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INVESTIGATION OF THE PARTICLE PARAMETERS  
ASSOCIATION WITH FLUIDIC CONTAMINATION

Final Report

R.Y. Chen and W.C. Chen

April 1981

U.S. ARMY RESEARCH OFFICE

DAAG29 77 G 0012; 79 G 0053  
DAAG29 80 C 0090

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 13614.0 E (15 AF 10) AD A098638	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
6. TITLE (and Subtitle) Investigation of the Particle Parameters Associated with Fluidic Contamination.	9.	5. TYPE OF REPORT & PERIOD COVERED Final Report, 1 Nov 1976 - 28 Feb 81
		6. PERFORMING ORG. REPORT NUMBER None
7. AUTHOR(s) R.Y. Chen W.C. Chen	15.	8. CONTRACT OR GRANT NUMBER(s) DAAG29 77 G 0012; 79 G 0053 DAAG29-80-C-0090 -JH-27-1-3-0-1-1
9. PERFORMING ORGANIZATION NAME AND ADDRESS New Jersey Institute of Technology Newark, NJ 07102		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 11. Ap
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Research Office Post Office Box 12211 Research Triangle Park, NC 27709		12. REPORT DATE
		13. NUMBER OF PAGES 12 2 p
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)  Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)  NA		
18. SUPPLEMENTARY NOTES The view, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A numerical analysis of the mechanics of deposition in horizontal and vertical conduits of constant, diverging, and diverging cross-sectional area under the combined influences of diffusion, electrostatic charge, gravitation and inertia forces has been made. The analysis also identified the conditions under which some of these forces may be neglected. Experiments and theoretical		

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Unclassified

20. Abstract (Cont'd.)

analysis showed that electrostatic charge effect is the major cause of deposition. The other significant forces affecting the deposition are gravity, surface adhesive force, diverging angle of the conduit, particle inertia and the diffusive force of the particle.

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## CONTENTS

	Page
1. Introduction . . . . .	4
2. Theoretical Analyses . . . . .	4
2.1 Horizontal Flow in Conduits . . . . .	4
2.2 Vertical Flow in Conduits . . . . .	6
2.3 Inertia Effect on Deposition . . . . .	6
3. Experimental Investigation . . . . .	11
4. Summary . . . . .	14
5. List of Publications . . . . .	16
6. List of Participating Personnel . . . . .	16
Nomenclature . . . . .	17
Bibliography . . . . .	19

## FIGURES

1. Inertia effect on deposition in a channel at small axial distance with $dY/dT=Y_0$ at $X^*=0$ . . . . .	8
2. Inertia effect on penetration in a channel with $dY/dT=Y_0$ at $X^*=0$ . . . . .	9
3. Inertia effect on penetration in a channel with $dY/dT=0$ at $X^*=0$ . . . . .	10
4. Inertia effect on deposition in a diffuser (circular cone of 4-degree half-angle) and a nozzle (4-degree half-angle) with $4N_\alpha/N_\beta=0.45$ , $N_S=0.022$ , and $N_\delta=0.85$ for uniform flow. . . . .	11
5. Apparatus for vertical tube flow. . . . .	12
6. Comparison of test data with theory for vertical circular tubes. . . . .	13

## 1. INTRODUCTION

The purpose of this study is to investigate theoretically and also experimentally the deposition of suspensions in horizontal and vertical conduits.

In the theoretical analysis, the geometrical configurations considered are parallel-plate channel, two-dimensional converging and diverging channels, and circular converging tubes. The driving forces that affect the deposition of particles are diffusion, electrostatic charge, gravity, particle inertia, configuration of the channel, and velocity profile of the flow.

In the experimental investigation, 27-micrometer aluminum oxide powder was used to measure the deposition in a vertical tube and a vertical diverging tube. Measurements of the flow rate, deposition and electrostatic charge on the particles were taken, and the particle parameters associated with the flow were calculated. Comparisons with the theory were also made. In another set-up 3-micrometer latex particles were generated and charge per unit mass was measured.

## 2. THEORETICAL ANALYSES

Theoretical analyses are divided into three parts: horizontal flow in conduits, vertical flow in conduits, and inertia effect on deposition.

### 2.1 Horizontal Flow in Conduits

In this analysis, the two-dimensional conduit is either a constant area, a diverging, or a converging conduit. For laminar and steady flow with dilute suspensions subject to the usual boundary layer assumptions, the governing equations for the fluid phase are the continuity equation and the momentum equation in the axial direction. For the particle phase the governing equations consist of the diffusion equation, which includes the electric charge and gravity effect, the momentum equations, and the Poisson equation [1-5]

$$\begin{aligned}u_p \frac{\partial v_p}{\partial x} + v_p \frac{\partial v_p}{\partial y} &= F(v - v_p) - \left(\frac{q}{m_p}\right) \frac{\partial w}{\partial y} - g \\ \frac{\partial^2 w}{\partial y^2} &= -\frac{\rho_p q}{\epsilon_0 m_p} \\ u \frac{\partial \rho_p}{\partial x} + v \frac{\partial \rho_p}{\partial y} &= \frac{\partial}{\partial y} \left( \frac{q \rho_p}{m_p} \frac{\partial w}{\partial y} \right) + \frac{\partial}{\partial y} \left( D_p \frac{\partial \rho_p}{\partial y} + \frac{\rho_p g}{F} \right) \\ u_p \frac{\partial u_p}{\partial x} + v_p \frac{\partial u_p}{\partial y} &= F(u - u_p) + \frac{D_p}{\rho_p} \frac{\partial}{\partial y} \left( \rho_p \frac{\partial u_p}{\partial y} \right)\end{aligned}$$

The width of the channel is  $2h(x)$ , the centerline at  $y=0$ , the lower wall at  $y=-h(x)$ , and the upper wall at  $y=h(x)$ . The boundary conditions for the fluid are uniform inlet velocity and non-slip velocity condition at the wall. The particle cloud enters the channel at uniform density (i.e. uniform concentration) and uniform velocity (equal to that of the fluid). When a particle falls towards the wall, it will either stick to the wall or re-entrain into the flow field depending on the adhesive forces at the wall.

The governing equations were nondimensionalized. Some important dimensionless parameters are listed below.

$$N_R u_0 h / \nu = \text{Reynolds number}$$

$$N_B u_0 h / D_p = \text{diffusive Peclet number}$$

$$N_\alpha \frac{P_{p0}}{4} \frac{q^2}{m_p^2} \frac{h^2}{FD_p} = \text{charge-diffusion}$$

$$N_\lambda \frac{h f_w}{FD_p} = \text{surface adhesion number}$$

$$N_n \frac{hg}{D_p F} = \text{gravity-diffusion}$$

A trapezoidal mesh was superimposed on the entire flow field and the partial differential equations were written in the implicit finite difference form. The flow field was discretized into 21 mesh points in the Y-direction, and up to 141 mesh points in the X-direction. The increments in X (which is the ratio of the axial distance to the inlet half width) varied from 0.001 to 0.1. Different values of the half diverging angle ranged from -10 to 0 degree for nozzles, and 0 to 10 degrees for diffusers were used. The values of the dimensionless parameters were, in particular, the Reynolds number  $N_R=1000$ , the diffusive Peclet number  $40 \leq N_B \leq 10^7$ , the charge-diffusion parameter  $0.2 \leq N_\alpha \leq 10$ , and the gravity-diffusion parameter  $0.2 \leq N_n \leq 10$ . The (fractional) deposition of particles is based on the particle velocity in the axial direction and is calculated from

$$\text{Deposition} = 1 - \text{Penetration} = 1 - \int_0^1 U_p R \, dY.$$

From this investigation, the results for parallel-plate, converging and diverging channel flows are summarized as follows. An increase of the particle size causes greater deposition rate on the bottom wall. An increase of the electrostatic charge on the particles causes a greater deposition rate on both walls. Higher surface adhesive force will also cause higher deposition rate particularly near the inlet section of the channel. As the diverging angle is increased, greater deposition due to charges and gravity takes place on both walls. At larger angles of divergence, the deposition rate increases very rapidly on the bottom wall near the point of separation. In a converging channel, the deposition decreases with increasing converging angle. The above statements on the effect of diverging and converging angles on the deposition are based on small wall adhesive forces. In such a flow, particles may re-entrain into the flow stream and the particle density near the bottom wall is much higher than that at the centerline. At very high adhesive forces, the rate of deposition decreases with increasing diverging angle and no rapid increase in the rate of deposition near the point of separation is observed. These concluding remarks are based on the ranges of the parameters investigated. For  $N_\alpha$  and  $N_n$  ranged from 0 to 10, the particle is usually less than 3 microns.

In the analysis described above, both the momentum equations for the fluid phase and that for the particle phase are employed. The local axial velocity of the particle phase  $U_p$  is, therefore, in general different from that of the fluid phase  $U$ . In other analyses it was assumed that  $U_p = U$ , and thus two momentum equations for the particle phase were eliminated. Using this approach,

depositions of flow in a parallel-plate channel and a circular tube were investigated with an integral method [6,7] and also a numerical analysis [8,9]. The penetration far downstream from the inlet was found to decrease exponentially with the axial distance. In these analyses, the particles that come into contact with the wall were assumed to be completely absorbed by the wall.

When considering both diffusion and electrostatic charge, it was found that if the charge-diffusion parameter  $N_\alpha$  is greater than 50, then the diffusive term may be neglected and the deposition may be determined from the effect of the electrostatic charge only.

## 2.2 Vertical Flows in Conduits

In this analysis it is assumed that each particle enters from the top of a vertical conduit at a uniform inlet velocity equal to the fluid velocity plus the terminal velocity of the particle and that the particle maintains its velocity equal to the local fluid velocity plus the terminal velocity. The gravitational acceleration is in the direction of the flow.

Deposition of suspensions in the entrance region of a vertical channel as well as a vertical tube due to diffusive and gravity effects was studied numerically.

Deposition in the entrance region is a function of the diffusive Peclet number ( $N_g = u_0 h / D$ ), the ratio of the terminal velocity to the mean fluid velocity ( $N_\delta = u_g / u_0$ ), the axial distance, and the Schmidt number ( $= \nu / h$ ). The deposition for developing flow is very close to that for uniform flow near the inlet, and as the velocity becomes more fully-developed, the deposition approaches that for fully-developed flow. As expected, the deposition at a given axial distance decreases as the velocity ratio  $N_\delta$  is increased. Deposition for uniform flow (i.e. Schmidt no. = 0) is higher than that in fully-developed flow (i.e. Schmidt no. =  $\infty$ ).

Deposition of suspensions in a vertical channel due to gravity and electrostatic charge effects was also analyzed numerically [8,9,10]. In this analysis the diffusive effect was neglected and, therefore, the results are useful for flow with charge-diffusion parameter  $N_\alpha$  greater than 50. The results also indicate decreasing deposition with increasing gravity effect. A new dimensionless axial distance,  $4 N_\alpha X / [(N_\delta + 1) N_g]$ , was found to give a very compact set of curves for deposition at various value of the velocity ratio  $N_\delta$ .

## 2.3 Inertia Effect on Deposition

The purpose of this analysis is to study the effect of particle inertia on the deposition using the trajectory approach. Uniform and fully-developed laminar flow of fluid suspended with highly charged particles in a parallel plate channel is analyzed with a numerical method. The diffusive effect of the particles is neglected in this analysis.

The following dimensionless parameters are introduced:

$$N_i = \rho_{po} q^2 / m^2 \epsilon_0 F^2 \text{ (charge-inertia parameter)}$$

$$X^* = 4 N_{\alpha} X / N_{\beta} = X \rho_{po} q^2 / \epsilon_0 m_p^2 F u_0$$

$$Y = y/h$$

$$E = e m_p \epsilon_0 / h \rho_{po} q$$

$$T = t \rho_{po} q^2 / \epsilon_0 m_p^2 F$$

$$U = u/u_0$$

$$R = \rho_p / \rho_{po}$$

where h is the half width of the parallel-plate channel. The governing equations become:

$$N_i d^2 X / dT^2 = U - dX/dT \dots \dots \dots (1)$$

$$N_i d^2 Y / dT^2 = E - dY/dT \dots \dots \dots (2)$$

$$\partial E / \partial Y = R \dots \dots \dots (3)$$

$$U \partial R / \partial X = E \partial R / \partial Y - R^2 \dots \dots \dots (4)$$

The boundary and the initial conditions in dimensionless forms are as follows:

$$E = 1 \text{ at } X^* = 0, 0 < Y < 1,$$

$$E = \partial R / \partial Y = 0, \text{ at } Y = 0, X^* > 0$$

$$X^* = 0, Y = Y_0, \text{ and } dX^* / dT = U(0, Y) \text{ at } T = 0.$$

$$dY / dT = E(0, Y) = Y_0 \text{ at } T = 0.$$

In writing a computer program to calculate particle trajectories, Eqs. (1) and (2) were integrated with the Range-Kutter method and Eqs. (3) and (4) were solved with backward difference forms using 41 nodal points. The time increment was chosen in such a way that  $\Delta Y < 0.003$  and  $|\Delta U_p| < 0.01$ . Starting at  $Y = U_0$ , a particle was considered to have deposited on the wall as soon as it reached the wall. Since all of the particles that entered the inlet plane of the channel between  $Y = Y_0$  and  $Y = 1$  would have deposited on the wall, the fraction of deposition was calculated from

$$\text{Deposition} = 1 - \int_0^1 U_p R \, dY$$

where the particle velocity at the inlet are  $U_p = 1$  for uniform flow and  $U_p = 1.5(1-Y^2)$  for fully-developed flow. In this analysis the particle cloud distribution at the inlet plane of the channel was assumed to be uniform and its velocity was assumed to be equal to the inlet fluid velocity.

For uniform velocity profile the axial velocity of particle remains the same as that of the fluid throughout the flowfield and the velocity in y-direction also remains at the initial value of  $Y_0$ . The deposition is independent of the dimensionless parameter  $N_i$  and is equal to the deposition calculated from Eqs. (3) and (4) using  $1 - U R \, dY$ . The fraction of deposition for uniform flow is

$$\text{Deposition} = 1 - \text{Penetration} = 1 - 1 / (1 + X^*) \dots \dots (5).$$

$$\text{where } X = 4 N_{\alpha} X / N_{\beta} = X \rho_{po} q^2 / F^2 m_p^2 u_0 \epsilon_0.$$

For parabolic velocity profile (fully-developed flow), the deposition is a function of  $X^*$  and  $N_i$ . The parameter,  $N_i = (\rho_p q^2 / m_p^2 \epsilon_0) (1 / F^2)$ , is the product of charge effect on a particle and the inertia effect of a particle on the viscous flow (noting that  $u_0 / F\eta = m_p u_0 / 6\pi\eta h$  is the Stokes number  $N_s$ ).

Two special cases for fully-developed flow should be examined. In the first case  $N_i = 0$  for negligible inertia force and the particle velocity is equal to the fluid velocity. The deposition is calculated from Eqs. (3) and (4). In the second case  $N_i = \infty$  for extremely large particles with high electrostatic charges. The solution is  $X^* = 1.5 (1 - Y_0^2) (1 - Y_0) / Y_0$ . Depositions for  $0 < N_i < \infty$  fall between these two special cases. In Fig. 1 the fraction of deposition at small axial distance is shown for uniform flow (single curve for all  $N_i$ )

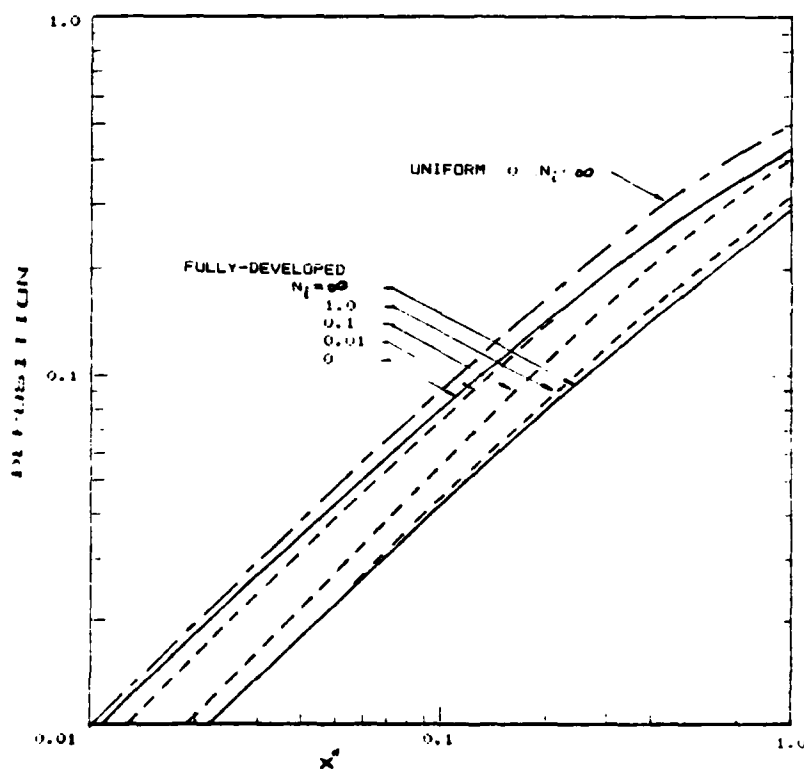


Fig. 1. Inertia effect on deposition in a channel at small axial distance with  $dY/dT = Y_0$  at  $X^* = 0$

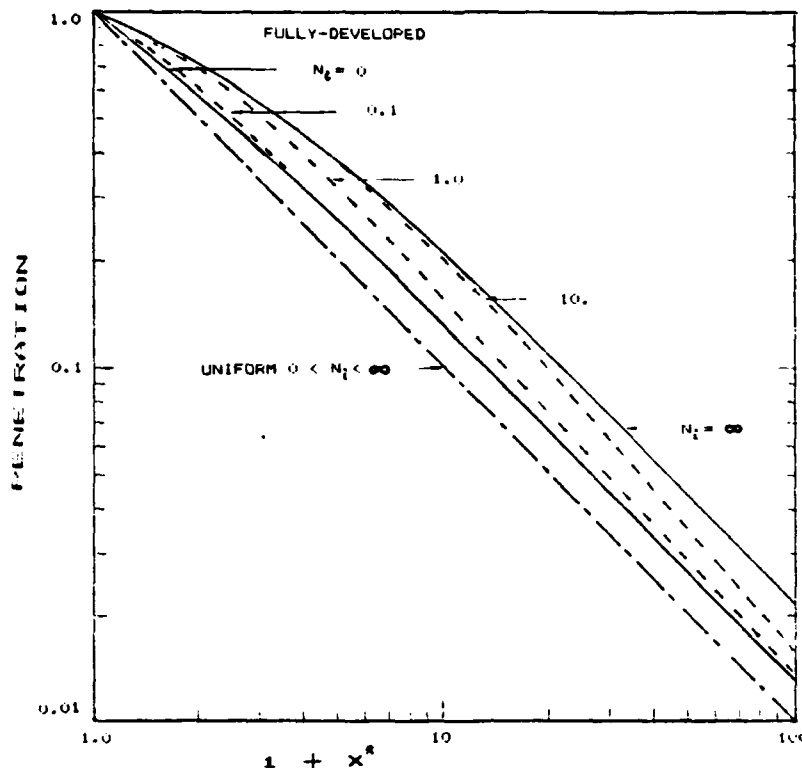


Fig. 2. Inertia effect on penetration in a channel with  $dY/dT=Y_0$  at  $X^*=0$ .

and fully-developed flow for various values of  $N_i$ . Clearly the deposition in a uniform flow is higher than that in a fully developed flow. For the latter case the deposition decreases with increasing  $N_i$ . In Fig. 2 the deposition is plotted against the dimensionless axial distance  $1 + X^*$ . It was found that for  $N_i = 0.01$  and  $X^* > 1$  (and also for  $N_i = 0.1$  and  $X^* > 3$ ), the deposition is practically equal to that for  $N_i = 0$ . For  $N_i > 10$  and  $X^* > 3$  the deposition is nearly equal to that for  $N_i = \infty$ .

The above results are based on the initial condition that  $dY/dT = E(0, Y) = Y_0$ . This is to assume that the particle has exposed itself to the space charge sufficient length of time to acquire that velocity. For a large particle this may not be the case and an initial condition of  $dY/dT = 0$  at  $T = 0$  may be more realistic. Fig. 3 shows the penetrations based on this initial condition. As is seen, the effect of inertia on the penetration on both uniform and fully-developed flow is greatly increased.

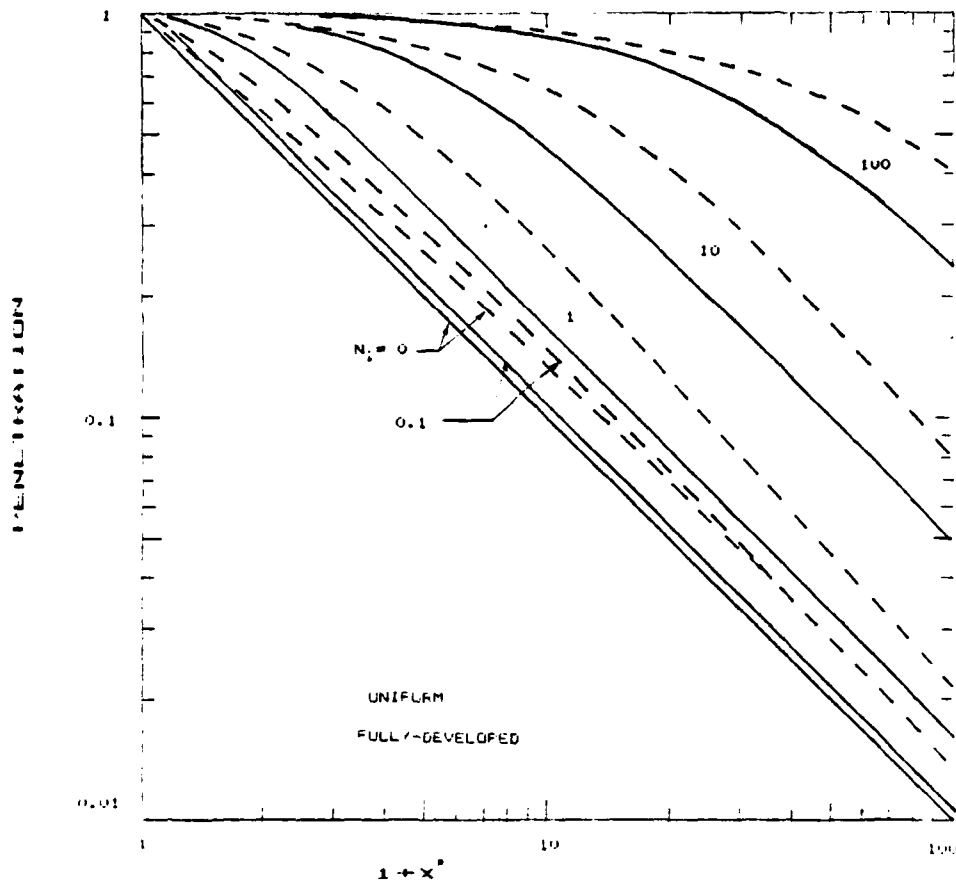


Fig.3. Inertia effect on penetration in a channel with  $dY/dT=0$  at  $X^*=0$

In general the deposition in a conduit decreases with increasing inertia of the particle.

Similar analysis for flow in a vertical tubes and diffusers has also been done for a circular tube and a diffuser. The result are shown in Fig. 4.

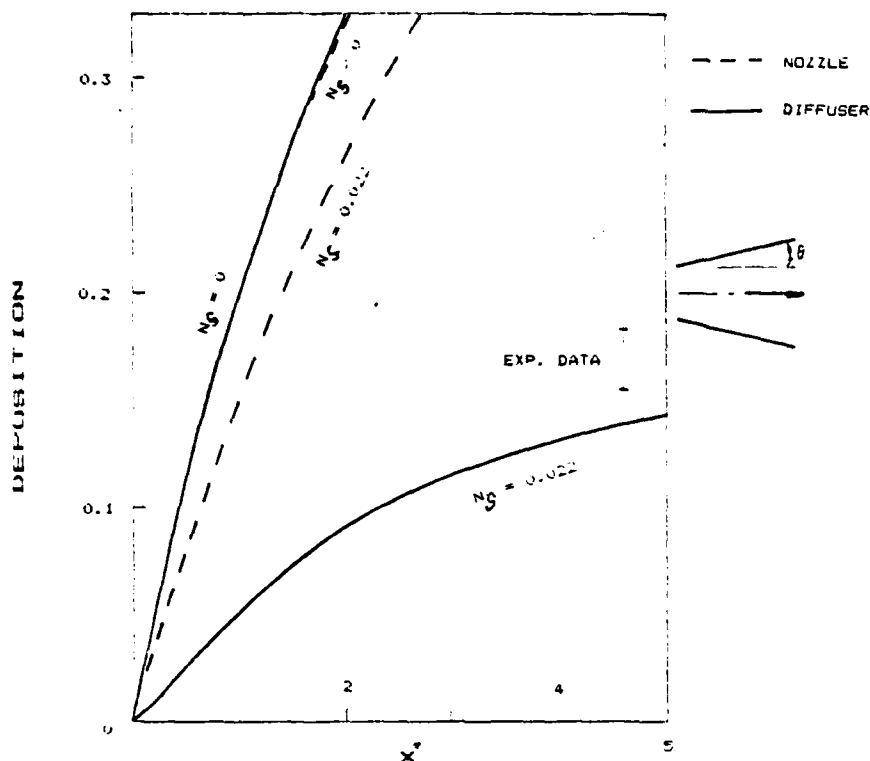


Fig. 4. Inertia effect on deposition in a diffuser (circular cone of 4-degree half-angle) and a nozzle (4-degree half-angle) with  $4N_x/N_p=0.45$ ,  $N_s=0.022$ , and  $N_p=0.85$  for uniform flow.

For flow in a vertical diffuser, the deposition is a function of the length of the diffuser  $x/h$  (where  $h$  is the inlet diffuser radius), the angle of the diffuser, the charge parameter  $4N_x/N_p$ , the Stokes' number  $N_s (= u_0/Fh)$  and the ratio of terminal velocity to mean fluid velocity  $N_p$ .

Fig. 4 depicts the effects of inertia and the diverging angle on the deposition. When the inertia is completely ignored, the diffuser ( $\theta=4^\circ$ ) gives higher deposition than the nozzle ( $\theta=-4^\circ$ ). When inertia force is considered (at Stokes' number 0.022) the deposition is higher in the nozzle. Since a uniform velocity profile was employed and only one set of parameters was used in Fig. 4 further investigation is required.

### 3. EXPERIMENTAL INVESTIGATION

The experimental set-up as shown schematically in Fig. 5 has the capability of producing a uniform and steady suspension flow at a desired concentration. Compressed air is dried and filtered before entering the rotameters (2800 cc/s and 320 cc/s capacity). A pressure regulator is installed at the inlet of each rotameter to control the flow rate. The aerosol generator contains a mechanical vibrator which mixes aluminum oxide powder with the incoming air, and a vibrator

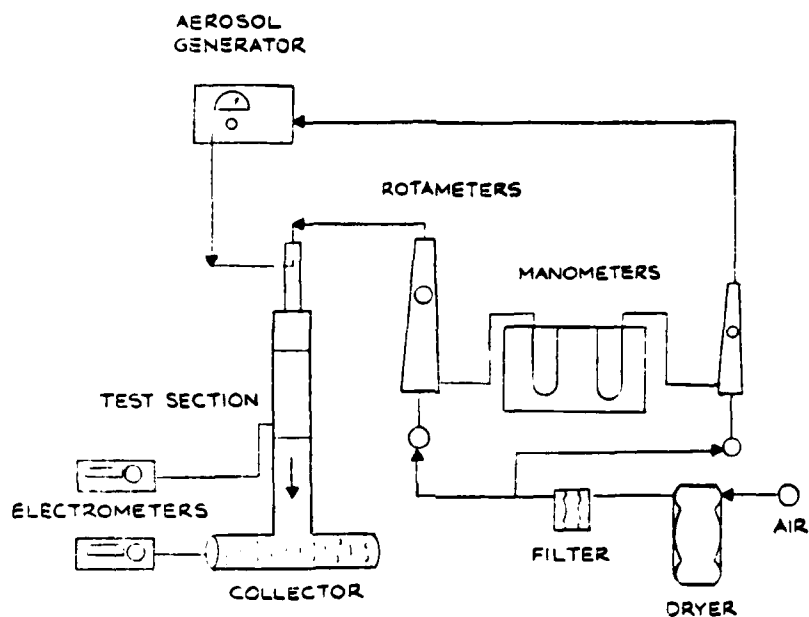


Fig. 5. Apparatus for vertical tube flow.

regulator which controls the particle flow rate. The mixing chamber is made of a plastic tube in which the main air stream from the high flow rotameter and the air-powder mixture from the aerosol generator meet and mix together. The test section is made of aluminum metal sheet (7.6 cm diameter x 15.2 and 30.5 cm length tube or 7.6 cm inlet x 17.5 cm length x 4 degree diverging angle diffuser). The particle collector is also made of aluminum metal sheet and is packed with stainless steel metal sponges. A Keithley 616 digital electrometer (0.1 to  $10^{-13}$  ampere as an ammeter and  $10^{-5}$  to  $10^{-12}$  coulomb as a coulombmeter) is connected between the test section and the ground, and another one is connected between the collector and the ground. An electronic digital balance ( $60 \pm 0.001$  gram and  $600 \pm 0.01$  gram) is used to measure the test section and collector.

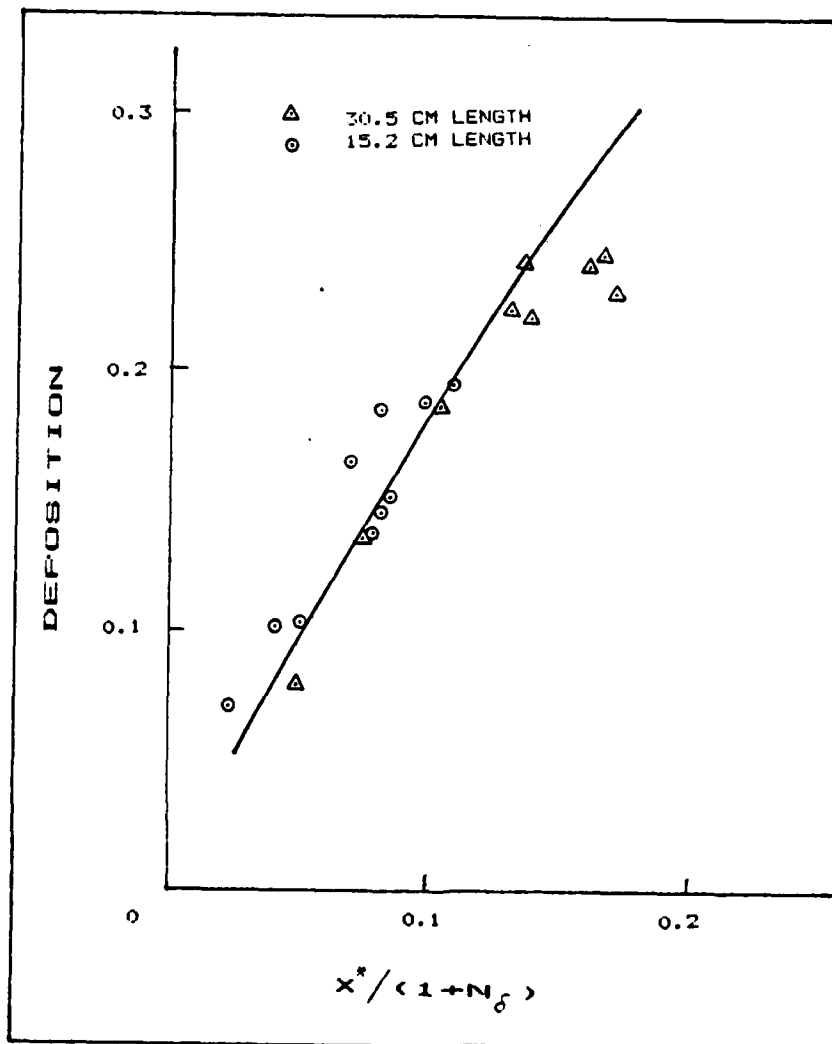


Fig. 6. Comparison of test data with theory for vertical circular tubes.

The experimental data for vertical circular tubes are presented in Fig. 6. The velocity ratio  $N_\delta$  for these data is 0.7 and the charge-inertia parameter  $N_i$  ranges  $0.0021 < N_i < 0.0009$ . At this range of  $N_i$ , the inertia terms in Eqs. (2.1) and (2.2) are negligible. The deposition based on the diffusion equation (2.3) and the Poisson's equation (2.4) are plotted in Fig. 6. Due to the high velocity ratio  $N_\delta = 0.7$ , the theoretical result for uniform flow and fully-developed flow are undistinguishable for the range of axial distance  $X^*$  investigated. As is seen from the figure, the result agrees quite well with the theoretical analysis (Eq. 2.5 for uniform flow) based on deposition due to electrostatic charge effect alone. This is an indication that the electrostatic charge is the major cause of deposition for flow of suspensions in laminar flow and that in a short vertical tube, the velocity profile is insignificant when the ratio of terminal velocity to fluid velocity is about one or greater than one. It also that the particle-wall adhesive force increases with increasing charge.

Data for a vertical diffuser (4-degree diverging angle, 7.6 cm inlet diameter and 17.5 cm in length) were also obtained using 27-micrometer aluminum oxide. As mentioned in section 2.3, the deposition in a vertical diffuser for a highly charged particles is a function of the axial distance, the diverging angle, the charge parameter  $4 N_\alpha / N_\beta$ , the Stokes number  $N_s$ , and the velocity ratio  $N_\delta$ . The data were higher than those predicted by the corresponding theoretical calculations based on uniform flow by about 10 to 30%, but were less than those predicted by zero inertia force as shown in Fig. 4. The magnitude on charge per particle mass for the 27-micrometer aluminum oxide particles was  $0.2$  to  $0.8 \times 10^{-6}$  coulomb/gram.

In another set-up, 3-micrometer latex particles were generated from monodisperse latex suspension using an atomizer and a diffusion drier [12]. The particles suspended in air flowed through a 2.5 cm x 10 cm rectangular duct. A particle mass monitor (TSI model 3205) was used to measure the mass concentration and an aerosol electrometer (TSI model 3068) was used to measure the charge. It was found that the average charge particle mass was  $2.5 \times 10^{-6}$  coulomb/gram.

#### 4. SUMMARY

Analytical investigations on the deposition of suspensions in laminar flow in a horizontal and vertical conduits have been made. The conduits considered are a parallel-plate channel, a two-dimensional diffuser, a twodimensional nozzle, a circular tube, and a circular diffuser.

Among the forces that affect the deposition, the most significant force is the electrostatic charge and then, the gravity, the inertia force, the adhesive force between the wall and the particle, the diffuser angle, the diffusive force of the particles, and the velocity profile of the flow.

When considering both diffusion and electrostatic charge, the diffusive force may be neglected if the charge-diffusion parameter  $N_\alpha > 50$ . The rate of deposition increase with increasing  $N_\alpha$ . When considering the inertia and charge effects on flow in a constant area conduit, the velocity of the particle and that of the fluid are essentially the same if the charge-inertia parameter  $N_i < 0.01$ . As  $N_i$  increases the inertia effect increases and the deposition in a constant area conduit decreases. The inertia force increases the deposition in a converging conduit (decreases in a diverging conduit). At high electrostatic charge, the rate of deposition is very high near the entrance.

Deposition in a uniform (plug) flow is higher than that in a fully-developed flow and deposition in a developing flow falls between these two flows. In a diverging channel the deposition may increase greatly near the point of separation, if the adhesive force of the wall is small. In such circumstances, the particulate concentration is very high near the wall. However, if the adhesive force is very high, the particulate concentration near the wall is much smaller than that at the centerline and no rapid increase in deposition near the point of separation.

The terminal velocity of a particle increases with increasing particle size, and when the terminal velocity of a suspension is higher than the fluid velocity, the deposition rate in a short straight conduit may be calculated using uniform velocity profile. Increasing terminal velocity decreases the deposition.

Experimental investigation showed that the electrostatic charge per mass of particles is in the order of  $10^{-6}$  coulomb/gram. The charge-diffusion parameter  $N_{\alpha}$  increases rapidly from order of one at one micrometer particle to  $10^7$  at 27 micrometer particle. Thus for particle larger than 5 micrometers the diffusive effect may be neglected. It was also found that at high  $N_{\alpha}$  the adhesive force between the surface and the particle become very large and a complete adhesion of particles on the wall is possible. The deposition rate is the highest near the inlet of a tube and decreases rapidly in the direction of flow. Deposition in a diffuser is less than that in a constant area tube of the same length.

The results presented in this report is not only useful in the understanding of the contamination in a fluidic device, but also useful in the study of industrial hygiene associated with dust contamination.

5. LIST OF PUBLICATIONS

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## NOMENCLATURE

$a$	radius of a particle
$D_p$	particle diffusivity
$e$	electric field intensity
$E$	dimensionless electric field intensity
$f_w$	adhesive force per unit mass of particle at the wall
$F$	inverse of relaxation time for momentum transfer, $6\pi\mu a/m_p$
$g$	local acceleration of gravity
$h$	half the inlet diffuser or channel width or tube radius
$h(x)$	half the diffuser width for $x > 0$
$m_p$	mass of a particle
$N_i$	charge-inertia parameter, $\rho_{p0}q^2/m_p^2\epsilon_0F^2$
$N_R$	Reynolds number $u_0h/\nu$
$N_S$	Stokes' number, $u_0/hF$
$q$	electrostatic charge
$R$	dimensionless density of particle cloud, $\rho_p/\rho_{p0}$
$t$	time
$T$	dimensionless time, $\rho_{p0}q^2t/\epsilon_0m_p^2F$
$u, v$	axial and vertical component of fluid velocity
$U, V$	dimensionless axial and vertical velocity of fluid, $u/u_0, v/u_0$
$x, y$	axial and vertical coordinates, respectively
$X, Y$	dimensionless coordinates, $X=x/h, Y=y/h$
$X^*$	dimensionless axial distance, $4N_i X/hN_p$
$w$	electric field potential
$N_x$	charge-diffusion parameter, $\rho_{p0}q^2h^2/4\epsilon_0m_p^2F D_p$

$N_{\beta}$	diffusive Peclet number, $U_0 h / D_p$
$N_{\delta}$	terminal-fluid velocity ratio, $g / F u_0$
$N_{\eta}$	gravity-diffusion parameter, $g h / D_p F u_0$
$N$	adhesive force parameter, $h f_w / F D_p$
$\mu$	dynamic viscosity of fluid
$\nu$	kinematic viscosity of fluid
$\rho$	density of fluid
$\epsilon_0$	permittivity of free space
$\theta$	half diffuser angle

#### SUBSCRIPTS

$o$	initial uniform condition
$p$	particle property

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