DEVELOPMENT OF AN AEROSOL SIZE CLASSIFIER:
A TWO-DIMENSIONAL SELF-SIMILAR VIRTUAL IMPACTOR

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ABSTRACT

DEVELOPMENT OF AN AEROSOL SIZE CLASSIFIER: A TWO-DIMENSIONAL SELF-SIMILAR VIRTUAL IMPACTOR

The purpose of this research is to characterize the performance of a rectangular slit self-similar virtual impactor. A mathematical description of two-dimensional jets of ideal fluid impinging upon a void has been developed with conformal mapping techniques. The analysis has been extended to include converging throat geometries and variable secondary flows into the void space. Particle trajectories have been simulated for a number of theoretically admissible instrument geometries.

Visual observations of two-dimensional self-similar jets impinging upon a void were conducted with a scaled-up water model. It was found that the limiting void width h_{lim}/w marking the onset of fluid instabilities increased for an intermediate value of the fluid deflecting plate angle β for useful values of throat angle β_0 and that h_{lim}/w increased with larger secondary flows into the void. Experiments were performed with $2.5 \mu m$ DOP droplets over a wide range of prototype geometries to measure the magnitude of internal losses and to fully characterize the instrument response.

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1. INTRODUCTION

Fine suspended atmospheric particles represent a significant and potentially serious form of air pollution because of their size. Small airborne particles, defined here as solid or liquid aerosols less than three microns ($<3\mu\text{m}$) in diameter, are typically formed by a spectrum of physical and chemical processes such as high temperature metallurgical operations or fossil fuel combustion. These processes produce metallic fumes, inert ash, and solid or liquid hydrocarbons. In addition, a large mass fraction of small particulate matter consisting of potentially toxic substances (both soluble and insoluble) is formed by atmospheric photochemical gaseous reactions involving nitric and sulfur oxides in combination with water vapor. These fine particles because of their size remain suspended longer, readily scatter light causing haze and reduced visibility and penetrate the natural defense mechanisms of the human respiratory system leading to retention within the deeper recesses of the lungs.

Until recently, routine methods of sampling airborne particulate matter involved either the use of a Hi-Volume Sampler over a 24 hour period for compliance with ambient air quality standards or a multi-stage cascade impactor in specific studies to determine the particulate mass-size distribution and chemical composition. While the Hi-Volume sampler yields the total particulate mass concentration on a filter and with further analysis the total chemical composition, it fails to distinguish between particles of different sizes, i.e. respirable versus nonrespirable. Likewise, use of the cascade impactor provides the necessary mass-size distribution but involves the following problems:

particles bounce off both treated and untreated collection surfaces resulting in erroneous mass loadings, multiple heavy stages yield lower particulate mass loadings per stage resulting in reduced sensitivity, and gaseous pollutants and vapors react and absorb on the surface while volatile particulate evaporate. In addition, the fixed geometry of the cascade impactor makes it difficult to calibrate and susceptible to large internal wall losses.

Recently, attempts have been made to size-classify or at least to fractionate suspended particles into respirable and nonrespirable sizes with what are called virtual impactors. These single stage virtual impactors direct particle laden air at a collection surface in a manner similar to one stage of a cascade device. In both cases particles either impact on the collection surface or escape depending on their aerodynamic diameters. The virtual impactor, however, replaces the solid collection surface such as that which occurs in a cascade device with a virtual surface or air void. Thus, large particles impact into a stagnate air void and particle-surface-interaction problems are eliminated.

The purpose of this research is to characterize the performance of a two-dimensional self-similar virtual impactor. In particular, properties of the prototype device have been investigated both theoretically and experimentally. In Sec. 2 an ideal fluid flow solution of the flow field is outlined, Sec. 3 demonstrates the results of water model studies, while Sec. 4 describes the prototype design and test results. Finally, project management including personnel contributions and publications are listed in Sec. 5.

2. THEORY

2.1 Ideal Fluid Transformations

The cross-section of the device is shown in Fig. 1A, together with some features of the desired flow pattern. Compared with our previous analyses, two new characteristics complicate the problem: the converging throat, and the bleed flow. While the basic methods used are the same as in our previous work, all aspects are modified considerably. It is necessary, therefore, to document the transformations and analysis.

The physical device, represented in the z -plane, consists of an axial wall GO, and a wall AB inclined at an angle β_0 to it, to form a converging entrance jet. The width of the throat is w . The plate ED which guides the emerging jet at an angle β to the axial wall, and which has a perpendicular opening h , is to be placed so that its continuation intersects the axis at O, coincident with the continuation of AB. This self-similar geometry, a constructionally simplifying property, imposes a constraint which the subsequent transformations must allow for.

A fraction f of the incident flow Q is to be bled off into the void space. For simplicity it is assumed that the free streamline bounding the flow, which leaves the axial wall at the bifurcation point F, continues into the void, ultimately, at K, parallel to the plate EF. The plate is assumed to be infinitesimally thin at E, so that the streamline which arrives there divides into two parts, going to J in the bleed flow and to D in the emerging jet. The free streamline BC bounds the other side of this jet. At the point H on the axial wall the fluid velocity, zero at G and constant in magnitude from F to K, achieves its maximum value. It is evident that for the device properties to be consistent with ideal fluid flow, H must lie upstream of F, and be distinct from F. It is this requirement which will limit the value of the opening, h , of the plate. The two idealizations in the foregoing description, that the

bleed flow is ultimately parallel to the plate and that the plate has infinitesimal thickness at E, are not essential, and could be avoided. However, because of the small rate of bleed flow and of boundary layer effects not included here, they are not expected to affect significantly the results to be obtained.

The transformation planes which permit us to achieve the device are also shown in Fig. 1. The complex potential W of the flow (where $dW/dx = v^*$, the complex conjugate of v the fluid velocity) is confined to the infinite horizontal strip ACRG, of width equal to Q , the flow rate. The deflecting plate is horizontal in this plane, and displaced down a distance fQ corresponding to the fraction f of bleed flow into the void space. The origin is chosen to be the point F.

The straight boundaries and free streamlines of the device are all represented as straight boundaries in the plane of the Kirchhoff variable $\Omega = \log(u_f dz/dW)$, u_f being the velocity of the emerging jet. The points G and A, the outer ends of the converging jet where the fluid velocity is vanishingly small, go to infinity in this plane. The horizontal lines CD-JK and BA have vertical positions determined from the angles β and β_0 . The positions of the vertical line JK-F and the point H, related to the velocity of the free streamline FK and the maximum axial fluid velocity, are not prescribable, however, but must be determined by the mutual consistency of the mapping procedure.

To connect the variables W and Ω , they are both mapped onto the upper half-plane of a subsidiary variable ξ . The point F is taken as the origin in ξ , and B the point $\xi = 1$. The other characteristic points of the W and Ω planes, CD, E, JK, and H, then occur at the ξ values c'^2 , e^2 , c^2 and $-q^2$ respectively. These four quantities are parameters whose values must be chosen so as to reproduce if possible the desired dimensions of the z -plane device. (The variable ξ corresponds to the square of the variable ζ introduced in earlier work, and it is for consistency of present formulae with that work that the four

Fig 1 Transformation Planes

quantities are introduced as the squares of real quantities.) It is evident from the ξ -plane topology that $-q^2 < 0 < c'^2 < e^2 < c'^2 \leq 1$.

The Schwartz-Christophel transformation which maps the horizontal strip of the W -plane onto the upper half-plane of ξ leads to the differential relationship

$$\frac{dW}{d\xi} = (\xi - c'^2)^{-1/2} (\xi - e^2)^{-1/2} (\xi - c^2)^{-1/2}. \quad (1)$$

Integration of this equation, with constants determined by the position of F and the width Q of the strip, yields

$$W = \frac{Q}{\pi} \left[\frac{c'^2 - e^2}{c'^2 - c^2} \log \frac{c'^2 - \xi}{c'^2} + \frac{e^2 - c^2}{c'^2 - c^2} \log \frac{c'^2 - \xi}{c^2} \right]. \quad (2)$$

The condition that the fraction of the bleed flow is f then determines the parameter e^2 , in the form

$$e^2 = f c'^2 + (1-f) c^2. \quad (3)$$

Thus W is simply related to ξ by

$$\frac{\pi W}{Q} = f \log \frac{c'^2 - \xi}{c'^2} + (1-f) \log \frac{c'^2 - \xi}{c^2}. \quad (4)$$

In ξ , the flow pattern is that of two sinks at JK and CD , of relative strengths f and $1-f$, with E as the stagnation point between them. For any useful value of f not equal to zero, the relationship between W and ξ may be inverted only numerically.

The interior of the "dipper" shaped object of the Ω plane and the upper half of the ξ plane are linked by the Schwartz-Christophel relationship

$$\frac{d\Omega}{d\xi} = (\xi - 1)^{-1/2} (\xi - c'^2)^{-1/2} (\xi - c^2)^{-1/2} \xi^{-1/2} (\xi + q^2)^{-1/2}. \quad (5)$$

Its integral, in the form

$$\Omega = C \left\{ (q^2 + c'^2) F(\phi \backslash \alpha) + (1 - c'^2) E(1/c'^2; \phi \backslash \alpha) \right\} + D, \quad (6)$$

involves elliptic integrals of the first kind, $F(\phi|\alpha)$, and of the third kind, $\Pi(n;\phi|\alpha)$ as well as constants C and D to be related to the dimensions in the Ω plane. The argument ϕ of the elliptic integrals is

$$\phi = \tan^{-1} \left[\frac{\xi-1}{\xi} \frac{c'^2}{1-c'^2} \right]^{1/2}, \quad (7)$$

and the modular angle α is

$$\alpha = \cos^{-1} \left[\frac{1-c'^2}{c'^2} \frac{c^2}{1-c^2} \right]^{1/2}. \quad (8)$$

In the complex plane of ϕ the region of interest covers the vertical half-strip $0 \leq \text{Re } \phi \leq \pi/2$, $\text{Im } \phi > 0$. Both functions F and Π have a branch point at $\phi_c = \pi/2 + i \log \cot \alpha/2$, while Π has also a pole at $\phi_p = \sin^{-1} c'$. Fixing the constants C and D of the Ω expression requires the values of F and Π at the various extremities of the ϕ region, which for F involve $K(\alpha)$, $K'(\alpha)$ the complete elliptic integrals of the first kind. For the function Π the corresponding values are denoted as follows:

$$\phi + i\infty, \Pi \rightarrow i\Pi_a(1/c'|\alpha); \quad (9a)$$

$$\phi + \pi/2 + i \log \cot \alpha/2, \Pi \rightarrow \Pi_b(1/c'|\alpha) + i\Pi_c(1/c'|\alpha). \quad (9b)$$

In terms of these quantities and of the known dimensions in the Ω plane, the constants C and D may be determined to be

$$C = \beta_o / \left[(1-c'^2) \Pi_c \right], \quad (10a)$$

$$D = -i \beta_o. \quad (10b)$$

The ξ -plane parameter q^2 is also fixed by the consistency of the mapping to be

$$q^2 = (1-c'^2) \left[(\pi - \beta + \beta_o) \Pi_c / \beta_o - \Pi_a \right] / K'(\alpha) - c'^2. \quad (11)$$

Thus there now remain only two undetermined ξ -plane parameters, c^2 and c'^2 . The

constraints that implicitly determine them are the z-plane parameter ratio h/w and the requirement of self-similarity.

The design combination of bleed flow with a parallel incident jet is also accessible at this stage. It involves the $W(\xi)$ relationship deduced here, with the $\Omega(\xi)$ relationship obtained in our earlier work. In the present notation, that relationship takes the form

$$\Omega = \log(u_f w / Q) \{ F(\phi \backslash \alpha) / F(\sin^{-1} c' \backslash \alpha) - 1 \} . \quad (12)$$

It is the limiting case, as $\beta_0 \rightarrow 0$, of the more general expression used in the present work.

Another limiting case may also be noted, that of a solid plate ($h=0$) with a converging incident jet. This requires $f=0$ (no bleed flow) in the $W(\xi)$ expression, and an Ω mapping in which the vertical side JK-F goes to $\Omega = +\infty$. The parameter c'^2 of the ξ plane is no longer needed, and the Schwartz-Christophel transformation may be integrated in terms of elementary functions, to yield

$$\begin{aligned} \Omega &= (\beta_0 / \pi) \log [\xi' + (\xi'^2 - s^2)^{1/2}] - i \beta_0 \\ &- (1 - \beta / \pi) \log \frac{[\xi' + (\xi'^2 - s^2)^{1/2} + \frac{1}{2}(1 + c')^2]}{[\xi' + (\xi'^2 - s^2)^{1/2} + \frac{1}{2}(1 - c')^2]} \end{aligned} \quad (13)$$

where $\xi' = \xi - \frac{1}{2}(1 + c'^2)$ and $s = \frac{1}{2}(1 - c'^2)$. The other ξ -plane parameter q^2 has the value

$$q^2 = c'(\pi - \beta) / \beta_0 . \quad (14)$$

The relationship of the $W(\xi)$ and $\Omega(\xi)$ transformations to the z-plane, and thus the determination of the device dimensions produced by assumed values of c'^2 and c'^2 , is achieved by numerical integration. In principle the integrals may be defined by a contour of any prescribable shape in either of the planes W or ξ . The definition of Ω , which on inversion gives

$$\frac{dz}{dW} = \frac{1}{u_f} e^{\Omega} \quad (15)$$

leads to the two possible integrals for the distance between two points P_1 and P_2 in the z -plane:

$$z(P_2) - z(P_1) = \frac{1}{u_f} \int_{W(P_1)}^{W(P_2)} e^{\Omega(\xi[W])} dW \quad (16a)$$

$$= \frac{1}{u_f} \int_{\xi(P_1)}^{\xi(P_2)} e^{\Omega(\xi)} \frac{dW}{d\xi} d\xi . \quad (16b)$$

Inversion of the $W(\xi)$ relationship is required in the first of these expressions, which suggests that the second form may be more convenient. The converging nature of the flow in the ξ plane, however, means that roughly equal distances in z correspond to quite different distances in ξ , depending on how close to the sinks at c^2 and c'^2 the points P_1 and P_2 happen to be. A numerical integral with equal intervals can thus be very wasteful of computer time. The rather intricate numerical problem of the inversion of $W(\xi)$, to be done using Newton's method of linear extrapolation in the complex ξ plane, was finally achieved by the use of four separate starting approximations, for the four regions of incident jet, outgoing jet, bleed jet and the region around the plate edge E. With this inversion available for all W and ξ , it then proves much more straightforward to do the integrals in the W plane. For most of the integrals involved, the contour is a straight line joining $W(P_1)$ and $W(P_2)$. Integrals starting at the points B, E or F have a square-root end-point singularity, however, which for a small part of the integral near the point is allowed for by a suitable change of variable.

To obtain the physical dimensions of the device for assumed values of c and c' , the distances are calculated from B to E, and from B to a point P a little upstream of H, to give

$$\text{Im}[z(P)-z(B)] = w, \quad (17a)$$

$$z(B) - z(E) = h-w + id. \quad (17b)$$

The first of these results determines w , and thus the physical scale of the device. (The quantity Q/u_f introduces the dimension of length into the problem, but w itself is not prescribable.) By trigonometry, the intersections of the incident jet wall AB and of the plate DE with the axial wall GO may then be calculated. These two intersections will not in general be coincident. For a given value of c , a search is made on c' by Newton's method to find the value at which the continuations of the walls intersect at one point, at which stage self-similarity of the device has been achieved. The device at this stage has known dimensions w and h . The value of h/w may now be explored as a function of the angles β_0 and β .

For self-similar geometries (i.e. a determined value of c' for a given c) a search may now be made on c to obtain a prescribed value of h/w . As with an earlier study with a parallel incident jet, it is found that h/w may not take on all possible values. There is a superior limit h_{lim}/w which occurs (at varying values of c) when q^2 becomes equal to zero. In the z plane, the point H, where the axial velocity reaches its maximum value, touches F, the end of the free streamline on which the velocity is constant in magnitude. In the Ω plane the indentation HF disappears. It is evident in either plane that further motion of H is prohibited. For several values of the throat angle β_0 , the value of h_{lim}/w as a function of the plate angle β is shown in Fig. 5.

Fig 2 Fluid Streamlines

2.2 Particle Trajectories

The quite standard methods used in earlier work to calculate the trajectories of injected particles were made sufficiently flexible that they work in these generalized flow patterns with no substantial changes. The equation of motion of a particle of mass m , moving with velocity $\vec{v}$ in fluid of velocity $\vec{v}_f$, is according to Stokes' Law

$$m \frac{d\vec{v}}{dt} = K(\vec{v}_f - \vec{v}) . \quad (18)$$

The unit used for fluid velocities (in the definition of R , for example), and for $\vec{v}$ is u_f , the velocity of the outgoing jet. The unit for the device size and for the particle position $\vec{x}$ (where $\vec{v} = d\vec{x}/dt$) is w the throat opening. The dimensionless equations to be solved are thus

$$d(\vec{x}/w)/d\tau = \vec{v}/u_f , \quad (19a)$$

$$d(\vec{v}/u_f)/d\tau = (\vec{v}_f/u_f - \vec{v}/u_f)/\mu . \quad (19b)$$

where $\tau = u_f t/w$, and $\mu = mu_f/Kw$. With the simple assumption that $m = \frac{4}{3}\pi a^3 \rho$, where a is the particle radius and ρ its density, and that $K = 6\pi\eta a$ where η is the fluid viscosity, then $\mu = \frac{2}{9} \rho u_f a^2 / w\eta$.

The convenient dimensionless quantity to quote in practice should involve not u_f but $\bar{u}_0 = Q/w$, the average fluid velocity at the throat. The ratio $u_f/\bar{u}_0 = R$ is obtained during the calculation of the flow pattern. The customary dimensionless variable ψ is thus given by $\psi = \mu/R$ and it is the quantity

$$\psi^{\frac{1}{2}} = a \left(\frac{2}{9} \rho \bar{u}_0 / w\eta \right)^{\frac{1}{2}} , \quad (20)$$

directly proportional to the particle radius, that is used to characterize the particle-sizing properties of the device.

For a given device configuration a file of information is calculated which contains positions in the z plane and fluid velocities on a grid of points,

rectangular in the W plane, that adequately cover the device. By third-order two-dimensional interpolation from the four closest points, the fluid velocity at any position $\vec{x}$, $\vec{v}_f(\vec{x})$, may be obtained. Particles are inserted into the incident jet, at some reasonable distance from the throat, with initial velocities equal to the local fluid velocity. The initial position is in fact specified in the W plane, as $W_s = (x_w - iy_w)Q$. The starting coordinate $\vec{x}_s$ calculated by Eq.(16a) from W_s , for y_w ranging from zero to one, lie approximately on a circle centered at 0, the wall intersection point. As a function of the Stokes parameter $\psi^{\frac{1}{2}}$ and of the starting position as specified by y_w , the rest of the problem is the same as it was for a straight jet. A trajectory is followed until (A) it enters the void space or the bleed flow, or (B) it collides with the plate or will asymptotically do so, or (C) it escapes with the emerging jet. Functions $y_w(\psi^{\frac{1}{2}})$ corresponding to the A:BC separation (from those particles which hit the edge E) and to the AB:C separation are shown in Fig. 3. It is evident from the procedure described that these are, or provide the material for (in the case that $y_w(\psi^{\frac{1}{2}})$ is double-valued) the separation efficiencies desired.

Fig 3 Efficiency Curves

3. MODEL STUDIES

3.1 Scaled-up Water Model

Features of the impactor flow field were observed and recorded with a scaled-up Plexiglas water model as illustrated in Fig. 4. The model was immersed and anchored in a 25 gal water tank with the outlet connected directly to a centrifugal pump. Dye was injected into the throat of the model from tygon tubing connecting three stainless steel injector nozzles to a cylindrical reservoir suspended above the tank. Tubing clamps regulated the flow of washable, water diluted, black India ink into the three injection lines positioned at the model throat in a plane midway between the top and bottom model surfaces. The model was designed with a fixed throat angle $\beta_0 = 45^\circ$ and a variable deflecting plate angle $\beta = 101^\circ, 90^\circ, 79^\circ, \text{ and } 68^\circ$.

3.2 Onset of Indeterminate Geometries

The potential flow solution for virtual impactor geometries becomes indeterminate for large normalized void widths h/w . The value of $h/w = h_{lim}/w$ at the onset of theoretically indeterminate geometries marks the development of fluid instabilities near the leading edge of the fluid deflecting plate. These instabilities appear as a kink or curl on the fluid streamline intersecting the leading edge of the plate. If the void width h/w is increased further the jet begins to protrude down into the void space below the impaction region and the flow field, in general, becomes less stable. Theoretical values of the limiting void width h_{lim}/w have been determined over a range of deflecting plate angles β for each

Fig 4 Scaled-up Water Model

of three throat angles $\beta_0 = 30^\circ, 45^\circ, \text{ and } 60^\circ$ and bleedflows of $f = 0$ and 0.1 where f represents the fraction of the total flow which escapes into the void space, and the results are shown in Fig. 5. Visual observations of the onset of instabilities have been recorded with the water model and these values are also indicated in Fig. 5. As can be seen, the flow fields appear to be theoretically and experimentally more stable for intermediate values of the fluid deflecting plate angle β at all values of throat angle β_0 and bleedflows f . The effect of the secondary flow f on the magnitude of h_{lim}/w was also determined theoretically and experimentally. Figure 6 demonstrates that the range of determinate geometries increases with increasing flow rate f .

Fig 5 Limiting Void Width as a Function of Deflecting Plate Angle

Fig 6 Limiting Void Width as a Function of Secondary Flow $f = Q/Q_0$

4. PROTOTYPE TESTS

4.1 Virtual Impactor Design

A cross section of the two-dimensional prototype device constructed of brass and aluminum stock is shown in Fig. 7. The indicated knife edges are 2 cm wide and their position is adjustable with micrometers to within 2×10^{-3} cm. The instrument provides a variable throat angle β_0 and a fixed fluid deflecting plate angle $\beta = 90^\circ$ (see Sec. 2) and is designed such that both geometric (constant β_0 , β , h/w) and dynamic similarity (constant $Re = Q_0/\nu L$) can be maintained while changing the linear dimensions of the impactor throat. The self-similar feature of the instrument is achieved with a fixed volume flowrate of air Q_0 and plate angles β_0 and β which allows one to calibrate the instrument with a single test aerosol and particle diameter and to determine efficiency curves and loss spectra as a single function of particle Stokes number ψ . The latter feature also provides an adjustable particle cutoff diameter.

Initial tests with the virtual impactor indicate that large particle losses occurred at higher values of the particle Stokes number. This was found to be a result of particle contact with the inside front surface of the aerosol inlet. The magnitude of this problem was reduced by modifying the design to provide a sheath of clean air into the void space below the impaction region (see excess air inlet in Fig. 7). In addition, the primary and secondary exhausts of the instrument have been designed to minimize particle losses and to provide for either particle filtration or adaptation to optical particle counters.

Fig 7 Side View of Virtual Impactor

4.2 Experimental Procedure

Laboratory experiments were performed to determine particle efficiency curves and internal losses for the prototype impactor. The test aerosol was monosized dioctylphthalate (DOP) oil droplets with a uranine tracer. They were generated with a vibrating orifice aerosol generator, normally in the 2-3 μm size range. Particle size was independently determined by viewing the signals with an oscilloscope from a Royco Model 245 optical particle counter. The pulse height was used to determine the particle diameter with a Royco calibration curve. A typical one liter solution used to generate 2.3 μm DOP droplets contained 930 ml isopropanol, 69.6 ml deionized water, 0.394 ml DOP and 50 mg of uranine tracer. The solution was initially filtered twice using a 0.8 μm pore size Millipore filter and once a day during the experimental period. Any static particle charge was removed with a Kr-85 neutralizer (Thermo-System Model 3054) and the test aerosol was subsequently introduced into a 2' x 4' x 2.5' plexiglas holding chamber.

Particle efficiency and internal losses were determined by filtering the aerosol at the primary and secondary instrument exhausts while maintaining the device total flowrate of 30 l/min. A third filtered sampling probe positioned near the device was simultaneously operated at the same total flowrate and the amount of collected material was determined on all three filters fluorimetrically.

During a typical test procedure approximately 30 minutes was allowed to elapse after initiation of the test aerosol. The jet Reynolds number of the sampler was held constant at 1540 which corresponded to 30 l/min total flow for a period of approximately 10 minutes. After sampling, the

three filters were soaked in a beaker containing 25 ml of a 50% ethanol solution and the dissolved uranine solution was subsequently analyzed fluorimetrically with a Turner Model 110 Fluorimeter. A single value of particle collection efficiency and fraction lost to the internal surfaces of the instrument was then determined from the three fluorimeter readings. This procedure was repeated several times at fixed particle diameter, device geometry and flowrate (β , β_0 , h/w , Q_0) while decreasing the linear dimensions of the jet with the micrometers. This provided an efficiency curve and loss spectrum as a function of the particle Stokes number

$$\psi = \frac{\rho Q_0}{18 \mu L} \left(\frac{d}{w} \right)^2 \quad (21)$$

for a given device geometry and jet Reynolds number $Re \left(= \frac{Q_0}{\nu L} \right)$. Here ρ is the particle density, μ is the viscosity of air, $\nu (= \eta/\rho_a)$ is the kinetic viscosity, L is the device width, Q_0 is the air flowrate, w is the jet width, d is the particle diameter, and ρ_a is the air density (see Eq. 20 for derivation of Eq. 21 where $d = 2a$).

4.3 Test Results and Discussion

Particle efficiency curves and loss spectrums were determined over a range of normalized void widths h/w (see Sec. 4.4) for each of three throat angles $\beta_0 = 38^\circ$ ($s/w = 1.29$), $\beta_0 = 45^\circ$ ($s/w = 1.0$) and $\beta_0 = 58.2^\circ$ ($s/w = 0.62$). The jet Reynolds number $Re (= Q_0/L\nu)$ was set at 1540 where $Q_0 = 30$ l/min is the air flowrate, and $L = 2$ cm is the jet width. The effect of varying the bleedflow on the magnitude of the particle losses is demonstrated in Figs. 8 and 9 for two excess clean air flows $Q_e/Q_0 = 0.0$ and 0.05. Both figures

indicate that it is necessary to provide a secondary or bleedflow of at least $Q/Q_0 = 0.1$ to minimize particle losses to internal surfaces other than the fluid deflection plate and to achieve a distinct peak in the particle loss spectrum as theory predicts. The height of the peak also stabilized in Fig. 9 for the larger secondary flows. Figure 10 demonstrates the effect of increasing the excess clean air flow into the void space which minimizes the particle losses at large Stokes numbers. All of the remaining data were taken with the conditions $Q_e/Q_0 = 0.15$ and $Q/Q_0 = 0.1$ and these curves are shown in Sec. 4.4.

The data of Sec. 4.4 were used to determine the variation of three important parameters as a function of the instrument normalized void width h/w . The first, Fig. 11, is a plot of $\psi_{50}^{1/2} = \psi^{1/2}$ ($E = 0.5$) which represents a parameter proportional to the particle cutoff diameter. The second quantity, shown in Fig. 12, is the relative dispersion S calculated as

$$S = (\psi_{84}^{1/2} - \psi_{16}^{1/2}) / (0.68 \psi_{50}^{1/2}) \quad (22)$$

which is a measure of the spread of the efficiency curve around the cutoff value $\psi_{50}^{1/2}$. The final parameter A , plotted in Fig. 13, is an estimation of the normalized area under the loss spectrum and represents the fraction of particles which are lost to the top surface of the fluid deflection plate. The quantity A was measured by projecting the loss spectrum to the abscissa on both sides of the indicated peak in the experimental data. It is desirable to minimize both quantities S and A but, as one can see from Figs. 12 and 13, this is impossible since S increases with h/w while A decreases. However, an appropriate choice of h/w may be an intermediate value in the range, for example, $1.0 < h/w < 1.2$.

Fig 8 Efficiency Curves for Varying Secondary Flows $f = Q/Q_0$

Fig 9 Efficiency Curves for Varying Secondary Flows $f = Q/Q_0$

Fig 10 Efficiency Curves for Varying Clean Excess Air Q_e/Q_0

Fig 11 Particle Cutoff Parameter Versus Normalized Void Width

Fig 12 Relative Dispersion Versus Normalized Void Width

Fig 13 Integrated Particle Losses Versus Normalized Void Width

4.4 Virtual Impactor Data

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19

Fig. 20

Fig. 21

Fig. 22

Fig. 23

Fig. 24

Fig. 25

Fig. 26

Fig. 27

Fig. 28

Fig. 29

Fig. 30

Fig. 31

Fig. 32

Fig. 33

5. PROJECT MANAGEMENT

5.1 Project Compliance

The objectives of the proposal covering the time period have been accomplished. The potential flow solution has been extended to include converging throat geometries along with secondary flows or bleedflows into the void space. Tests have been made on the prototype device covering a wide range of instrument geometries. The effect on the particle loss spectrum of an excess clean air flow into the void space has been explored. Salient features of the efficiency curves and loss spectrums have been measured and recorded and the results will be correlated with theoretical results.

5.2 Personnel Contributions

<u>Name</u>	<u>Level</u>	<u>Period</u>
Dr. L. J. Forney	1/3 time	6/1/77-present
Dr. D. G. Ravenhall	1/4 time	6/1/77-present
Mr. D. S. Winn	1/3 time	1/21/77-6/21/77
Mr. S. S. Lee	2/3 time	8/1/77-8/1/78
Mr. W. M. Langlois	1/4 time	8/1/77-8/1/78
Mr. M. Jazayeri	NSF Fellowship	6/15/77-8/15/77
Mr. A. J. Hubbard	1/3 time	8/1/78-present
Mr. E. W. Cannon	1/3 time	8/1/78-present
Ms. Z. Giz	1/4 time	8/1/78-present

5.3 Presentations

- Forney, L. J. and Ravenhall, D. G., "Aerosol Impactors: A Two-Dimensional Jet of Ideal Fluid Impinging upon a Void," Proceedings of the Eighth U.S. National Congress of Applied Mechanics, Los Angeles, CA, June 1978.
- Forney, L. J. and Ravenhall, D. G., "Use of Potential Flow to Correlate Virtual Impactor Data," Proceedings of ACS 177th National Meeting, Honolulu, Hawaii, April 1979.
- Forney, L. J., "Recent Developments in Aerosol Sizing," Department of Civil Engineering, Georgia Institute of Technology, Atlanta, GA, January 1979.
- Forney, L. J., "Recent Developments in Aerosol Sizing," Atmospheric Science Laboratory, University of Illinois, February 1979.
- Ravenhall, D. G., "Theoretical Studies of Particle Impactors," Department of Physics, University of Illinois, February 1979.

5.4 Publications

- Forney, L. J., Ravenhall, D. G. and Winn, D. S., "Aerosol Impactors: A Study of a Fluid Jet Impinging upon a Void," Journal of Applied Physics, 49, 2339 (1978).
- Ravenhall, D. G., Forney, L. J. and Jazayeri, M., "Aerosol Sizing with a Slotted Virtual Impactor," Journal of Colloid and Interface Science, 64, 108 (1978).
- Ravenhall, D. G. and Forney, L. J., "Aerosol Impactors: Calculation of Optimum Geometries," Journal of Physics E., Scientific Instrumentation, submitted for publication (1978).
- Winn, D. S., "Flow Studies of an Ideal Fluid Impinging on a Void," M.S. Thesis, Department of Mechanical Engineering, University of Illinois (1977).

Forney, L. J. and Ravenhall, D. G., "Development of an Aerosol Size Classifier," Department of Energy Progress Report CDO-4319-1, January 1978.