01 Apr 1991

Aerosol Particle Bounding in Cascade Impactors

Bisma Husen

Recommended Citation

Husen, Bisma, "Aerosol Particle Bounding in Cascade Impactors" (1991). *Opportunities for Undergraduate Research Experience Program (OURE)*. 136.
https://scholarsmine.mst.edu/oure/136

AEROSOL PARTICLE BOUNCING IN CASCADE IMPACTORS

Bisma Husen

ABSTRACT

Particle deposition characteristics were observed from the aerosol sampling results of a UNICO cascade impactor. A simple model of particle motion combined with Hiemenz flow of stagnation flow on a flat plate were developed and discussed.

Both results and analysis were compared to recent models on particle bouncing errors or secondary deposition which included vortices formation around the edge of the slot, back spin (Magnus effect), and hydrodynamic conditions of the particles. The analysis was limited to a laminar inviscid and incompressible case. The main obstacle in the observation was the fact that impactor nozzles were unsymmetrical to a considerable degree, thereby deviating particle trajectory significantly from the predicted situation.

NOMENCLATURE

c_s	Slip correction factor
c_∞	Particle concentration far away from deposition plane
d_p	Particle diameter
g	Vector gravitational acceleration
m_p	Particle mass
t	Time
u_∞	Fluid velocity far away from deposition plane
v	Particle velocity vector
u_{xo}, v_{yo}	Components of initial particle velocity
v_{xI}, v_{yI}	Components of particle velocity at edge of boundary layer
x_I, $d_p/2$	Final particle position after deposition
α	Constant descriptive of flow field, $\lvert u_\infty \rvert / H$, x-axis
α'	Constant for y-axis
β	Friction coefficient, $3\pi\mu d_p / c_s m_p$
δ	Boundary Layer's thickness
ω	Particle's angular velocity
η	Kinematic viscosity
μ	Dynamic viscosity
ϕ	Function defining velocity profile inside boundary layer

INTRODUCTION

Aerosol is defined as any relatively stable suspension of particles in a gas, especially in air, including both the continuous (gaseous) and discontinuous (particulate) phases. During the last decade, great advances have been made in our knowledge of the behavior of aerosols and in the techniques available for studying them. Perhaps the greatest incentive for the present research has been the growing concern about the impact of man on his environment, particularly the extent to which he is polluting the atmosphere -locally, regionally, and worldwide. Another incentive is the need in many modern devices for closer tolerances that can be achieved only by manufacturing them in relatively dust-free rooms, the so-called clean rooms. Study of airborne particles are the main aspect of industrial hygiene, weather modification, and studies of the natural atmosphere. Investigation of the production, characterization and behavior of aerosols has therefore become a scholarly discipline.

The most important thing of aerosol investigation is the measurement of the suspended particles. Measurement refers to the determination of size distributions, concentration and shapes. Many methods have proposed to such measurement. Impaction method of measuring microstructural characteristics of a coarsely dispersed aerosol are one of those methods that are widely used. Impaction method means the settling of aerosol particles from the stream on obstacles due to their inertia.

Cascade impactor is one of many types of impactors that are being used. First introduced by May (1945) it has been gaining popularity due to its simple operation. A cascade impactor is a multistage impaction device used to separate airborne particles into aerodynamic size classes. In use, an aerosol is drawn through a series of progressively narrower jets, each followed by an impaction surface, usually placed at right angles to the axis of the jet and coated with certain substances such as gelatin or other chemicals. The jet may be a circular or rectangular slit. Each jet and its associated impaction surface is a "stage". Particle with the largest inertial mass are impacted, and deposited, onto the first stage substrate, and smaller particles are deposited successively on the following stages.

Many theoretical studies of the mechanism of particle deposition under a jet or rectangularly shaped nozzle illuminated well the main parameters affecting the motion of the solid particles or droplets under the nozzle and along the substrate sideward (May 1975, Ramarao and Tien 1989, Fuchs 1964). The results of these studies are briefly reviewed and several most salient and still unanswered questions are formulated. Among these is the particle bouncing at the substrate and its dependence on the flow pattern, state of the particle, and of the substrate at different environment conditions represents still one of the most attractive subjects of the particle separation an two-phase flow research (Dzubay 1976, Fuchs 1973, Berner 1988, Markowski 1987).

Most of the particle bouncing investigations in cascade impactors dealt with the jet flow pattern which might seemingly be simpler for mathematical modeling of particle deposition and comparison of the theoretical results with the experimental work. In this research, we used a simple two-dimensional Hiemenz flow model of boundary layer over a flat plate (Currie 1974) superimposed to the hyperbolic potential flow describing the particle deposition under a rectangularly shaped long nozzle, as noted by Ramarao and Tien (1989), which can be compared with the particle deposition in a four-stage UNICO impactor frequently used in our laboratory (figure 1). The main goal was to discuss the main question raised by several authors whether the particle bounce errors in impactor are caused by the flow pattern and vorticity formation around the nozzle's edge (Berner 1976) or by the back spin caused by some kind of Magnus effect (May 1975) acting on spherical particles in a shear flow close to the impactor's wall.

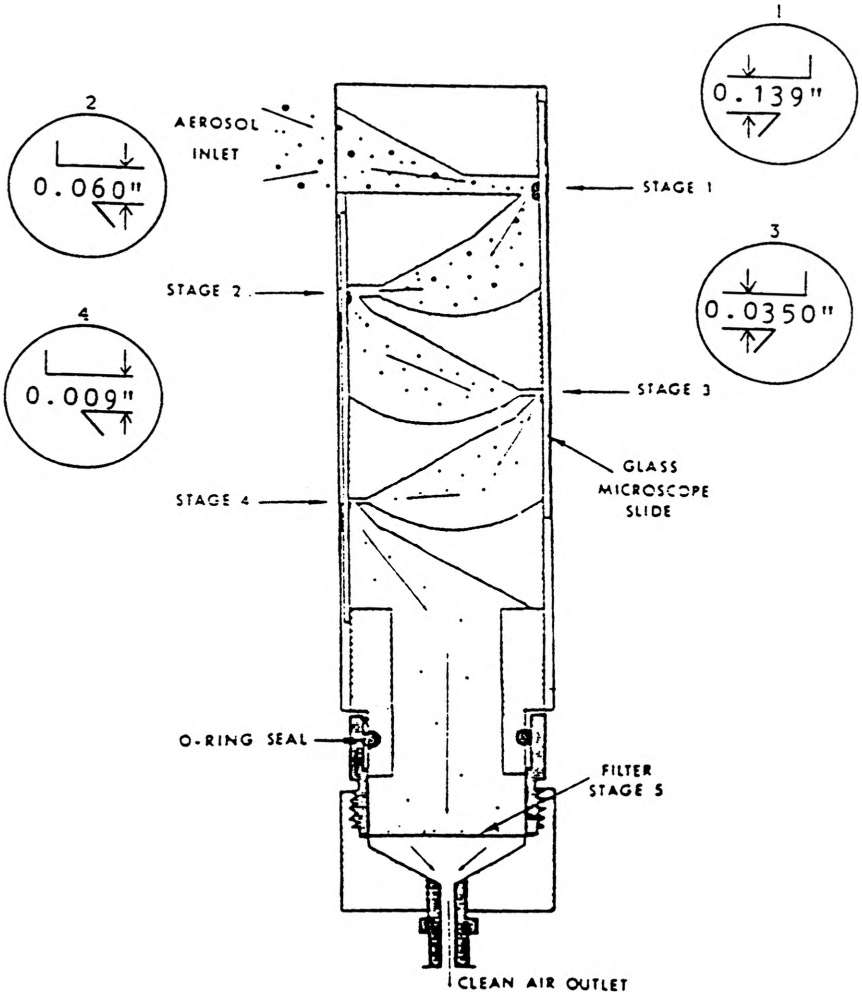

Figure 1

TWO-DIMENSIONAL STAGNATION FIELD

Classical stagnation flow is shown in figure two. The deposition plane is situated at $y = 0$, and the flow is directly towards the plane. Except for a region immediately adjacent to the deposition plane, $y \leq \delta$ (δ is boundary layer's thickness), flow is considered to be ideal, i.e.

$$u_y=-\alpha' y \tag{1}$$

$$u_y=-\alpha' y \tag{2}$$

assuming symmetrical slot, we can assume that $\alpha' = \alpha$.

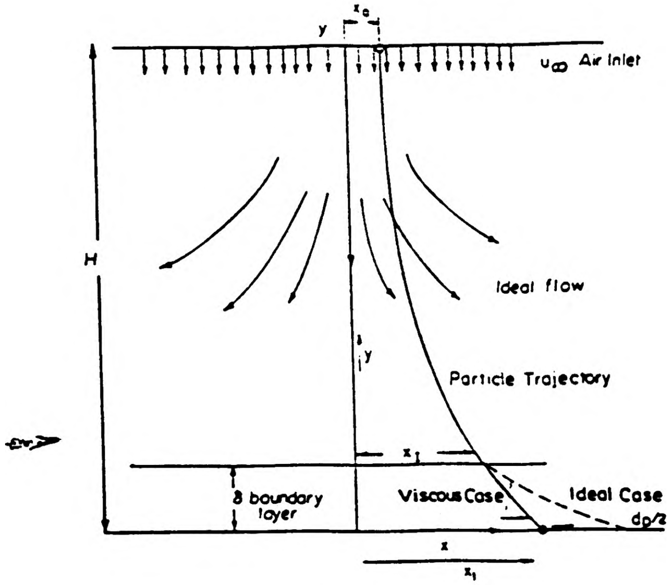

Figure 2

Within the boundary layer, according to Schlichting (1968)

$$u_x=xf'(y) \tag{3}$$

$$u_y=-f(y) \tag{4}$$

Hiemenz suggested f(y) as :

$$f(y)=\sqrt{\alpha\nu}\,\phi(\eta) \tag{5}$$

where ν is the kinematic viscosity of the gas and η is the

$$\eta=\sqrt{\alpha/\nu}\,y \tag{6}$$

similarity variable for boundary layer flow. Then $\phi(\eta)$ is the solution of the following non-linear differential equation :

$$\phi'''+\phi''-\phi^2+1=0 \tag{7}$$

boundary conditions for this equation :

$$\phi(0)=\phi'(0)=0,\ \phi'(\infty)=1 \tag{8}$$

Equation 8 was expanded using Taylor's series. Let $\phi' = u/U_\infty = R$, we get

$$-\left(1+\frac{\Delta\eta}{2}\phi_i^n\right)R_{i+1}^{n+1}+2R_i^{n+1}-\left(1-\frac{\Delta\eta}{2}\phi_i^n\right)R_{i-1}^{n+1}=\Delta\eta^2[1-(R_i^n)^2] \tag{9}$$

Using Tridiagonal Matrix Algorithm, we have the equation in the form of

$$-AR_{i+1}^{n+1}+BR_i^{n+1}-CR_{i-1}^{n+1}=D_i^n \tag{10}$$

We postulate the solution in the form of

$$R_i=E_iR_{i+1}+F_i \tag{11}$$

then substitute back to equation 10 we get

$$E_i=\frac{A}{B-CE_{i-1}} \tag{12}$$

The solution, according to Schlichting (figure 3), shows

$$F_i = \frac{D+CF_{i-1}}{B-CF_{i-1}} \tag{13}$$

that δ may be taken to be 2.4 $(\eta/\alpha)^{0.5}$ for u_x to reach 99% of the value given in equation 1. Ramarao and Tien (1989) suggested taking $\delta = 20\ (\alpha/\eta)^{0.5}$ to match within 2 % of the value given in equation 1. This last equation will be used for the equation of particle motion in the boundary layer.

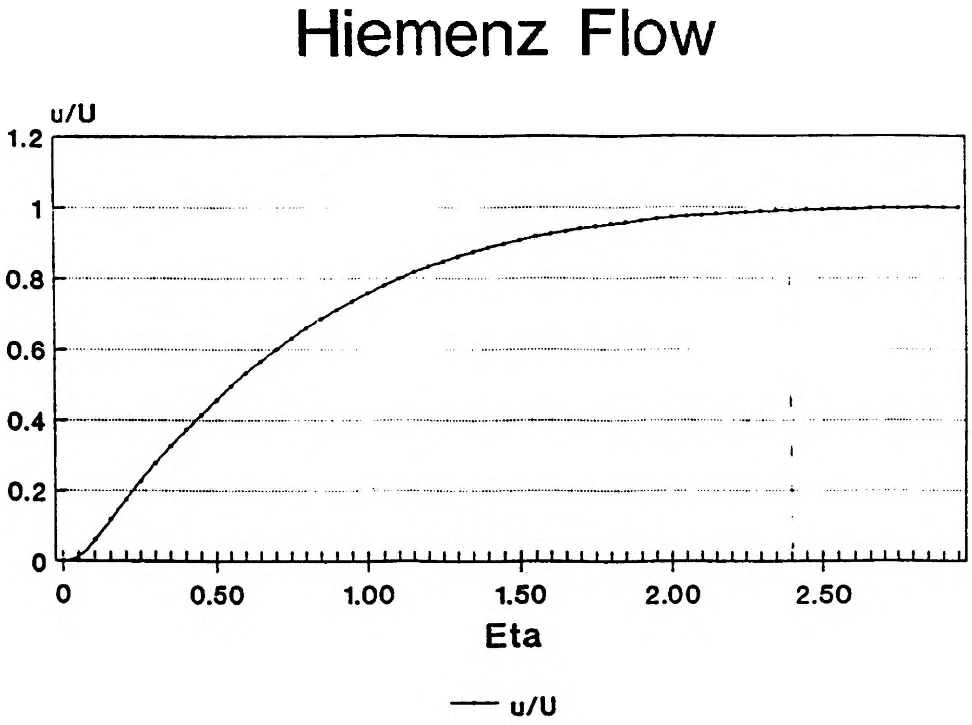

Figure 3

PARTICLE MOTION IN IDEAL FLOW

The equations that describe this situation :

$$\frac{d^2x}{dt^2} + \beta\frac{dx}{dt} - \beta\alpha x = 0 \tag{14}$$

$$\frac{d^2y}{dt^2}+\beta\frac{dy}{dt}+\beta\alpha y=-g \tag{15}$$

x,y are coordinates of the center of the particle and β is the slip factor expressed as :

$$\beta=\frac{3\pi\mu d_p}{c_s m_p} \tag{16}$$

where μ and d_p are the dynamic viscosity and diameter of the particle, and c_s is the Cunningham's correction factor mentioned in Marple and Willeke (1979).

Solutions to these equations subject to initial conditions $x = x_o$, $v_x = v_{xo}$ at $t = 0$

$$x=A_x e^{m_{1x}t}+B_x e^{m_{2x}t} \tag{17}$$

$$v_x=m_{1x}A_x e^{m_{1x}t}+m_{2x}B_x e^{m_{2x}t} \tag{18}$$

$$A_x=\left[v_{xo}+\left(\frac{\beta_{1x}+\beta}{2}\right)x_o\right]\Big/\beta_{1x} \tag{19}$$

$$B_x=\left[-v_{xo}+\left(\frac{\beta_{1x}-\beta}{2}\right)x_o\right]\Big/\beta_{1x} \tag{20}$$

$$m_{1x}=\frac{\beta_{1x}-\beta}{2} \tag{21}$$

$$m_{2x}=-\frac{(\beta_{1x}+\beta)}{2} \tag{22}$$

Similarly, the solutions of equation 15 subject to the initial conditions, $y = y_o = H$, $v_y = v_{yo}$ at $t = 0$, given as :

$$y=A_y y_{c1}+B_y y_{c2}+y_p \tag{23}$$

$$y_p=-g/\beta\alpha \tag{24}$$

The discriminant is $\Delta = \beta^2 - 4\alpha\beta$. For clean room application it is likely to be positive. The trajectory solutions are given by :

$$\begin{aligned} y=&\left[v_{yo}+H\frac{\beta_{1y}+\beta}{2}-\frac{2g}{\beta_{1y}-\beta}\right]\frac{e^{(\beta_{1y}-\beta)t/2}}{\beta_{1y}} \\ &-\left[v_{yo}-H\frac{\beta_{1y}-\beta}{2}+\frac{2g}{\beta1y+\beta}\right]\frac{e^{-(\beta_{1y}+\beta)t/2}}{\beta_{1y}} \\ &-\frac{4g}{\beta^2-\beta_{1y}^2} \end{aligned} \tag{25}$$

$$\begin{aligned} v_y=&\left[v_{yo}+H\frac{\beta_{1y}+\beta}{2}-\frac{2g}{\beta_{1y}-\beta}\right]\frac{(\beta_{1y}-\beta)}{2\beta_{1y}}e^{(\beta_{1y}-\beta)t/2} \\ &+\left[v_{yo}-H\frac{\beta_{1y}-\beta}{2}+\frac{2g}{\beta_{1y}+\beta}\right]\frac{(\beta_{1y}+\beta)}{2\beta_{1y}}e^{-(\beta_{1y}+\beta)t/2} \end{aligned} \tag{26}$$

where

$$\beta_{1y}=(\beta^2-4\alpha\beta)^{1/2} \tag{27}$$

If the boundary layer effect is considered, the equation of particle motion become :

$$\frac{d^2x}{dt^2}+\beta\frac{dx}{dt}-\alpha\beta x\phi'\left(\frac{y}{\sqrt{\alpha/\nu}}\right)=0 \tag{28}$$

$$\frac{d^2y}{dt^2}+\beta\frac{dy}{dt}+\beta\sqrt{\alpha\nu}\,\phi\left(\frac{y}{\sqrt{\alpha/\nu}}\right)=0 \tag{29}$$

Since ϕ is a complicated function of η, the solution of these equations must be made numerically and beyond the discussion of this paper. Equations 17, 18, 25, and 26 are sufficient to determine the trajectory path of the particle at the impaction plate.

The boundary layer effect in this problem will cause an aerosol particle to spin. Particles which escape the initial impaction will be skimming outward exceedingly close to the impaction plate, as implied by the ideal gravitational effects discussed above. It can be seen that the particles will initially experience a velocity gradient, their upper edge being urged forward by the outflowing air and their lower edge being retarded by the stationary boundary layer, causing them to spin. As the outflowing air rapidly slows, the particles by their inertia overshoot the air stream and dip into the plate by the so-called Magnus effect (May 1975), creating a secondary deposition on the same stage. Hapel and Brenner (1965) formulated the hydrodynamic frictional force and torque on a spinning rigid spherical particle using Faxen's laws. According to this, if a sphere to which fluid adheres is immersed in an unbounded fluid in motion at infinity with velocity v_∞ and if the sphere center translates with velocity U while the sphere spins with angular velocity ω, then the force and torque on the sphere are

$$F=6\pi\mu r_p([v_\infty]_o-U)+\mu\pi r_p^3(\nabla^2 v_\infty)_o \tag{30}$$

$$T_o=8\pi\mu r_p^3(\frac{1}{2}[\nabla x v_\infty]_o-\omega) \tag{31}$$

where r_p is the sphere radius, and subscript o implies evaluation at the location of the sphere center.

EXPERIMENTAL RESULTS

The schematic of the experiment is shown in figure 4. The aerosol was generated using a nebulizer. Three samples were taken, i.e. water, salt (NaCl), and Titanium Oxide. Within the confines of the wind-tunel the aerosol can be set to produce initial evaporated drops in the range of 0.2 to 30 µm by control of the air pressure to the spray. The main sample was the dry salt particles which was collected using a glass slide covered with a very thin gelatine layer. The Liesgang circle (spot test) technique was used for detecting the deposited salt particles (containing chlorides) if they impacted a gelatine layer sensitized by a weak solution of silver nitrate (to 8% gelatine solution 10% of AgNO3 was added in the ration of 20:1).

The results are shown in figure 5 which corresponds to particle deposition in stage I, II, III, and IV of the impactor. Similar pattern of deposited salt particles shown reveals that the wave length of the deposited particles is comparable and does not depend very much on the different geometry and different air speed in the individual nozzles of the impactor. For comparison, a similar investigation has been done with insoluble titanium oxide particles impacting a dry glass slide. The difference in deposited particle patern is explained by the different state of the sampling substrate, by different environmental conditions, and, possibly, by the different properties of the deposited particles (mainly their aerodynamic diameters). The main effect seems to have, however, the space behind the slightly unsymmetrical nozzle which affects the formation and possibly the releasing of vortices at the sharp edge due to the increasing pressure and bouncing of particles at the subsequent stage. The formulas suggsted by several authors for determining the location of a stable vortex at the nozzle's edge from its dimension

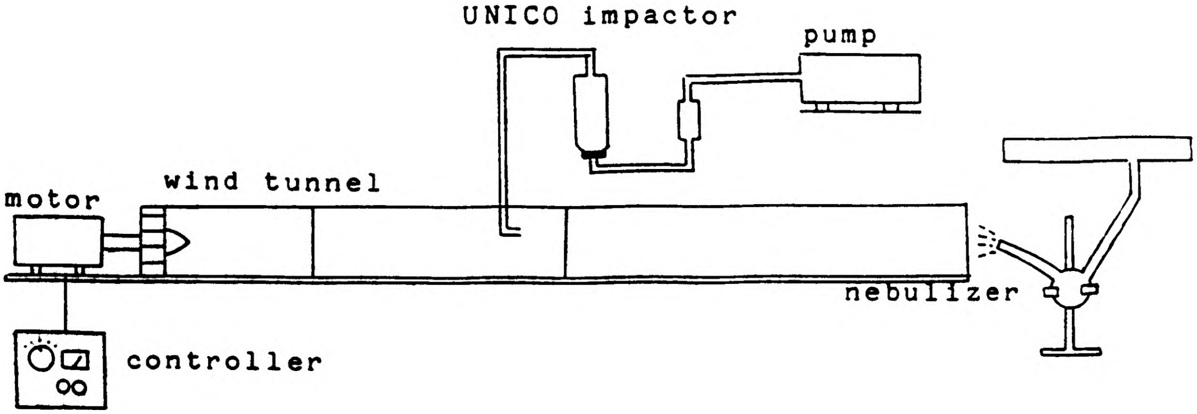

Figure 4

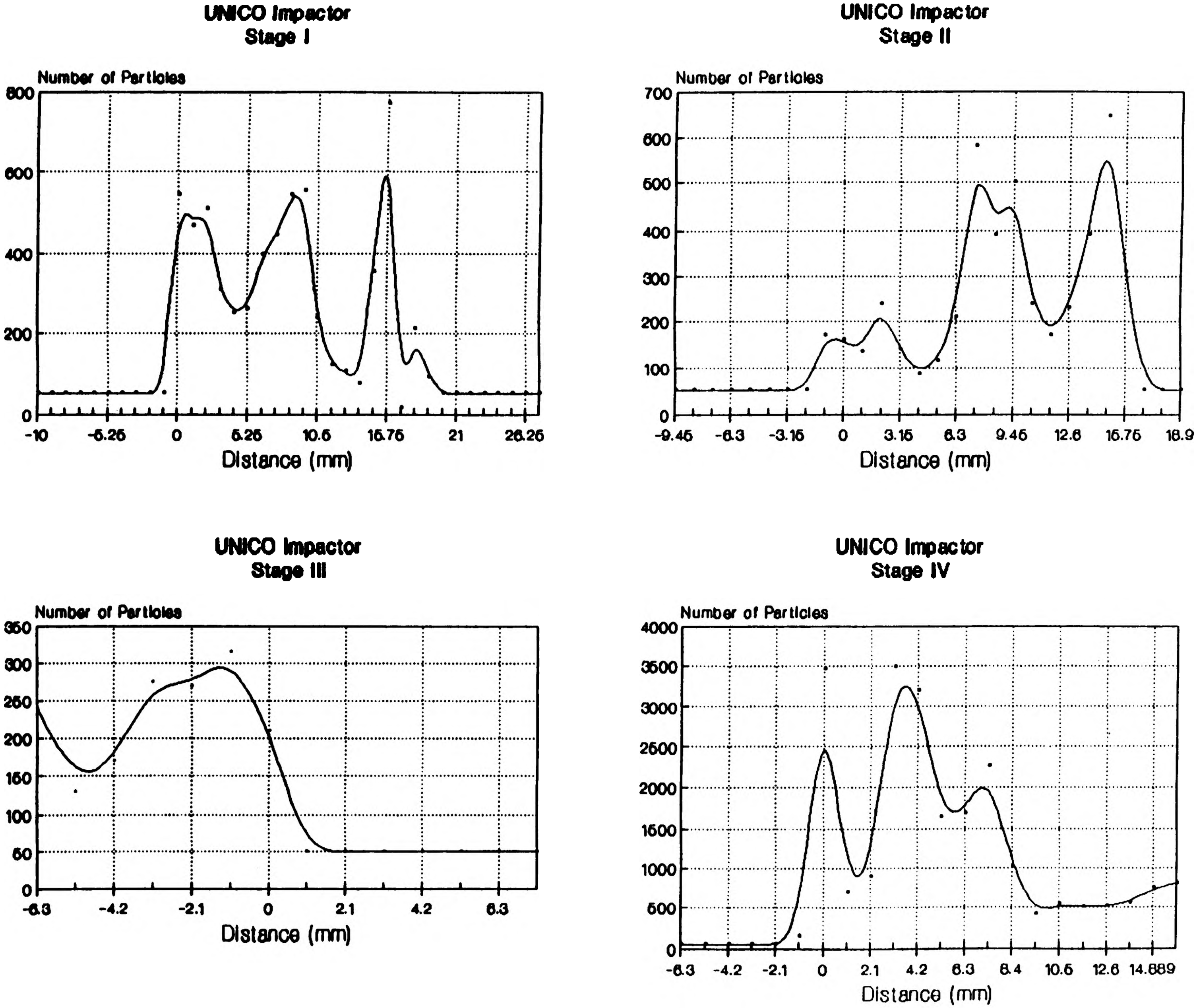
UNICO Impactor
Stage I
Number of Particles
0
200
400
600
800
-10
-5.25
0
5.25
10.5
15.75
21
26.25
Distance (mm)
UNICO Impactor
Stage II
Number of Particles
0
100
200
300
400
500
600
700
-9.45
-6.3
-3.15
0
3.15
6.3
9.45
12.6
15.75
18.9
Distance (mm)
UNICO Impactor
Stage III
Number of Particles
0
50
100
150
200
250
300
350
-6.3
-4.2
-2.1
0
2.1
4.2
6.3
Distance (mm)
UNICO Impactor
Stage IV
Number of Particles
0
500
1000
1500
2000
2500
3000
3500
4000
-6.3
-4.2
-2.1
0
2.1
4.2
6.3
8.4
10.5
12.6
14.889
Distance (mm)

Figure 5

distance from the sampling substrate and air flow parameters of a jet-impactor is not applicable for UNICO instruments. As can be noticed, α and α' in equations 1 and 2 will have different values, and will complicate the particle trajectory solution. Different approach on an unsymmetrical flow field or a more general derivation of Hiemenz stagnation flow is therefore needed for this kind of conditions.

CONCLUSION

In conclusion, we suggest the air flow conditions in and around the nozzle affect most the particle deposition in UNICO impator. The particle back spin near a shear flow, state of the particle and of the substrate might explain well the bouncing of the large particles and their deposition on the subsequent (smaller particle) stages. This research itself had therefore provided basic introduction to a more in depth study on aerosol reentrainment characteristics.

REFERENCES

Berner, A.W.(1988);"The Collection of Fog Droplets by A Jet Impaction Stage";The Sci of The Total Envirn vol.73, pp 217-228
Cadle,R.D. (1948);"The Measurement of Airborne Particles"; Environmental Science and Technology; 1948
Currie,I.G.(1974);"Fundamental Mechanics of Fluids"; McGraw-Hill Publishing Co.; 1974
Dzubay, T.G.(1976);"Particle Bounce Errors in Cascade Impactors"; Atm.Envirn. vol 10 pp 229-234
Fuchs (1964); "The Mechanics of Aerosols"; Pergamon Press; 1964
Fuchs (1973); "Preliminary Report on The Efficiency of Collisions between Dust Particles and Water Droplets"; Staub vol 33 no 4, 1973
Happel & Brenner (1965); "Low Reynolds Number Hydrodynamics with Special Applications to Particulate Media"; Prentice-Hall Inc., 1965
Lodge, Chan; "Cascade Impactor Sampling and Data Analysis"; Ame. Indust. Hygiene. Assc. 1986
Markowski,G.R. (1987); "On Identifying and Correcting for Reentrainment in Cascade Impactor Measurements";Ae.Sci. & Tech. 7:143-159 , 1987
Marple & Rubow (1986); "Theory and Design Guidelines"; from "Cascade Impactor Sampling and Data Analysis"; Lodge & Chan; Am. Ind. Hyg. Assc, 1986
Marple & Willeke (1979);"Inertial Impactors"; from "Aerosol Measurement"; editor Lundgren et.al.; Univ. Presses of Florida, 1979
May (1975); "Aerosol Impaction Jet"; J.Ae.Sci. 16:403-411; 1975
Ramarao & Tien (1989);"Aerosol Deposition in Two Dimensional Laminar Stagnation Flow";J.Ae.Sci. vol 20 no 7 pp 775-785
Ranade,M.B. (1987);"Adhesion and Removal of Fine Particles on Surfaces";Ae.Sci.&Tech 7:161-176(1987)
Schlichting (1955);"The Boundary Layer Theory";McGraw-Hill Book Co., 1955
Tillery, M.I. (1979);"Aerosol Centrifuges"; from "Aerosol Measurement"; editor Lundgren et.al.; Univ. Presses of Florida, 1979
Vanderpool & Lundgren, Marple & Rubow (1987);"Cocalibration of Four Large-Particle Impactors"; Ae.Sci.& Tech 7:pp177-185 , 1987