the nozzle diameter must be between 500 and 3000 for producing a sharp cutoff efficiency curve. Marple and Willeke (1976) used this theory to design multiple-hole impactors and developed charts to aid the design of round or rectangular impaction stages. Rader and Marple (1985) updated the theory by Marple and Liu (1974) by including second-order effects such as ultra-Stokesian drag on the particles and particle interception at the impaction plate. In these studies, gravitational effect of particles on collection efficiency was not considered.

Many low flow rate, small personal impactors have been designed and calibrated in the laboratory. The Reynolds numbers based on round nozzle diameter or rectangular slot width for these impactors are low, typically less than 1000 for upper stages. Rubow, Marple, Olin and Mccawley (1987) developed an 8-stage Marple personal cascade impactor with the cutoff aerodynamic diameter ($da_{50}$) of 21.3, 14.8, 9.8, 6.0, 3.5, 1.55, 0.93, and 0.52 μm for stages 1 to 8. Their data showed that the agreement between theoretical and experimental cutoff diameters was quite good for the stages with $da_{50}$ of 10 μm and less, while the agreement was not good for the stages with larger $da_{50}$. The over-prediction of theoretical results was 68, 32 and 12% for the stages 1–3, respectively. This discrepancy was also found to exist in the upper stage (stage 1, $da_{50}$: 9.8 μm) of the 2-stage MST Indoor Air Sampler (Marple, Rubow, Turner & Spengler, 1987) with theoretical over-prediction of 6%. This disagreement was thought to be due to particle gravitational effect (Lodge & Chan, 1986).

However this disagreement was not found for the upper stages of cascade impactors with higher flow rate. For example, the agreement between the theoretical and experimental $da_{50}$ was quite satisfactory for the MOUDI (Microorifice Uniform Deposit Impactor) developed by Marple, Rubow and Behm (1991) with the flow rate of 30 l $min^{-1}$. The collection efficiency curves of the MOUDI were shown to be sharp. Fang, Marple and Rubow (1991) investigated the influence of the cross-flow on the sharpness of the collection efficiency curves of the multi-nozzle impactor. Their results showed that sharpness of the collection efficiency curves of multi-nozzle impactors could be improved by keeping the cross-flow geometric parameter less than the critical value of 1.2.

An earlier experimental demonstration of the gravity effect on particle collection efficiency in the inertial impactor can be found in May (1975), who showed that gravity effect was predominant during low-velocity impaction of particles larger than 20 μm because of their large terminal velocity. Rader and Marple (1984) included the effect of gravity on numerical simulations of particle transport in an inertial impactor and found that low fluid velocities enhance the influence of gravity on the increase of particle collection efficiency. Recently, Swanson, Muzzio, Annapragada and Adjei (1996) acknowledged the importance of gravity to particle deposition in relatively slow-flowing inter-stage chambers of a cascade impactor. Gravitational force was included in their numerical analysis of particle deposition in a cascade impactor but without further detailed discussion.

The above review indicates that particle collection efficiency may deviate from the traditional Marple's theory when the Reynolds number based on the nozzle diameter is small and when particle aerodynamic diameter is large. In this paper, the gravitational effect of particles on the theoretical collection efficiency of an inertial impactor was investigated using numerical models which calculate flow field, particle trajectory and collection efficiency. The theoretical collection

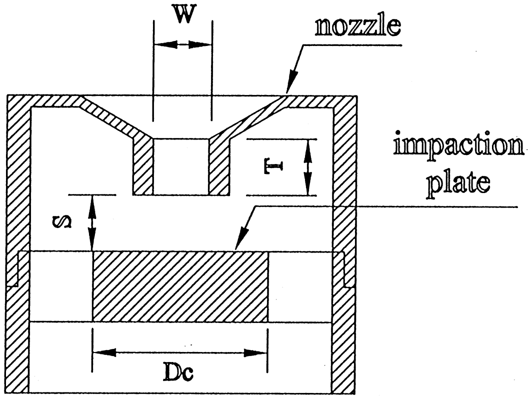


Fig. 1. The schematic diagram of an impaction stage used in this study. ($S$: jet-to-plate distance = 0.48 cm – stage 1, = 0.36 cm – stage 2; $T$: nozzle throat length = $S$; $D_c$: diameter of impaction plate = 1.5 cm; half angle of the tapered section of nozzle = 60°, depth = 0.369 cm – stage 1, = 0.404 cm – stage 2; diameter of nozzle opening = 1.759 cm.)

efficiency curves were compared with the experimental data of Rubow et al. (1987) and Marple et al. (1987). In this study, experimental collection efficiency data were also obtained for a single nozzle, 2-stage cascade impactor for comparing with the theoretical predictions. The schematic diagram of a stage is shown in Fig. 1. The flow rate is 2 l $min^{-1}$ and the nozzle diameter ($W$) of stages 1 and 2 is 0.48 and 0.36 cm, respectively.

## 2. Experimental method

The particle collection efficiency of the impactor was evaluated using monodisperse, oleic acid test particles containing fluorescein dye tracer. Monodisperse particles were generated by the vibrating orifice monodisperse aerosol generator (VOMAG, TSI MODEL 3450, TSI Inc., St. Paul, Minn.), using the techniques of Tsai and Cheng (1995). The particles were dried and neutralized before being introduced into the testing stage of the cascade impactor. After a sampling time of 5–30 min, the impactor plate, inner surfaces and after-filter were washed by distilled water buffered with 0.001 N NaOH in 20 ml. Afterwards, the washed solutions were measured using a fluorometer (Turner 10-AU, Cincinnati, USA) to determine the dye concentrations. Particle collection efficiency was calculated from the ratio of particle mass collected on the impaction plate to the total particle mass, which is the sum of all particles collected on impaction plate, after-filter and inner surfaces. An Aerodynamic Particle Sizer (APS, TSI Model 3310A) was used to check the monodispersity and steadiness of the testing aerosols before and after each test.

## 3. Theoretical method

### 3.1. Flow field

The flow field in the inertial impactor was simulated by solving the 2-D cylindrical or rectangular Navier–Stokes equations. The flow in the impactor was assumed steady, incompressible and

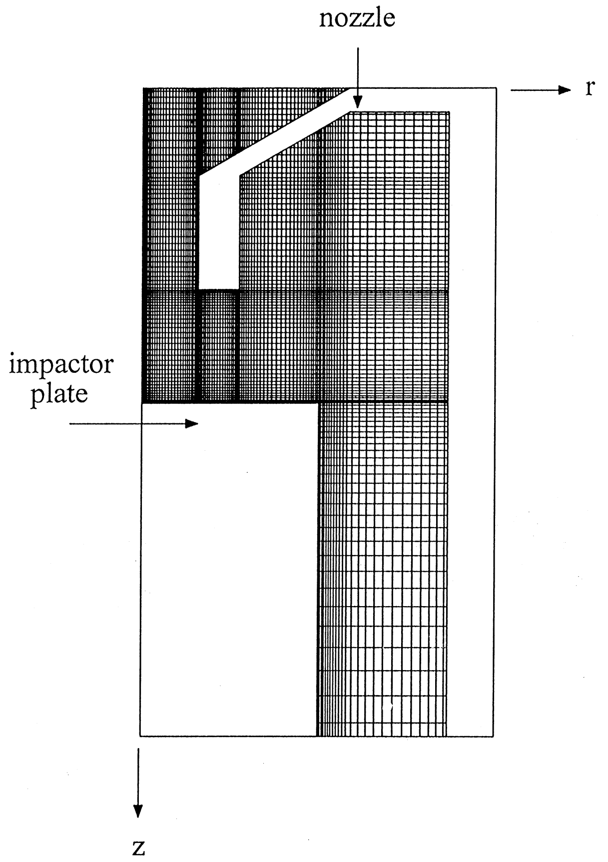


Fig. 2. Main control volume distribution for flow field calculation in the present design. Total number of grids for this single-fine grid spacing is 10,000.

laminar, and air condition was assumed to be 20°C and 1 atm. The governing equation was discretized by means of the finite volume method and solved by the SIMPLE algorithm (Patankar, 1980). One example of the calculation domain is shown in Fig. 2, where the number of grid squares (called single-fine) is 10,000 (100 in the $r$-direction $\times$ 100 in the $z$-direction). The grid spacing is finer near the wall and impaction surface where the velocity gradients are expected to be larger. In other calculations, double-fine (the number of grid is four times as fine as the single-fine grid) and triple-fine grid spacing were used for comparing the resolution of the particle collection efficiency.

### 3.2. Particle trajectory and collection efficiency

After obtaining the flow field, the particle equations of the motion were solved numerically to obtain particle trajectory and collection efficiency. In cylindrical coordinates, the particle equations of motion in $r$ (radial) and $z$ (axial) directions are

$$m_{\mathrm{p}}\frac{\mathrm{d}u_{\mathrm{pr}}}{\mathrm{d}t} = C_{\mathrm{d}}\mathrm{Re}_{\mathrm{p}}\frac{\pi\mu d_{\mathrm{p}}}{8C}(u_r - u_{\mathrm{pr}}), \quad (1)$$

$$m_{\mathrm{p}}\frac{\mathrm{d}u_{\mathrm{pz}}}{\mathrm{d}t} = C_{\mathrm{d}}\mathrm{Re}_{\mathrm{p}}\frac{\pi\mu d_{\mathrm{p}}}{8C}(u_z - u_{\mathrm{pz}}) + m_{\mathrm{p}}g. \tag{2}$$

Particle equations of motion in the rectangular coordinates are similar. In the above equations, $C_{\mathrm{d}}$ is the empirical drag coefficient; $\mathrm{Re}_{\mathrm{p}}$ the particle Reynolds number; $C$ the Cunningham slip correction factor; $\mu$ the air dynamic viscosity; $m_{\mathrm{p}}$, $d_{\mathrm{p}}$ and $g$ are the particle mass, diameter and the gravitational acceleration, respectively; $u_{\mathrm{pr}}$ and $u_{\mathrm{pz}}$ are the particle velocities, $u_r$ and $u_z$ are the local flow velocities in the radial and axial directions, respectively.

In order to examine the effect of gravity on collection efficiency, the particle equation of motion in the $z$-direction is non-dimensionalized as

$$\frac{\mathrm{d}u^*_{\mathrm{pz}}}{\mathrm{d}t^*} = \frac{C_{\mathrm{d}}\mathrm{Re}_{\mathrm{p}}}{12}\frac{1}{\mathrm{St}}(u^*_z - u^*_{\mathrm{pz}}) + \frac{1}{\mathrm{Fr}}, \tag{3}$$

where dimensionless variables are

$$t^* = \frac{tu_0}{W}, \quad u^*_z = \frac{u_z}{u_0} \quad \text{and} \quad u^*_{\mathrm{pz}} = \frac{u_{\mathrm{pz}}}{u_0}.$$

In the above equation, two dimensionless numbers are Stokes number, St, and Froude number, Fr (Fuchs, 1989), where

$$\mathrm{St} = \frac{\rho_{\mathrm{p}} C d_{\mathrm{p}}^2 u_0}{9\mu W}, \tag{4}$$

$$\mathrm{Fr} = \frac{u_0^2}{gW}. \tag{5}$$

From Eq. (3), it is seen that in addition to St and Re (Reynolds number based on the nozzle diameter, $\mathrm{Re} = \rho u_0 W/\mu$), the new dimensionless parameter, Fr, which is the ratio of the particle inertial force to its gravitational force, also affects particle trajectory and collection efficiency. It can be shown that the Reynolds number is directly related to the Froude number, Fr, as

$$\mathrm{Re} = \frac{\rho\sqrt{g}W^{3/2}}{\mu}\sqrt{\mathrm{Fr}}. \tag{6}$$

That is, for a given Reynolds number and known air condition, if the nozzle diameter of different impactor stages is different, then Fr will be different.

The calculation involves integrating Eq. (1) and (2) by means of the fourth-Runge–Kutta method, applying an empirical drag law for the ultra-Stokesian regime and considering particle interception effect (Rader & Marple, 1985). As the particle equations of motion are integrated through the domain of interest, its initial velocity is given equal to the local flow velocity, and the initial position is set at the entrance of the nozzle. The new particle position and velocity after a small increment of time is calculated by numerical integration. The procedure is repeated until the particle hits the impaction plate or leaves the calculation domain.

The collection efficiency of monodisperse aerosol particles in the impaction plate is defined as

$$\eta = \frac{\text{particles collected on the impaction plate}}{\text{particles entering the nozzle}}. \tag{7}$$

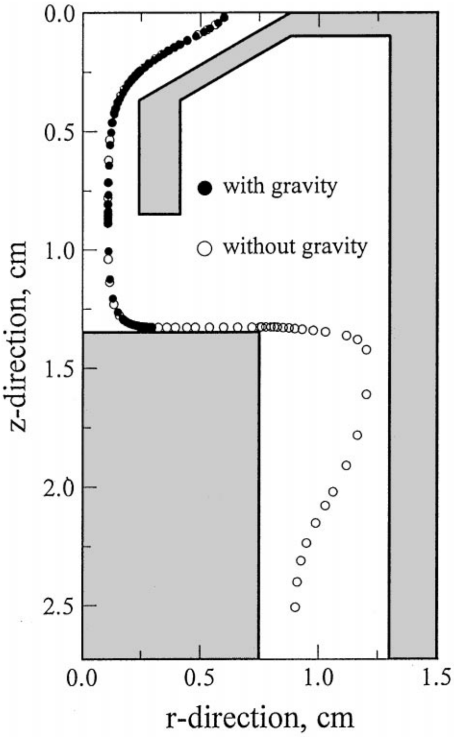


Fig. 3. Particle trajectories for particles 10 μm in aerodynamic diameter in the stage 1 of the present design. (Only a few computational points of particle trajectories are shown.)

If the particle concentration and velocity profiles are assumed to be uniform at the entrance of the nozzle, then the collection efficiency can be calculated as

$$\eta = (r_c/(W/2))^2 \quad \text{circular jet of throat diameter } W, \tag{8}$$

$$\eta = r_c/(W/2) \quad \text{rectangular slot of width } W, \tag{9}$$

where $r_c$ is the critical particle radius (cylindrical coordinate) or distance from the centerline (rectangular coordinate) obtaining from the numerical study.

## 4. Results and discussion

### 4.1. Particle trajectory

Fig. 3 illustrates the gravitational effect on particle trajectories for particles 10 μm in aerodynamic diameter in the stage 1 of present design. Starting at the same initial starting position, the particle with gravity impacts on the impaction plate while the particle without gravity follows airs streamline and exits the impactor. Therefore, the collection efficiency is expected to be higher when gravitational effect is considered.

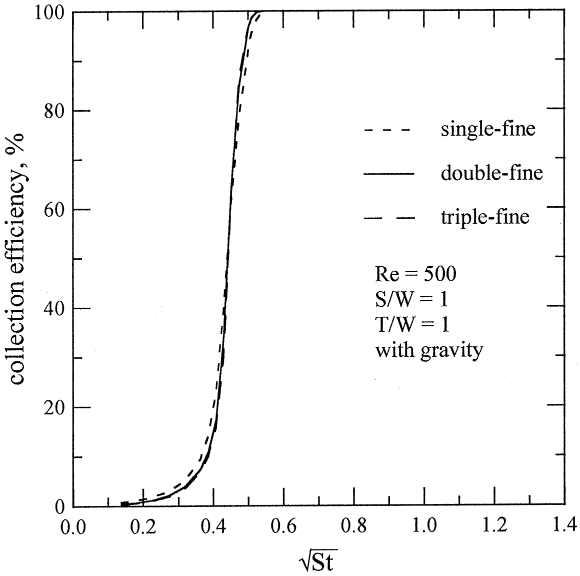


Fig. 4. Effect of grid spacing on collection efficiency curves.

### *4.2. Effect of grid spacing on the collection efficiency*

Fig. 4 shows the efficiency curves considering the gravitational effect for stage 1 of the present design at Reynolds number of 500 using different grid spacings. As the resolution of the flow improves through grid refinement, the collection curve steepens while $\sqrt{St_{50}}$ (stokes number at 50% collection efficiency) remains almost the same. The sharpness of the collection efficiency curve caused by grid refinement is consistent with the results of Rader and Marple (1985). However, since the number of single-fine grid, 10,000, is nearly ten times as many as that used in Rader and Marple (1985), the difference in sharpness of the collection efficiency curves between the single- and double-fine grids is not much. The collection efficiency curves for both double- and triple-fine grids almost overlap each other. Hence in the subsequent simulation, the double-fine grid spacing is used.

### *4.3. Effect of gravity on collection efficiency at different Reynolds numbers*

The effect of gravity on the efficiency curves is shown in Fig. 5 at Reynolds number of 10, 100 and 3000. Compared to the case without gravity, there is a substantial shift of the efficiency curve to the left as particle gravitational effect is considered at Reynolds number of 10 and 100. However, at higher Reynolds number of 3000, the collection efficiency curve does not change whether or not the gravitational effect is considered. That is, the effect of gravity is to increase the collection efficiency at the same $\sqrt{St}$ only when the Reynolds number is low, and the effect is negligible at high Reynolds number.

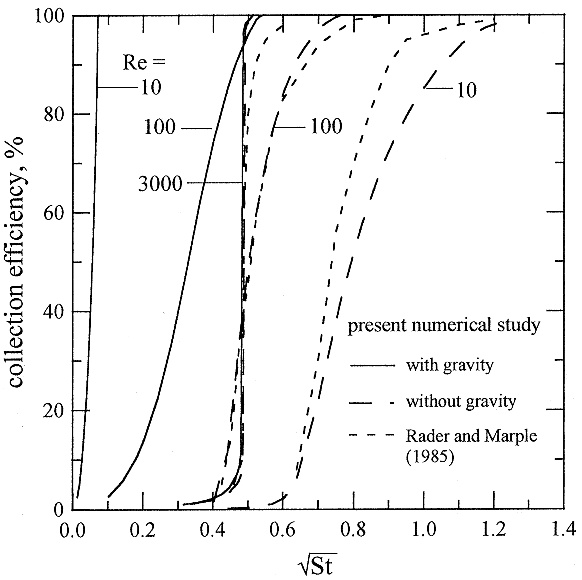


Fig. 5. Effect of gravity on particle collection efficiency curves at Re = 10, 100 and 3000.

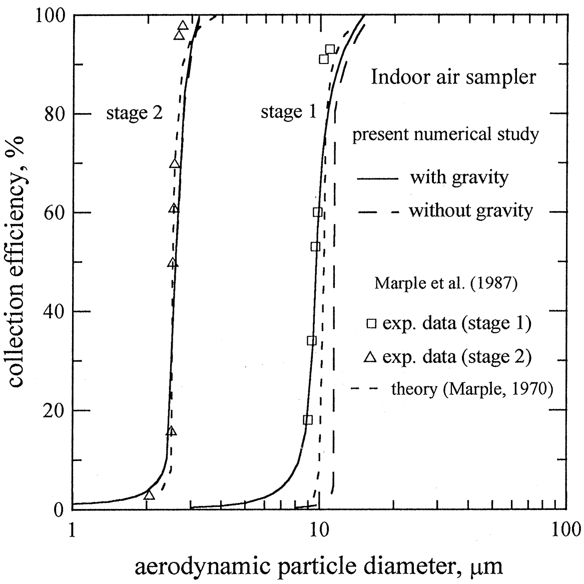


Fig. 6. Comparison of numerical results with the experimental data of Marple et al. (1987).

Also shown in Fig. 5 are the theoretical collection efficiency curves of Rader and Marple (1985) who did not consider the effect of gravity. It is seen that these curves are similar to those calculated in this study without considering gravity.

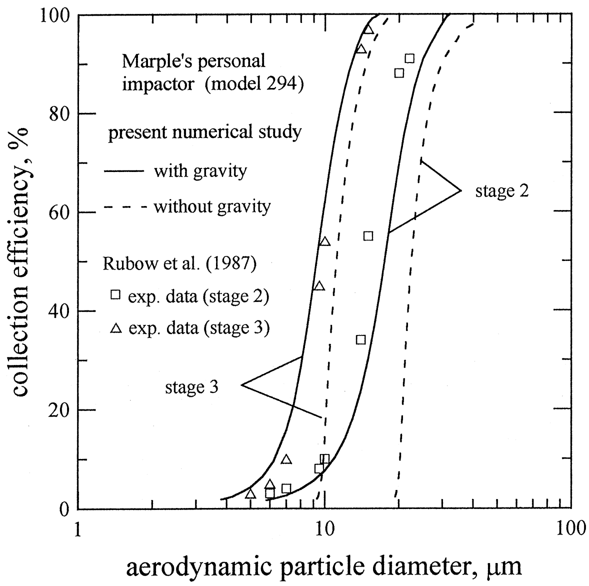


Fig. 7. Comparison of numerical results with the experimental data of Rubow et al. (1987).

### *4.4. Comparison of theoretical results with experimental data*

To further test the accuracy of the present theoretical results with consideration of gravity, we have compared the theoretical results with the experimental data of Marple et al. (1987), Rubow et al. (1987) and the present study. The numerical data of Marple et al. (1987) were for a round-jet impactor while those of Rubow et al. (1987) were for a rectangular-slot impactor. Exact dimensions and geometries of these impactors were used in the present numerical simulation except that the inlet of the nozzle was similar to that shown in Fig. 1. Fig. 6 shows the present numerical results are in very good agreement with the experimental data of Marple et al. (1987) for both stages 1 and 2 of the MST Indoor Air Sampler. Without considering gravity, both the present and Marple's numerical results under-predict the collection efficiency for stage 1 ($da_{50} = 9.8$ μm), and both numerical results are still accurate for stage 2 ($da_{50} = 2.52$ μm), i.e., gravity has an effect on the collection efficiency only for the stage with larger cutoff aerodynamic diameter for a small impactor.

A similar conclusion can be reached when the present numerical results are compared with the experimental data of Rubow et al. (1987), shown in Fig. 7, and the present experimental data, shown in Fig. 8. In both cases, the numerical results considering gravity are close to the experimental data, while the results without considering gravity under-predict the experimental data.

Numerical $da_{50}$ and experimental data of Marple et al. (1987), Rubow et al. (1987) and those obtained in the present study are compared and shown in Table 1. It is seen that without considering gravitational effect, the present study shows that $da_{50}$ will be over-predicted at low Reynolds numbers. For example, at Re = 76 and Fr = 11, over-prediction of experimental data

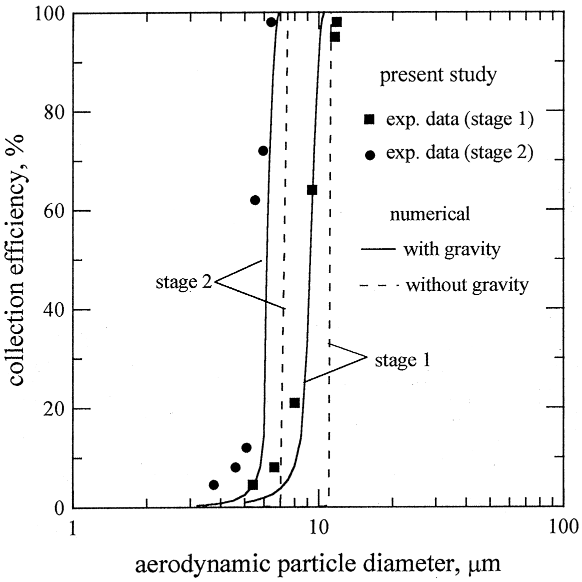


Fig. 8. Comparison of numerical results with present experimental data.

Table 1
Comparison of numerical $da_{50}$ with experimental data

| | MST sampler (Marple et al., 1987) | | Marple's personal impactor (Rubow et al., 1987) | | Present design | |
|---|---|---|---|---|---|---|
| | Stage 1 | Stage 2 | Stage 2 | Stage 3 | Stage 1 | Stage 2 |
| Re | 900 | 2140 | 76 | 76 | 588 | 784 |
| Fr | 80 | 8474 | 11 | 65 | 72 | 304 |
| Experimental data (μm) | 9.8 | 2.52 | 14.8 | 9.8 | 9.0 | 5.5 |
| Present study (with gravity) | 9.7 | 2.6 | 17.5 | 9.7 | 9.3 | 6.1 |
| | ( − 1.0%)[a] | ( + 3.2%) | ( + 18.2%) | ( − 1.0%) | ( + 3.3%) | ( + 10.9%) |
| Present study (without gravity) | 11.4 | 2.6 | 22.5 | 11.2 | 11.1 | 7.2 |
| | ( + 16.3%) | ( + 3.2%) | ( + 52.0%) | ( + 14.3%) | ( + 23.3%) | ( + 30.9%) |
| Marple's theory (1970) | 10.4 | 2.52 | 19.6 | 11.0 | 10.0 | 6.3 |
| | ( + 6.1%) | (0) | ( + 32.4%) | ( + 12.2%) | ( + 11.1%) | ( + 14.5%) |

[a] Percent difference with experimental data.

will be as high as 52%. However at higher Reynolds number, the numerical results without considering gravitational effect are still accurate. For example, at Re = 2140 and Fr = 8474, percent difference with the experimental data is only 3.2%. In general, the present numerical study considering gravitational effect is more accurate than Marple's theory (1970).

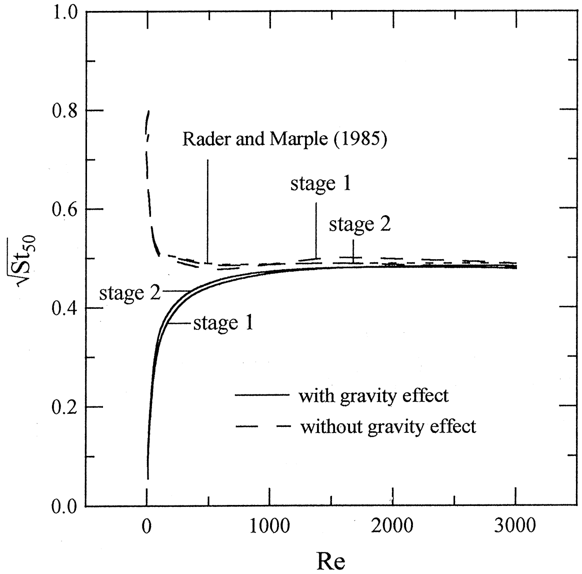


Fig. 9. The influences of Re on $\sqrt{\mathrm{St}_{50}}$ with or without gravity.

### 4.5. *Parametric study of factors influencing* $\sqrt{\mathrm{St}_{50}}$

It is of great interest to know the influence of Re and Fr on $\sqrt{\mathrm{St}_{50}}$ based on the simulation of stages 1 and 2 of the present round-nozzle impactor. Without considering gravity, Fig. 9 shows that $\sqrt{\mathrm{St}_{50}}$ decreases as Re is increased and reaches a constant when Re is greater than 1500. $\sqrt{\mathrm{St}_{50}}$ decreases very drastically with increasing Re when Re is smaller than 100. When Re $> 1500$, $\sqrt{\mathrm{St}_{50}} = 0.50$ and 0.49 for stages 1 and 2, which agrees very well with the theoretical value of Rader and Marple (1985), 0.49, and Marple and Liu (1974), 0.477.

To the contrary, when gravity is considered, $\sqrt{\mathrm{St}_{50}}$ increases when Re is increased. Also, $\sqrt{\mathrm{St}_{50}}$ increases very drastically when Re is smaller than 100. When Re is greater than 1500, $\sqrt{\mathrm{St}_{50}}$ reaches the same constant as the case without considering gravity. Fig. 10 shows the influence of Fr on $\sqrt{\mathrm{St}_{50}}$ by plotting $\sqrt{\mathrm{St}_{50}}$ versus Fr from Fig. 9 based on Eq. (6), the air condition was assumed to be 20°C and 1 atm. It is seen that $\sqrt{\mathrm{St}_{50}}$ decreases as Fr is decreased. Fr has an obvious effect on $\sqrt{\mathrm{St}_{50}}$. When Fr is greater than 470 for stage 1 ($W = 0.48$ cm) or 1120 for stage 2 ($W = 0.36$ cm), $\sqrt{\mathrm{St}_{50}}$ remains nearly constant. In Table 1, both the present numerical results without considering gravity and Marple's theoretical results are more accurate for a larger Fr. When Fr $> 470$, theoretical results that do not consider the gravity is accurate within 15% of the experimental data. Therefore for impactor with small flow rate, we recommend that Marple's theory, which does not consider gravity effect, be used for Re $> 1500$. If Re $< 1500$ the gravity effect must be considered and present numerical results must be used.

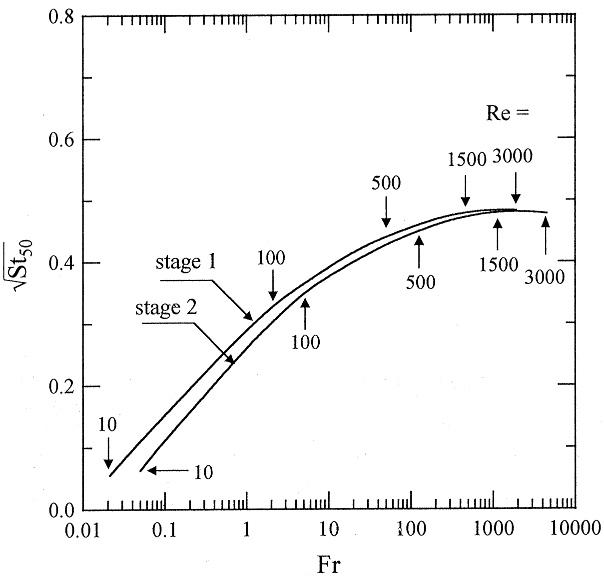


Fig. 10. The influences of Fr on $\sqrt{St_{50}}$.

## 5. Conclusions

When designing a small cascade impactor with a small flow rate, a single nozzle is often used. In this situation, the Reynolds number is usually small for upper stages. Without considering gravity, this study shows that Marple's theory can over-predict $\sqrt{St_{50}}$ very much depending on Re or Fr. The study shows that gravitational force decreases $\sqrt{St_{50}}$ as Re is decreased. $\sqrt{St_{50}}$ remains nearly constant when Re is greater than 1500, or when the dimensionless parameter, Fr, is above 470 for $W = 0.48$ cm or 1120 for $W = 0.36$ cm. Compared to Marple's theory, present numerical results which consider gravity are in much better agreement with the experiment data of Marple et al. (1987), Rubow et al. (1987) and those obtained in the present study. We recommend that Marple's theory be used only for $Re > 1500$ or $Fr > 470$ (for $W = 0.48$ cm) or 1120 (for $W = 0.36$ cm), to design the upper stages of a personal cascade impactor.

For multi-nozzle impactor, there is an additional complication due to cross-flow effect (Fang et al., 1991). In the future, it is worthwhile to investigate the effect of gravity and the size of the impaction plate on the collection efficiency for the upper stages of this kind of the impactor. However, if the flow rate is high and Reynolds number is above several thousands, gravity is not expected to affect the collection efficiency too much.

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