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Influence of Impaction Plate Diameter and Particle Density on the Collection Efficiency of Round-Nozzle Inertial Impactors

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This study has investigated the influence of impaction plate diameter (*Dc*) and particle density on the particle collection efficiency of single round-nozzle inertial impactors numerically assuming incompressible flow. The study shows that computed $\sqrt{\mathrm{St}_{50}}$ values range from 0.473 to 0.485, which are nearly independent of *W/Dc* (*W* is the nozzle diameter) for the nozzle Reynolds number, Re $>$ 1500, and when $W/Dc < 0.32$. $\sqrt{\mathrm{St}_{50}}$ values agree quite well with the theoretical values of Rader and Marple (1985), 0.49, and Marple and Liu (1974), 0.477. For a smaller impactor plate diameter such that $W/Dc > 0.32$, $\sqrt{\mathrm{St}_{50}}$ will increase slightly. It increases from 0.483 to 0.507 (Re = 3000) or from 0.479 to 0.495 (Re = 1500) when *W/Dc* is increased from 0.32 to 0.48. When the nozzle Reynolds number is smaller than 1500, the influence of *W/Dc* on $\sqrt{\mathrm{St}_{50}}$ is found to be much more pronounced. The effect of particle density on the collection efficiency has also been investigated. When particle gravity is included, the results show that $\sqrt{\mathrm{St}_{50}}$ is not affected by particle density ranging from 0.5 to 10 g/cm^3, although the particle collection efficiency increases slightly with increasing particle density at high ends of the collection efficiency curves at high nozzle Reynolds number due to an ultra-Stokesian effect. The particle interception effect does not affect the collection efficiency curves at high Reynolds numbers at all, and the effect is negligibly small at low Reynolds numbers.

INTRODUCTION

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 particle equations of motion to obtain the particle trajectories and collection efficiency curves (Marple 1970; Marple and Liu 1974; Marple and Willeke 1976; Rader and Marple 1985). These computations give the collection efficiency as a function of the dimensionless parameter, Stokes number, St (Marple and Liu 1974), at different nozzle Reynolds numbers, where St and Re are defined as

$$\mathrm{St} = \frac{\rho_p C d_p^2 u_0}{9\mu W}, \qquad [1]$$

$$\mathrm{Re} = \frac{\rho u_0 W}{\mu}, \qquad [2]$$

where ρ_p is the particle density, ρ is the air density, d_p is the particle diameter; C is the Cunningham slip correction factor, μ is the air viscosity, u_0 is the average air velocity in the nozzle, and W is the nozzle diameter.

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. The dimensionless number, $\rho/(\rho_p C)$, was also found to influence the particle collection efficiency at Re = 10 and 3000, respectively. Their results showed that when the Reynolds number Re is low (Re = 10), the deviation from Stokes law is small and there is no ultra-Stokesian effect. The interception distance decreases with increasing particle density of the same $\sqrt{\mathrm{St}}$, resulting in a decrease in the collection efficiency. For a high nozzle Reynolds number (Re = 3000), the efficiency curves shift to the left as particle density increases due to the ultra-Stokesian effect. The higher density particle of the same $\sqrt{\mathrm{St}}$ has a smaller particle Reynolds number and drag force, thus resulting in a higher collection efficiency compared to the particle with a smaller density.

The influence of impaction plate diameter on the particle collection efficiency has not been considered in the previous study. Flagan and Seinfeld (1988) indicated that if the diameter of the impaction plate is extended to infinity, the particles will sooner or later hit the plate and are collected. However, in reality the impaction plate diameter of the real impactor stages is finite. Experimentally, the particle deposition patterns on the impaction plate from the circular jet was measured (Sethi and John 1993)

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and showed that the spot radius of the deposited particles was about one-half the nozzle radius at $\sqrt{\mathrm{St}} = 1.6$. As $\sqrt{\mathrm{St}}$ was decreased, the peak in the surface area density of particles moved rapidly to a larger radius and reached the nozzle radius at about $\sqrt{\mathrm{St}} = 0.5$. Thus we infer that the 50% collection efficiency may be dependent on the size of the impaction plate, a point not ordinarily considered in the previous study of inertial impactors.

In our previous study (Huang and Tsai 2001), the effect of gravitational force on the particle collection efficiency in inertial impactors was investigated. The results showed that gravitational force increases the particle collection efficiency when the Reynolds number is below 1500. The influence of gravitational force on the collection efficiency is nearly negligible when the Reynolds number is >1500.

In this paper, the effects of the impaction plate diameter ($W/Dc = 0.127 \sim 0.48$) and particle density ($0.5 \sim 10$ g/cm^3) on the particle collection efficiency of a round-nozzle inertial impactor were investigated using numerical models that calculate flow field, particle trajectory, and collection efficiency. To study the Reynolds number effect, the particle collection efficiency of the inertial impactor with the different W/Dc values was simulated at different average air velocities through the nozzle.

METHOD

The particle collection efficiencies of the inertial impactors were simulated using the numerical models described in Huang and Tsai (2001). The flow field in the inertial impactor was simulated by solving the two-dimensional Navier–Stokes equations in the cylindrical coordinate. The fluid flow in the impactor was assumed steady, incompressible, and laminar, and air was assumed to be at 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). Grid independence checks (not presented in this article) were performed using different grid spacings. These checks revealed that approximately 40,000 grids were necessary to obtain a grid independent solution.

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

$$m_p \frac{du_{pr}}{dt} = C_d \mathrm{Re}_p \frac{\pi \mu d_p}{8C}(u_r - u_{pr}), \qquad [3]$$

$$m_p \frac{du_{pz}}{dt} = C_d \mathrm{Re}_p \frac{\pi \mu d_p}{8C}(u_z - u_{pz}) + m_p g. \qquad [4]$$

In the above equations, C_d is the empirical drag coefficient, Re_p is the particle Reynolds number, m_p and g are the particle mass and the gravitational acceleration, respectively, u_{pr} and u_{pz} are the particle velocities, and u_r and u_z are local flow velocities in the radial and axial directions, respectively.

The calculation involves integrating Equations (2)–(3) by means of the fourth Runge–Kutta method, applying an empirical drag law for the ultra-Stokesian regime and considering particle interception effect (Rader and 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.

If the particle concentration and velocity profiles are assumed to be uniform at the entrance of the nozzle, and particles are assumed to be collected when they hit the impaction plate, then the collection efficiency can be calculated as

$$\eta = \left(\frac{r_c}{(W/2)}\right)^2, \qquad [5]$$

where r_c is the critical radius within which particles will be collected. For comparison, the particle collection efficiency of the impactor without considering gravitational effect was also simulated.

RESULTS AND DISCUSSION

Particle Trajectories

Figure 1 illustrates the impactor configuration and particle trajectories at different $\sqrt{\mathrm{St}}$ for the present calculation at Re = 500. At high Stokes number, $\sqrt{\mathrm{St}} \approx 1.37$, there is a focusing

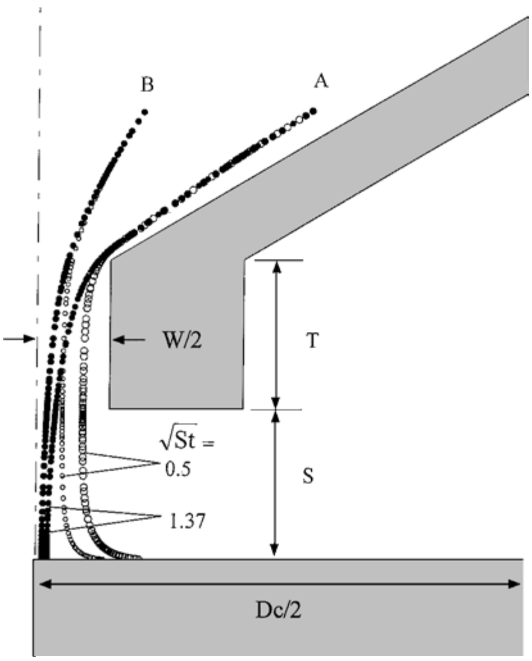

Figure 1. The impactor configuration and particle trajectories at different $\sqrt{\mathrm{St}}$, present calculation at Re = 500. Points A and B represent the starting positions of particle trajectories corresponding to 70.3 and 10.5% collection efficiency, respectively. (W: nozzle diameter; S: jet-to-plate distance; T: nozzle throat length; Dc: diameter of impaction plate.)

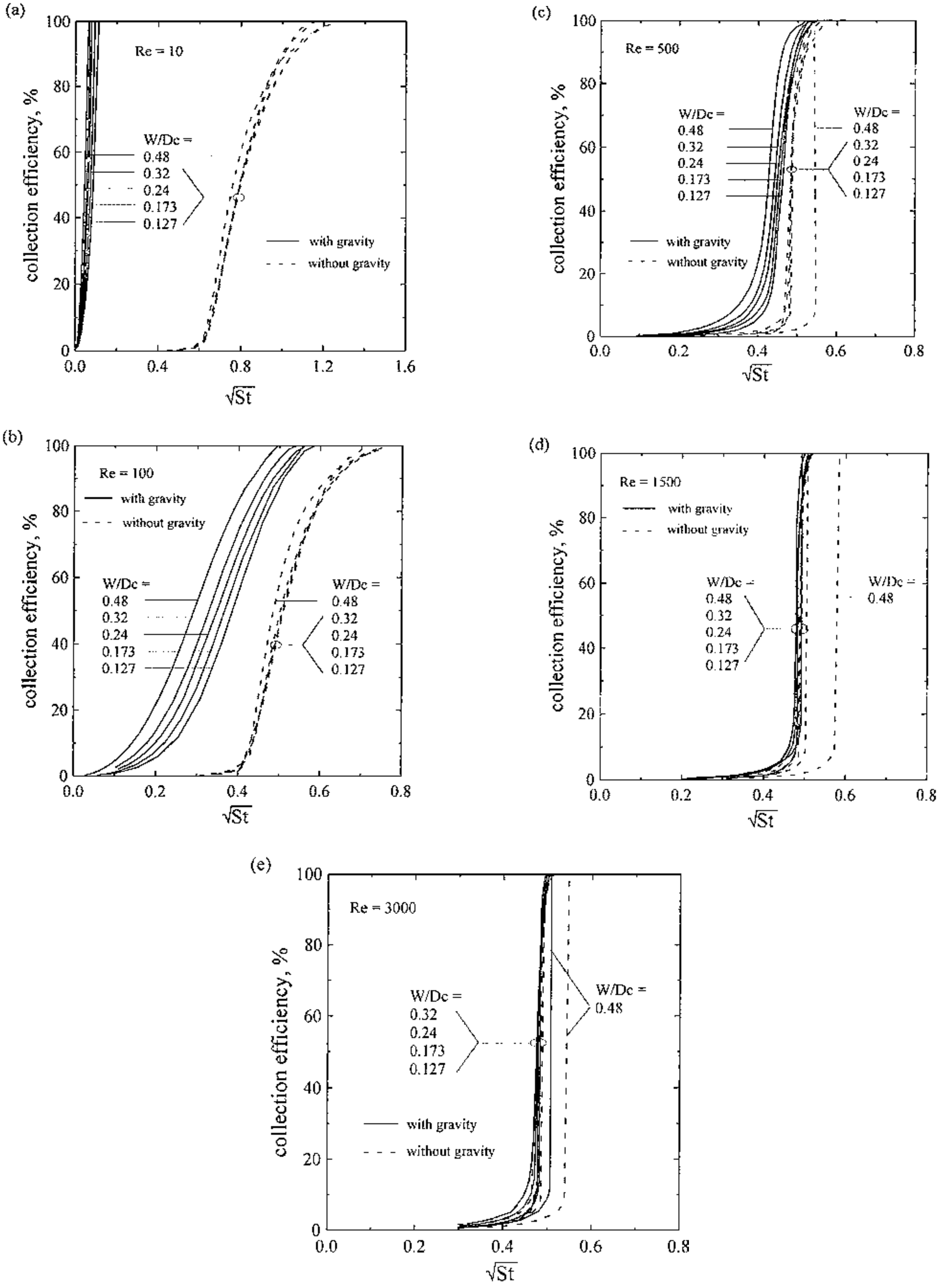

Figure 2. The effect of W/Dc and Re on the particle collection efficiency curves. (a) Re = 10; (b) Re = 100; (c) Re = 500; (d) Re = 1500; and (e) Re = 3000.

effect producing a spot radius smaller than the nozzle diameter. For particles of smaller Stokes number, $\sqrt{\mathrm{St}} \approx 0.5$, the impaction points move to a larger radius than the nozzle diameter. Similar results were found at different Reynolds numbers. Therefore the W/Dc is expected to influence the collection efficiency curves of the inertial impactor and the effect depends on Stokes number and Reynolds number. In addition, the inlet geometry also affects the collection efficiency curves. Jurcik and Wang (1995) found that the geometry of the impactor stage does not affect the 50% cut size, but has a strong effect on the sharpness and shape of the efficiency curves. Their results showed that nozzles without taper enhance the collection of small particles resulting in a tail at the low efficiency end. In our study, the half angle of the tapered section of nozzle is 60°.

Effect of W/Dc and Re on Particle Collection Efficiency Curve

The effects of W/Dc and Re on the particle collection efficiency curves are presented in Figures 2a–e. Without considering gravity, the particle collection efficiency curve (dotted lines in the figures) is nearly independent of W/Dc, except when $W/Dc = 0.48$ for all Reynolds numbers. When $W/Dc = 0.48$ and $\mathrm{Re} > 500$, the collection efficiency curve shifts to the right of other efficiency curves. The exception at $W/Dc = 0.48$ is due to the fact that the diameter of the impaction plate is too small to collect the particles, resulting in a decrease in the collection efficiency. When $\mathrm{Re} < 500$, the collection efficiency curve at $W/Dc = 0.48$ shifts slightly to the left of other curves. This is due to the difference in the flow field, which favors particle collection for large W/Dc.

Compared to the case without gravity, there is a substantial shift of the efficiency curves (solid lines in the figures) to the left as particle gravitational effect is considered for the Reynolds numbers smaller than 1500. However, the difference in the collection efficiency curves is small for the Reynolds numbers >1500. It is seen from Figure 2a that the collection efficiency is nearly independent of W/Dc at the low Reynolds number of 10 when gravity dominates the particle collection efficiency. Particles deposit directly around the center of the impaction plate, thus the collection efficiency is not affected by the impaction plate diameter. But in the case of higher Reynolds number of 100 and 500, inertial impaction starts to take effect on the collection efficiency besides gravitational force. The particle collection efficiency increases as W/Dc is increased at a fixed $\sqrt{\mathrm{St}}$, as shown in Figures 2b and c. For a given Re, the velocity through the nozzle with larger W/Dc is smaller than that with smaller W/Dc. Due to particle gravitational effect, the collection efficiency will be increased when the flow velocity through the nozzle is small. Moreover, it is notable that for the Reynolds numbers of 100 and 500, the collection efficiency curves considering gravity effect are more S-shaped compared to the case of other Reynolds numbers. The curve has a longer tail at low efficiency end when $\sqrt{\mathrm{St}}$ is small. Jurcik and Wang (1995) also found numerically that the collection efficiency curves of the impactor were S-shaped mainly because the nozzle in their study had no taper. The gravitational effect was not included in their calculation.

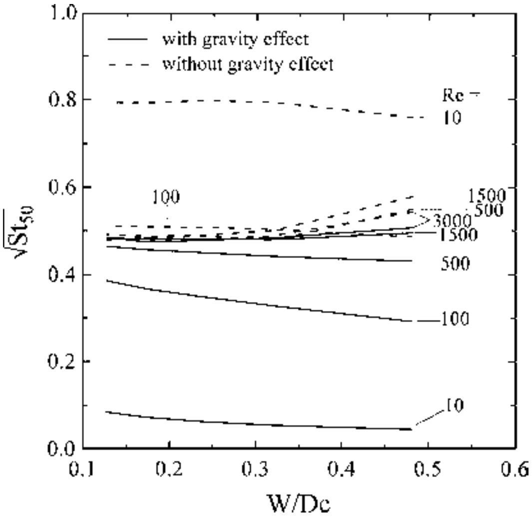

Figure 3. The influence of Re and W/Dc on $\sqrt{\mathrm{St}_{50}}$, with or without gravity.

When $\mathrm{Re} = 1500$ and 3000 (Figures 2d and e), the collection efficiency curves do not change with W/Dc whether or not the gravitational effect is considered, except $W/Dc = 0.48$. That is, the effect of gravity is negligible at high Reynolds number when $W/Dc \leq 0.32$.

Factors Influencing $\sqrt{St_{50}}$

Figure 3 is a summary of the influence of Re and W/Dc on $\sqrt{\mathrm{St}_{50}}$. Without considering gravity, it shows that $\sqrt{\mathrm{St}_{50}}$ decreases as W/Dc is decreased and reaches a constant of 0.48–0.5 when W/Dc is smaller than 0.32 for $\mathrm{Re} = 500$–3000. In the case of $\mathrm{Re} = 10$ and 100, $\sqrt{\mathrm{St}_{50}}$ is about 0.8 and 0.5, respectively, and is nearly independent of W/Dc.

When gravity is considered, the computed $\sqrt{\mathrm{St}_{50}}$ values are nearly independent of W/Dc for the nozzle Reynolds number >1500 and when $W/Dc < 0.32$. $\sqrt{\mathrm{St}_{50}}$ values range from 0.473 to 0.485, which agree quite well with the theoretical values of Rader and Marple (1985), 0.49, and Marple and Liu (1974), 0.477. For a smaller impactor plate diameter such that $W/Dc > 0.32$, $\sqrt{\mathrm{St}_{50}}$ increases slightly. It increases from 0.483 to 0.507 ($\mathrm{Re} = 3000$) or from 0.479 to 0.495 ($\mathrm{Re} = 1500$) when W/Dc is increased from 0.32 to 0.48. When the nozzle Reynolds number is smaller than 1500, the influence of W/Dc on $\sqrt{\mathrm{St}_{50}}$ is found to be much more pronounced. $\sqrt{\mathrm{St}_{50}}$ is smaller for a smaller Reynolds number and it decreases with an increasing W/Dc.

Effect of Particle Density on Collection Efficiency Curve

Figure 4 shows the effect of particle density on the collection efficiency curves at particle densities of 0.5, 1.0, and 10 g/cm^3, considering both ultra-Stokesian and interception effects. Also

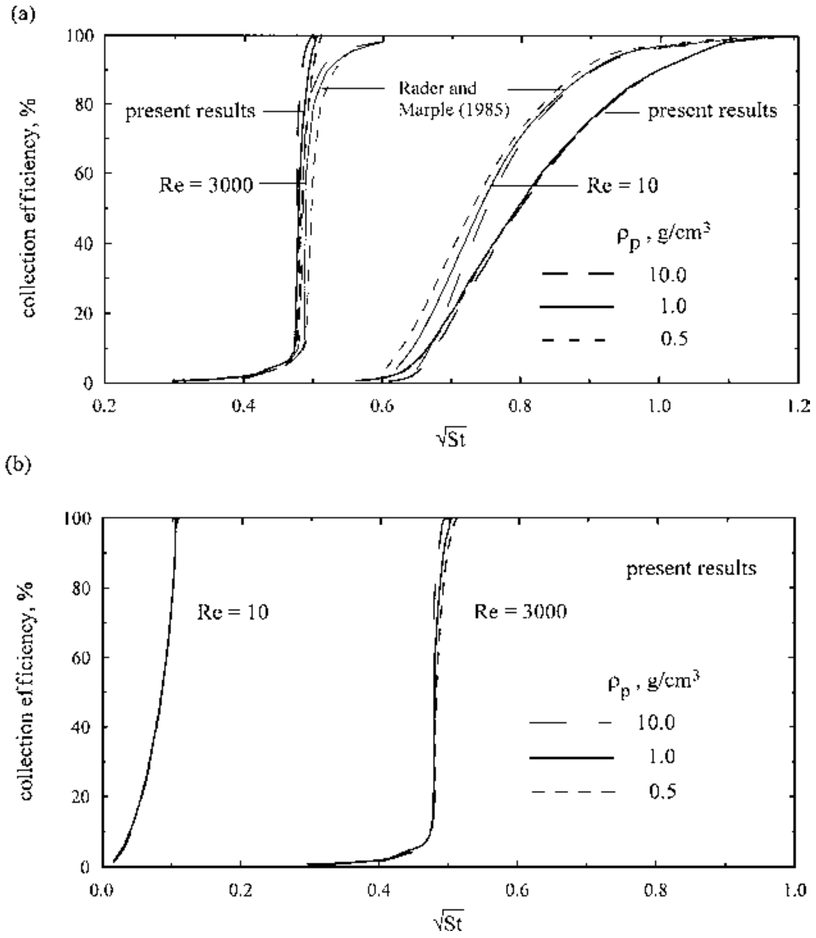

Figure 4. The effect of particle density on the collection efficiency curves considering both the ultra-Stokesian and interception effects. (a) Without gravity; (b) with gravity.

shown for comparison are the curves from Rader and Marple (1985), who did not consider particle gravitational force in the simulation. A comparison shows that in general the present simulation results are close to those of Rader and Marple (1985) at a high Reynolds number of 3000 and the collection efficiencies are slightly higher at a low Reynolds number of 10. The collection efficiency curves of the present simulation are steeper than those of Rader and Marple (1985) due to much finer grids (40,000 versus 4,000 grids) used in this study.

Without considering gravity, Figure 4a shows that the efficiency curves of the present study are slightly different from each other as the particle density is increased from 0.5 to 10.0 g/cm^3 for Re = 10 and 3000. For the low nozzle Reynolds number of 10, the low efficiency ends of the curve shift slightly to the right as particle density is increased from 1.0 to 10.0 g/cm^3. However, there are no differences in the high efficiency ends of the curves of different particle densities. Additional simulation that does not include particle interception is shown in Figure 5a, which indicates that slight differences in the curves of different particle densities disappear. At the same $\sqrt{\mathrm{St}}$, particles with smaller densities have larger geometric sizes than those with higher densities. Due to the particle interception effect, the collection efficiency will increase. However the increase is limited below 4%. In comparison, the effect of particle density on the collection efficiency at Re = 10 is more pronounced in the results of Rader and Marple (1985), who also considered the ultra-Stokesian drag and particle interception effects but not gravity. At the low end of the collection efficiency curves, the increase of collection efficiency can be as high as 20% when the particle density is decreased from 10 to 0.5 g/cm^3. The difference in the finding of the interception effect may be due to the number of grids used. The present simulation uses 10 times finer grids than those of Rader and Marple (1985) and should lead to better results.

At Re = 10 and when gravity is considered, Figure 4b shows that the collection efficiency is totally independent of particle density. This is because gravity dominates the particle collection efficiency at the low Reynolds number of 10. In this case, particle interception has no effect on the particle collection efficiency as revealed in the additional simulation shown in Figure 5b, where it shows that not considering the interception effect does not result in any differences in the collection efficiency curves.

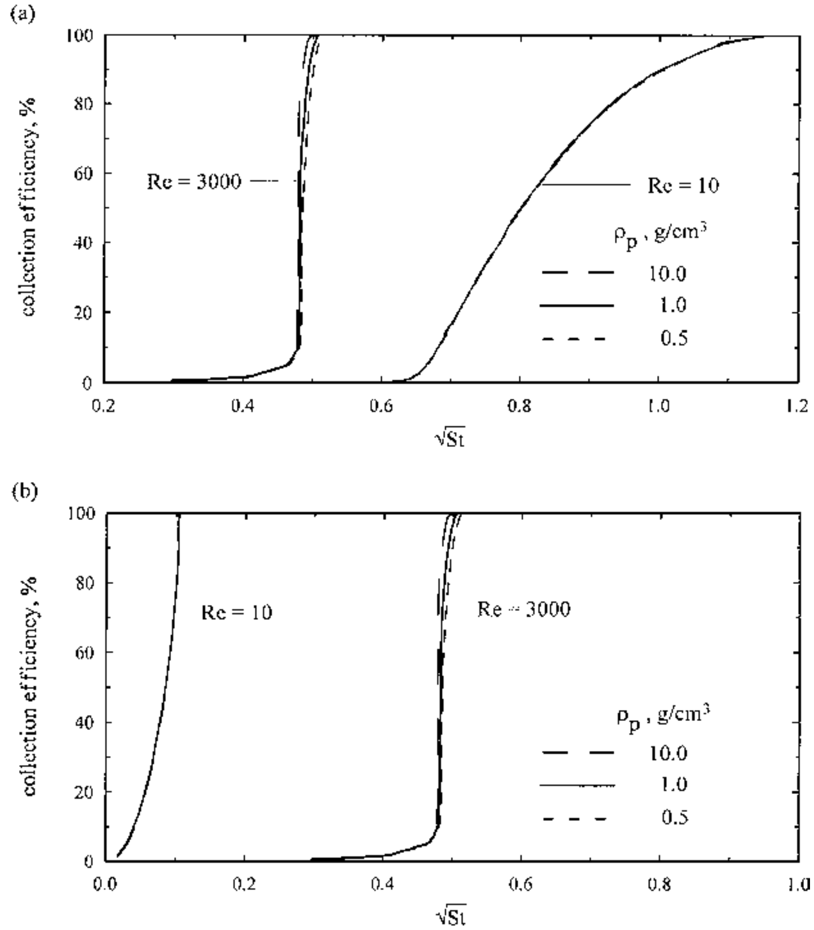

Figure 5. The effect of particle density on the collection efficiency curves when the interception effect is removed and only the ultra-Stokesian effect is considered. (a) Without gravity; (b) with gravity.

In the case of a high Reynolds number of 3000 as shown in Figures 4a and b, the slight shift in the efficiency curves at the high ends of the curves is due to the ultra-Stokesian effect. Whether gravity is considered or not, the curves are the same. Ultra-Stokesian effect is indeed responsible for the increase of collection efficiency as particle density is increased at the same $\sqrt{\text{St}}$; this can be further confirmed when the interception effect is not considered, as shown in Figures 5a (without gravity) and 5b (with gravity).

Without considering particle gravity, the simulated results of Rader and Marple (1985) show a similar extent of ultra-Stokesian effect on particle collection efficiency as the present study, as can be seen in Figure 4a.

CONCLUSIONS

This study is an extension of the previous work on the influence of the particle gravity on the particle collection efficiency in the inertial impactor. Effects of impaction plate diameter (W/Dc) and particle density on the collection efficiency are considered. This study shows that the impaction plate diameter has a limited effect on the $\sqrt{\text{St}_{50}}$ at Reynolds numbers higher than 1500 and when $W/Dc < 0.32$, whether or not the particle gravity effect is considered. The computed results of $\sqrt{\text{St}_{50}}$ ranging from 0.473 to 0.485 agree well with the theoretical values of Rader and Marple (1985), 0.49, and Marple and Liu (1974), 0.477.

When the nozzle Reynolds number is <1500, there is an effect of increasing W/Dc on $\sqrt{\text{St}_{50}}$, which depends on the nozzle Reynolds number and whether or not particle gravity is considered.

The effect of particle density on the collection efficiency is mainly manifested at a high Reynolds number due to the ultra-Stokesian effect. At a high Reynolds number of 3000, the high ends of the collection efficiency curves are affected and higher density particles have higher collection efficiency at the same $\sqrt{\text{St}}$ due to the ultra-Stokesian effect. At a low Reynolds number of 10, there is a limited effect of particle density on the collection efficiency near the low ends of the collection efficiency curves due to the interception effect, which is negligibly small. The results of the present study will aid in the design and use of the single round-nozzle inertial impactor. The effects due to impaction plate size are relatively modest and thus will not be very significant in most typical applications.

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