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RESEARCH REPORT

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SUBJECT Investigation of a Perfusion Impaction Dust Separator
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ABSTRACT

Collection efficiency of an impaction dust separator with a porous plate as the impaction surface was investigated theoretically and experimentally. To provide continuous removal of deposited material, water perfused through the plate in a direction opposite to the impaction direction. The determination of theoretical collection efficiencies as a function of particle and jet properties was attempted by analyzing the governing equations. Experimental collection efficiency was measured for an aerosol jet of organic liquid particles in air.

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Contents

	<u>Page</u>
1. Summary	4
2. Introduction	4
2.1 Background	4
2.2 Previous Work	4
2.3 Objectives	8
3. Theoretical Development	8
4. Apparatus and Procedure	18
5. Results and Discussion	21
5.1 Experimental Approach	21
5.2 Theoretical Approach	21
6. Conclusions	24
7. Recommendations	24
8. Acknowledgment	24
9. Appendix	25
9.1 Order of Magnitude Analysis of Navier-Stokes Equations	25
9.2 Estimation of Gas Velocity at Nozzle Exit	26
9.3 Solution of Velocity Field Finite Difference Equations	28
9.4 Computer Program	31
9.5 Experimental Jet Dimensions	42
9.6 Location of Data	42
9.7 Nomenclature	42
9.8 Literature References	45

1. SUMMARY

A modified impaction dust separator was investigated to determine experimentally and theoretically the operating characteristics and collection efficiencies. The mathematical approach consisted of the computer calculation of the finite difference form of the Navier-Stokes equations for flow field determination between the jet and the plate of the impactor, and the iterative, short interval tracing of particles by use of integrated force balance equations which were derived assuming no gas velocity change over the intervals.

For the experimental aspect of this investigation, aerosol particles of dioctyl phthalate were created in a Sinclair-LaMer generator. They were then counted in samples taken before and after the impactor. The ratio of the number of counts for a particular size range of particles yielded the collection efficiency for that range taken under that particular set of operating conditions.

2. INTRODUCTION

2.1 Background

Current industrial dust collection devices, which utilize inertial forces to impact the dust onto a collection plate or fibrous filtration material, are not capable of continuous operation. Thus, a contaminated air stream must occasionally be rerouted or discontinued to expedite the removal of the impacted material from the receiving plate or filter. The rerouting or discontinuation of the airstream requires duplication or shut-down of process equipment. In either case, cleaning requires materials handling.

A perfusion-impaction collector recently proposed by J.D. McDowell permits continuous operation (5). Instead of a dry plate, this collector contains a porous impaction surface through which liquid perfuses opposite to the impaction direction, thus continuously cleansing the surface. The relatively concentrated water-particle suspension is then collected and more easily treated than the dilute condensate obtained from steam scrubbers.

2.2 Previous Work

In 1945, May (4) developed the cascade impactor which consisted of a series of jets with decreasing slit width and jet-to-plate distances. By arranging the cascade in this way, May was able to impact particles of decreasing size on glass slides suitable for microscopic analysis. Samples of aerosols containing particles ranging from 1-50 μ in diameter were analyzed in this manner and an experimental curve of impaction efficiency as

a function of a size parameter,

$$I = \frac{\rho_p D_p^2 V_A}{\mu D_c} \quad (1)$$

was obtained. May was the first to report quantitative experimental data on the performance of impactors and also the first to perform a dimensional analysis on the variables describing impactor operation.

In 1951, Ranz and Wong (10) experimented with single jet impactors of various geometries. They also developed analytical models for rectangular and circular orifices based on the following assumptions:

1. The velocity profile of the gas emanating from the jet is flat.
2. The particles have the same velocity as the gas at the nozzle exit.
3. The gas is a Newtonian fluid (constant density and viscosity) unaffected by particle motion.
4. The particles that impact are collected.
5. The efficiency of impaction is equal to the ratio of the cross-sectional area of the orifice from which the particles hit the plate to the total orifice cross section.
6. The flow is inviscid.

A final set of assumptions is established in the theoretical model proposed by Ranz and Wong pertaining to a hypothetical stagnation region (see Fig. 1). This region is bounded in the y-dimension by ± 1 and in the x-dimension by the y-axis and $x=-1$ where the units of measure are half slit widths. Within this region, the normalized velocity components at a point are equal in magnitude to the respective coordinates of the point. Between the orifice and the stagnation region boundary, the x-component of normalized velocity equals one; above $y=1$ and below $y=-1$ but for $-1 < x < 0$, the y-component of velocity equals one and minus one, respectively. Furthermore, a particle is assumed to impact the plate if, when the particle is located at $y = \pm 1$, the x-component of normalized particle velocity is greater than the x-coordinate magnitude of the particle position (which corresponds to the normalized gas velocity at that point).

These assumptions defining the flow field and particle motion, together with a particle force balance equation, were used to develop analytical models describing rectangular and circular jet impaction systems. An impaction parameter, ψ^2 , a dimensionless group obtained from the analysis, was used as the abscissa against which efficiency was plotted for the theoretical and experimental data obtained by Ranz and Wong and the experimental data collected by May as shown in Fig. 2. Note that the plot of data points collected by May correlates well with the theoretical curve of Ranz and Wong,

--- Streamline
 — Particle Trajectory

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AEROSOL JET AND PLATE

DATE 9-24-75	DRAWN BY FG/ASL	FILE NO. CEPS-X-215	FIG. 1
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but that the data obtained by Ranz and Wong did not correlate closely with either of the others. Ranz and Wong did not explain the differences in the results.

2.3 Objectives

The objectives were:

1. To develop a theoretical model to calculate the impaction efficiency of a jet impinging on a flat plate. The Navier-Stokes and the continuity equations describe the fluid velocity distribution in the region between the nozzle and the porous perfusion plate. These equations can be solved by finite difference techniques with appropriate boundary conditions. The force balance equation on each particle can be solved after the velocity distribution of fluid between nozzle and plate has been computed. The theoretical collection efficiency can be found by calculating the fraction of particles which impact on the plate as indicated in the solution of the force balance equation.
2. To generate dioctyl phthalate particles with a modified Sinclair-LaMer aerosol generator. A particle counter classifies particles in a particular size range before and after impaction. The experimental collection efficiency can be determined as the fractional loss of particles due to impaction on the porous perfusion plate.
3. To compare the theoretical collection efficiency with the experimentally measured collection efficiency in graphical form.

3. THEORETICAL DEVELOPMENT

As noted in the previous section, Ranz and Wong developed an analytical model based on several simplifying assumptions. Since high speed computers are now available, many of the assumptions needed to solve the model analytically will not be necessary for the numerical analysis of an equivalent model. For instance, the assumption that the velocity profile is flat at the nozzle exit is reasonable if the jet is operating in the turbulent region or if the entrance region to the jet is too short to allow flow development. If the entrance is short, however, the larger particles cannot accelerate as quickly as the gas, and impaction efficiency is low. A short entrance region would therefore invalidate the assumption that the particles have the same velocity as the gas at the nozzle exit. Consequently, for the two assumptions to be made simultaneously, the model could only describe jets operating in the turbulent flow region which would not fairly represent the experimental data obtained by May and Ranz and Wong. Therefore only one of these assumptions will be used in the development of the new model, and since the initial velocity profile is relatively easy to construct numerically (see Appendix 9.2), the assumption of a flat initial profile will not be used.

Another assumption made by Ranz and Wong is that the gas is a Newtonian fluid unaffected by particle motion. The Newtonian fluid aspect of this assumption is certainly justifiable since the experimentation performed by Ranz and Wong occurred at room temperature and atmospheric pressure. The independence of gas flow and particle motion is reasonable if the dispersed density of the particles in suspension is less than the gas density (2). This assumption will also be used in the current model.

The assumption that all of the impacted particles are collected may not be realistic for dry particles impacting on a dry plate since reentrainment is possible. But for the wet, continuously cleansed system proposed by McDowell, this may be a reasonable approximation and therefore it will be used.

Ranz and Wong also assumed that the efficiency of impaction equals the ratio of the cross-sectional area of the orifice from which the particles impact the plate to the total orifice cross section. This assumption implies that the particles are uniformly dispersed over the entire jet cross section which is statistically accurate providing that the entrance region to the jet is gradual. An abrupt change in this region could cause the particles flowing along the outer edges of the gas stream to impact the jet walls, thus affecting the distribution of particles across the slit. In the model being developed, however, we will assume no abrupt changes in the entrance region and that the particles are equally distributed.

The assumption that the flow is inviscid neglects both the entrainment of the surrounding fluid by the jet stream and the boundary layer at the plate. Entrainment decreases the momentum of the jet stream and thus will affect the impaction of particles (particularly the smaller more responsive ones). The boundary layer should not be neglected because the gas velocity approaches zero near the plate and the other solid boundaries. This decreased gas velocity will decelerate the particle and consequently affect the efficiency of impaction.

In summary, the new theoretical model will be based on the following assumptions:

1. The particles have the same velocity as the gas at the nozzle exit.
2. The particles that impact are collected.
3. The efficiency of impaction equals the ratio of the cross-sectional area of the orifice from which the particles impact the plate to the total orifice cross section.
4. The gas is a Newtonian fluid (constant density and viscosity) unaffected by particle motion.

The gas flow field will not be assumed, but instead, calculated from the continuity and the Navier-Stokes equations. However, the theoretical development will apply only to two dimensional gas flow issuing from a slot jet. Flow in the direction of the major axis of the jet will be considered

negligible since in the experimental apparatus, this jet dimension is twenty-nine times the slit-width, and also because the flow is blocked by a wall at either end of the slit. The mathematical coordinate system originates at the stagnation point and the x-z plane is parallel to the plate face with the z-axis parallel to the major jet axis, and the y-axis coincident with the axis of symmetry of the jet.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v_x) + \frac{\partial}{\partial y}(\rho v_y) + \frac{\partial}{\partial z}(\rho v_z) = 0 \quad (2)$$

is the general continuity equation (1). Since the system is operating at steady state, density is constant, and the gas velocity in the z-direction is negligible, the equation simplifies to

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0 \quad (3)$$

The two pertinent Navier-Stokes equations for Newtonian flow (1) are

$$\rho \left(\frac{\partial v_x}{\partial t} + v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} + v_z \frac{\partial v_x}{\partial z} \right) = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2} + \frac{\partial^2 v_x}{\partial z^2} \right) + \rho g_x \quad (4)$$

and

$$\rho \left(\frac{\partial v_y}{\partial t} + v_x \frac{\partial v_y}{\partial x} + v_y \frac{\partial v_y}{\partial y} + v_z \frac{\partial v_y}{\partial z} \right) = -\frac{\partial p}{\partial y} + \mu \left(\frac{\partial^2 v_y}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} + \frac{\partial^2 v_y}{\partial z^2} \right) + \rho g_y \quad (5)$$

Since the gas is flowing at steady state, the two transient terms are zero. Since velocity does not change with the z-direction, all z-dependent derivatives are zero. By an order of magnitude analysis, the gravitational terms are negligible (see Appendix 9.1). Therefore, the Navier-Stokes equations for Newtonian flow reduce to:

$$\rho \left(\frac{v_x \partial v_x}{\partial x} + \frac{v_y \partial v_x}{\partial y} \right) = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2} \right) \quad (6)$$

and

$$\rho \left(\frac{v_x \partial v_y}{\partial x} + \frac{v_y \partial v_y}{\partial y} \right) = -\frac{\partial p}{\partial y} + \mu \left(\frac{\partial^2 v_y}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} \right) \quad (7)$$

The continuity and Navier-Stokes equations may be solved simultaneously to obtain the gas flow field. These equations will be converted into finite difference form and solved numerically.

The network of points needed for the conversion of the Navier-Stokes and continuity equations to finite difference form (3) are shown in Fig. 3. The object is to solve for the velocity components of v_0 in terms of the y-variation in velocity considering points v_4 and v_2 and the x-variation in velocity considering v_3 and v_1 . For instance, a first order variation in the y-component of velocity in the x-direction would be $v_{3y} - v_{1y}$, and the second order difference would be $(v_{3y} - v_{0y}) - (v_{0y} - v_{1y})$ or $(v_{3y} - 2v_{0y} + v_{1y})$. Since each point is separated from the neighboring four points by distance H , $\Delta x = \Delta y = 2H$ and $\Delta x^2 = \Delta y^2 = H^2$. Therefore, the finite difference equivalent to each derivative is:

$$\frac{\partial v_x}{\partial x} = \frac{v_{3x} - v_{1x}}{2H}$$

$$\frac{\partial^2 v_x}{\partial x^2} = \frac{v_{3x} - 2v_{0x} + v_{1x}}{H^2}$$

$$\frac{\partial v_y}{\partial x} = \frac{v_{3y} - v_{1y}}{2H}$$

$$\frac{\partial^2 v_y}{\partial x^2} = \frac{v_{3y} - 2v_{0y} + v_{1y}}{H^2}$$

$$\frac{\partial v_x}{\partial y} = \frac{v_{4x} - v_{2x}}{2H}$$

$$\frac{\partial^2 v_x}{\partial y^2} = \frac{v_{4x} - 2v_{0x} + v_{2x}}{H^2}$$

$$\frac{\partial v_y}{\partial y} = \frac{v_{4y} - v_{2y}}{2H}$$

$$\frac{\partial^2 v_y}{\partial y^2} = \frac{v_{4y} - 2v_{0y} + v_{2y}}{H^2}$$

$$\frac{\partial p}{\partial x} = \frac{p_3 - p_1}{2H}$$

$$\frac{\partial p}{\partial y} = \frac{p_4 - p_2}{2H}$$

If the appropriate terms are substituted into the continuity equation [Eq. (3)],

$$\frac{v_{3x} - v_{1x}}{2H} + \frac{v_{4y} - v_{2y}}{2H} = 0 \quad (8)$$

or

$$v_{3x} = v_{2y} + v_{1x} - v_{4y} \quad (9)$$

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FINITE DIFFERENCE METHOD NETWORK

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Similarly, the finite difference forms of the Navier-Stokes equations are:

$$\frac{v_{0x}}{2H}(v_{3x} - v_{1x}) + \frac{v_{0y}}{2H}(v_{4x} - v_{2x}) = -\frac{P_3 - P_1}{\rho 2H} + \frac{\nu}{H^2}[(v_{3x} - 2v_{0x} + v_{1x}) + (v_{4x} - 2v_{0x} + v_{2x})] \quad (10)$$

and

$$\frac{v_{0x}}{2H}(v_{3y} - v_{1y}) + \frac{v_{0y}}{2H}(v_{4y} - v_{2y}) = -\frac{P_4 - P_2}{\rho 2H} + \frac{\nu}{H^2}[(v_{3y} - 2v_{0y} + v_{1y}) + (v_{4y} - 2v_{0y} + v_{2y})] \quad (11)$$

Every term in the above equations is dependent solely upon velocity except for the pressure terms. If we assume that the kinetic energy of the gas is converted only into potential, and that viscous energy dissipation is negligible over a small increment, then

$$\Delta P = -\Delta \frac{1}{2} \rho v^2 \quad (12)$$

and therefore,

$$P_1 - P_3 = \frac{1}{2} \rho [v_{3x}^2 + v_{3y}^2 - (v_{1x}^2 + v_{1y}^2)] \quad (13)$$

$$P_2 - P_4 = \frac{1}{2} \rho [v_{4x}^2 + v_{4y}^2 - (v_{2x}^2 + v_{2y}^2)] \quad (14)$$

Inserting these expressions into the Navier-Stokes equations and normalizing all velocity components with respect to the average inlet velocity, v_{a0} , yields the normalized set of equations:

$$\bar{v}_{3x} = \bar{v}_{2y} + \bar{v}_{1x} - \bar{v}_{4y} \quad (15)$$

$$\begin{aligned} \bar{v}_{ox}(\bar{v}_{3x} - \bar{v}_{1x}) + \bar{v}_{oy}(\bar{v}_{4x} - \bar{v}_{2x}) &= \frac{1}{2}[\bar{v}_{3x}^2 + \bar{v}_{3y}^2 - (\bar{v}_{1x}^2 + \bar{v}_{1y}^2)] \\ &+ \frac{2\nu}{v_{ao}H}[(\bar{v}_{3x} - 2\bar{v}_{ox} + \bar{v}_{1x}) + (\bar{v}_{4x} - 2\bar{v}_{ox} + \bar{v}_{2x})] \quad (16) \end{aligned}$$

and

$$\begin{aligned} \bar{v}_{ox}(\bar{v}_{3y} - \bar{v}_{1y}) + \bar{v}_{oy}(\bar{v}_{4y} - \bar{v}_{2y}) &= \frac{1}{2}[\bar{v}_{4x}^2 + \bar{v}_{4y}^2 - \bar{v}_{2x}^2 - \bar{v}_{2y}^2] \\ &+ \frac{2\nu}{v_{ao}H}[(\bar{v}_{3y} - 2\bar{v}_{oy} + \bar{v}_{1y}) + (\bar{v}_{4y} - 2\bar{v}_{oy} + \bar{v}_{2y})] \quad (17) \end{aligned}$$

The two Navier-Stokes equations in finite difference form are then solved simultaneously to form explicit equations for v_{ox} and v_{oy} . These equations will be functions of the known velocity components of the four surrounding points. The continuity equation is a necessary constraint to the system needed to obtain a solution from the two Navier-Stokes equations. Therefore, the continuity equation will be solved for $\bar{v}_{3x}$ and forced into the finite difference Navier-Stokes equations which will then become:

$$\begin{aligned} \bar{v}_{oy} &= \frac{1}{(\bar{v}_{4y} - \bar{v}_{2y}) + \frac{8\nu}{v_{ao}H} + \frac{(\bar{v}_{3y} - \bar{v}_{1y})(\bar{v}_{2x} - \bar{v}_{4x})}{(\bar{v}_{2y} - \bar{v}_{4y}) + \frac{8\nu}{v_{ao}H}}} \times \\ &\left[\frac{\bar{v}_{1y} - \bar{v}_{3y}}{\bar{v}_{2y} - \bar{v}_{4y} + \frac{8\nu}{v_{ao}H}} \left[\frac{1}{2}[(\bar{v}_{2y} + \bar{v}_{1x} - \bar{v}_{4y})^2 + \bar{v}_{3y}^2 - \bar{v}_{1x}^2 - \bar{v}_{1y}^2] \right. \right. \\ &\quad \left. \left. + \frac{2\nu}{v_{ao}H}(2\bar{v}_{1x} + \bar{v}_{2x} + \bar{v}_{2y} + \bar{v}_{4x} - \bar{v}_{4y}) \right] \right. \\ &\quad \left. + \frac{1}{2}(\bar{v}_{4x}^2 + \bar{v}_{4y}^2 - \bar{v}_{2x}^2 - \bar{v}_{2y}^2) + \frac{2\nu}{v_{ao}H}(\bar{v}_{1y} + \bar{v}_{2y} + \bar{v}_{3y} + \bar{v}_{4y}) \right] \quad (18) \end{aligned}$$

$$\begin{aligned}
\bar{v}_{ox} = & \frac{1}{(\bar{v}_{2y} - \bar{v}_{4y}) + \frac{8v}{v_{ao}H} + \frac{(\bar{v}_{4x} - \bar{v}_{2x})(\bar{v}_{1y} - \bar{v}_{3y})}{\bar{v}_{4y} - \bar{v}_{2y} + \frac{8v}{v_{ao}H}}} x \\
& \left[\frac{\bar{v}_{2x} - \bar{v}_{4x}}{\bar{v}_{4y} - \bar{v}_{2y} + \frac{8v}{v_{ao}H}} \left[\frac{1}{2}(\bar{v}_{4x}^2 + \bar{v}_{4y}^2 - \bar{v}_{2x}^2 - \bar{v}_{2y}^2) \right. \right. \\
& \left. \left. + \frac{2v}{v_{ao}H}(\bar{v}_{1y} + \bar{v}_{2y} + \bar{v}_{3y} + \bar{v}_{4y}) \right] + \frac{1}{2}[(\bar{v}_{2y} + \bar{v}_{1x} - \bar{v}_{4y})^2 \right. \\
& \left. \left. + \bar{v}_{3y}^2 - \bar{v}_{1x}^2 - \bar{v}_{1y}^2] + \frac{2v}{v_{ao}H}(2\bar{v}_{1x} + \bar{v}_{2x} + \bar{v}_{2y} + \bar{v}_{4x} - \bar{v}_{4y}) \right] \quad (19)
\end{aligned}$$

(The intermediate steps of this development are given in Appendix 9.3).

The flow field between the jet and the plate may be determined by establishing a grid of equidistant points and solving the above equations for the velocities at every point in the grid. However, since each velocity at a point depends on the value of the velocities at the neighboring points, and they, in turn, depend on velocities at their neighboring points, one may either obtain an unmanageable set of simultaneous equations, or iterate from point to point on the grid. Velocities for the entire grid of points would be recalculated until every current value of velocity has converged to within a specified tolerance of the previous value.

The iteration of the finite difference equation is performed for the grid area defined in Fig. 4 which is a schematic of half of the jet plate system, bounded by the axis of symmetry. The value "S" in the diagram is an adjustable parameter which controls the grid point density and the numbers represent the relative dimensions of the experimental impactor. To complete the model of this flow system, the boundary conditions were defined as:

1. All velocities are zero at the solid boundaries.
2. The velocities are symmetric about the centerline.
3. There is an initial velocity profile in the jet orifice.
4. At a distance far from the axis of symmetry, the velocities at a point (I,J) are equal to the velocities at the point (I+1,J).
5. The velocities at a point (I,J) colinear with the line representing the plate are equal to the velocities at the point (I, J-1).

S = number of grid units for
half a slit width

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COMPUTER MODEL DIAGRAM

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After the flow field has been defined, the particle motion may be determined by solving a force balance on a particle traveling at velocity $\vec{u}$. A general force balance is given by:

$$\vec{F}_{\text{total}} = m \frac{d\vec{u}}{dt} = -f \frac{\pi \bar{u}_p}{4} \frac{1}{2\rho} (\vec{u} - \vec{v})(\vec{u} - \vec{v}) + m\vec{g} + S\nabla\bar{T} + \vec{F}_e \quad (20)$$

where the net force is equal to the sum of drag, gravitational, thermal and electrostatic forces, respectively. In this particular jet impaction dust separator, the thermal gradient and electrostatic forces are zero, and since the particles are non-settleable, the gravitational force is negligible. Since the flow of fluid around the aerosol particle is laminar, the friction factor may be assumed to be the laminar fluid friction factor, 24, divided by the Reynolds number, or can be set equal to this value with allowance made for non-laminar flow by the introduction of a correction factor C . The simplified component equations normalized in velocity and time by v_{a0} and D_c/v_{a0} , respectively, are:

$$\psi \frac{d\bar{u}_x}{d\bar{t}} = -(\bar{u}_x - \bar{v}_x) \quad (21)$$

$$\psi \frac{d\bar{u}_y}{d\bar{t}} = -(\bar{u}_y - \bar{v}_y) \quad (22)$$

where:

$$\psi = \frac{C_D \rho v_{a0} D_p^2}{18\mu D_c}$$

An equivalent set of equations in terms of particle position is:

$$\psi \frac{d^2\bar{x}}{d\bar{t}^2} + \frac{d\bar{x}}{d\bar{t}} = \bar{v}_x \quad (24)$$

$$\psi \frac{d^2\bar{y}}{d\bar{t}^2} + \frac{d\bar{y}}{d\bar{t}} = \bar{v}_y \quad (25)$$

If we now assume that over a very short interval of distance (unrelated to the grid unit), the gas velocities are constant, the particle motion equations may be solved explicitly to yield the closed form solutions.

$$\bar{u}_x = (\bar{u}_{x0} - \bar{v}_x) e^{-\bar{t}/\psi} + \bar{v}_x \quad (26)$$

$$\bar{u}_y = (\bar{u}_{y0} - \bar{v}_y) e^{-\bar{t}/\psi} + \bar{v}_y \quad (27)$$

and

$$\bar{x} = \bar{x}_0 + \psi(\bar{u}_{x0} - \bar{v}_x)(1 - e^{-\bar{t}/\psi}) + \bar{v}_x \bar{t} \quad (28)$$

$$\bar{y} = \bar{y}_0 + \psi(\bar{u}_{y0} - \bar{v}_y)(1 - e^{-\bar{t}/\psi}) + \bar{v}_y \bar{t} \quad (29)$$

where $\bar{t}$ is an adjustable time interval which can be decreased for increased accuracy. Particle paths, originating from various positions along the jet slit, may be traced by integrating the above equations. Naturally, since the particle position will not often coincide with a grid point, interpolation of the gas velocities is required. The gas velocities were obtained by a linear interpolation between the four grid points surrounding the particle position.

In summary, equations which describe gas flow and particle motion have been derived from Navier-Stokes, continuity, and particle force balance equations in conjunction with the four basic assumptions listed prior to the derivation. The computer program created to solve the system of equations is described in Appendix 9.6.

4. APPARATUS AND PROCEDURE

The apparatus for measuring the experimental collection efficiencies is shown in Fig. 5. Compressed air was available at a pressure of 20 psig and at a temperature of $78 \pm 2^\circ\text{F}$. Since the air may have carried water, oils, and dust which are potentially an uncontrollable source of nuclei, the air was directed through a drier to remove water and then through a 0.45 μ millipore filter to remove suspended particulates. The clean air was then divided into three streams, each controlled by a needle valve and monitored by a rotameter. The rotameters were calibrated with a wet test meter before starting the experimentation.

The nuclei rotameter measured the air flow rate through the nuclei generator. This flow rate influenced the concentration of the salt nuclei generated by salt sublimation. A Variac controlled the voltage supplied to the heat source for the salt sublimation. The amount of nuclei generated at a constant voltage will determine the particle size distribution. For example, if at constant temperature the concentration of nuclei is decreased, the amount of vapor available per nuclei increases so that more

liquid will condense on each nuclei thus increasing the particle size distribution. Finally, the air stream transfers the nuclei to the aerosol generator.

The mixing rotameter controls the flow rate of the stream flowing directly to the aerosol generator to mix the liquid dioctyl phthalate vapor with the nuclei in the first two-liter pyrex flask located in the oven. Increasing the flow rate of the mixing stream, everything else constant, will decrease the concentration of nuclei in the aerosol generator increasing the amount of the ester vapor available per nuclei. Again, the particle size distribution will tend to the large diameter ranges.

After establishing a 2.21 liter/min total air flow rate through the nuclei and the mixing rotameters, the temperature in the aerosol generator, which is a modified Sinclair-Lalmer generator (6), is permitted to stabilize. The temperature ranged from 67 to 120°C. The temperature was initially controlled by a bi-metallic thermostat in the oven which proved to be inadequate. A proportional temperature controller was then installed. Constant temperature is required since the amount of vapor changes with temperature influencing the particle size distribution.

The liquid vapor and the nuclei, after mixing in the first two-liter flask, are transferred to a second two-liter pyrex flask inside the oven for reheating and further mixing. Two 1.0-mm nozzles sealed at the downstream end of the glass fitting between the two-liter flasks enhance the mixing.

As the stream flows out of the second pyrex flask into the cooling column, the vapor of the ester condenses on the nuclei. The air flow rate determines the residence time of the stream in the cooling column and influences the particle size distribution. If the residence time increases, more condensate will form on the nuclei increasing the particle diameter.

The aerosol stream at the top of the cooling column is mixed with the air stream supplied through the dilution rotameter. The dilution stream is utilized if different flow velocities are desired at the same particle distribution. A different flow velocity might be desired, since the velocity of the gas will change the inertial impaction parameter of the particles and consequently the impaction efficiencies. The aerosol stream then flows through a 1-in.-ID tygon tubing to the inlet sampling tank.

From the inlet tank, the aerosol stream is directed to the perfusion-impaction collector (see Appendix 9.5 for jet dimensions). Water pumped by a syringe pump at 0.21 ml/min perfuses through a porous plate normal to the aerosol stream flow direction. The water is collected in a beaker. The aerosol stream then flows into the outlet sampling tank. The exhaust from the outlet sampling tank is vented in the hood.

A sample port is located in the top of each sampling tank. Samples of 150 cc/min are drawn from each tank by a particle counter which is able to count particles in fourteen different diameter ranges. A digital recorder

prints the number of particles counted by the particle counter for each specified diameter range.

After approximately three hours, steady state is achieved in the apparatus at a given aerosol generator temperature and total air flow rate. Steady state is assumed when the difference between consecutive readings for a particular tank is less than 10% for a particle counting period of 0.92 min. First, a count of all the diameter ranges is taken to establish the range with the largest amount of particles. Then, readings of the established range are followed in the inlet tank and the outlet tank - alternating the tanks every two readings. The experimental collection efficiency is calculated as the ratio of the means of the particle readings for both tanks.

5. RESULTS AND DISCUSSION

5.1 Experimental Approach

The experimental approach was not successful. Only one collection efficiency was obtained. The range of particles for which the collection efficiency was calculated is that from 4 to 5 μ . The means of several readings from both tanks were calculated. From these data the collection efficiency for the 4 to 5 μ range was calculated. The calculated efficiency is plotted in Fig. 6.

To determine the particle size distribution for the 2.21 liter/min flow rate, consecutive readings were taken for the first stagnation tank. The cumulative percent of distribution was calculated and plotted against the corresponding particle sizes. The distribution curves for two inlet samples representative of all other data is presented in Fig. 7.

The single collection efficiency obtained does not lead to any conclusion. However, comparing the plotted experimental collection efficiency to May's experimental curve and to Ranz and Wong's experimental curve in Fig. 6, the collection efficiency of the experimental data is greater than the results of May and Ranz and Wong for the same impaction parameter.

5.2 Theoretical Approach

The flow field equations did not converge with the techniques employed in the computer program. In fact, the equations diverged rather rapidly because of the instability of the velocity terms approximating the pressure drop. At this point one may question the pressure drop approximation of the computer technique. The validity of performing a Bernoulli balance to obtain the expression for the pressure drop terms may be questionable as the Bernoulli balance is macroscopic and in this case is applied to a microscopic balance. The computer technique of evaluating the gas velocity

--- Panz & Wong theoretical

- - - May experimental

— Panz & Wong experimental

● Experimental datum

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RESULTS OF RANZ AND HONG AND
THE EXPERIMENTAL DATUM

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FIG.
6

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INLET PARTICLE SIZE DISTRIBUTION

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components by marching consecutively from one point to the next may also be the source of some problems. Evaluating the velocity field by the method of residuals or by Liebmann's method may be necessary.

6. CONCLUSIONS

Undoubtedly, more work is necessary in both the experimental and the theoretical aspects of this problem. The experimental data point is depressing in uniqueness, but encouraging in value, though obviously there can be nothing stated conclusively based on one datum. The theoretical approach needs some work, but does not appear to be too far from completion. Again, the pressure drop approximation should be reconsidered, and possibly a different approach to solving the gas flow field finite difference equations utilized.

7. RECOMMENDATIONS

In view of the problems that have been encountered in this project, the following steps are recommended:

Theoretical:

1. Determine whether the pressure drop approximation in the flow field finite difference equations is applicable.
2. If necessary solve the finite difference equations by the method of residuals or Liebmann's method instead of consecutive marching.
3. Test the particle tracing subroutine.
4. Check convergence of the solutions to the velocity and particle motion equations by decreasing step size.
5. Perform the calculations on the IBM 360 for increased computational efficiency.

Experimental:

1. Improve the oven temperature control to obtain a more stable particle size distribution.
2. Operate at higher total gas flow rates.

8. ACKNOWLEDGMENT

The authors wish to acknowledge the invaluable assistance of R.D. Spence.

9. APPENDIX

9.1 Order of Magnitude Analysis of Navier-Stokes Equations

The length of the slit is sufficiently long to allow an assumption of two-dimensional flow in the x and y-directions. The Navier-Stokes equations (2) for incompressible Newtonian fluid are:

With the x-component:

$$\rho(v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y}) = -\frac{\partial p}{\partial x} + \mu(\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2}) + \rho g_x \quad (4)$$

With the y-component:

$$\rho(v_x \frac{\partial v_y}{\partial x} + v_y \frac{\partial v_y}{\partial y}) = -\frac{\partial p}{\partial y} + \mu(\frac{\partial^2 v_y}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2}) + \rho g_y \quad (5)$$

To show that the effect of gravity is negligible, one must show that

$$\rho v_x \frac{\partial v_x}{\partial x} \gg \rho g_x$$

or

$$\frac{g_x}{v_x \frac{\partial v_x}{\partial x}} \leq 0.1$$

Since the distance between the plate and the nozzle is 0.26 cm, and the nozzle velocity is approximately 50 cm/sec, the criteria becomes

$$\frac{980 \text{ cm/sec}^2}{(50 \text{ cm/sec})(\frac{50 \text{ cm/sec}}{0.26 \text{ cm}})} \stackrel{?}{\leq} 0.1$$

which is true.

9.2 Estimation of Gas Velocity at Nozzle Exit

Schlichting (12) has numerically solved and plotted the dimensionless velocity profile as a function of dimensionless distance for two-dimensional channel flow from the entrance to the region of fully developed flow. Since the experimental jet walls were not parallel, an approximation to an equivalent entrance region was calculated as shown in Fig. 8. The distance B' is the actual half-slit width and B is equal to 120% of actual half-slit width A . An equivalent slit width is taken as 110% of A , and the equivalent entrance length is taken as the difference between B' and A' . By geometry,

$$\begin{aligned} B' - A' &= \sqrt{R^2 - (R - B)^2} - \sqrt{R^2 - (R - A)^2} \\ &= \sqrt{(2.54)^2 - (2.54 - 0.0526)^2} - \sqrt{(2.54)^2 - (2.54 - 0.00438)^2} \\ &= 0.0446 \end{aligned}$$

$$\text{equivalent entrance length} = 0.0446 \text{ cm}$$

$$\text{equivalent half width, } a = \frac{110}{100}(0.438) = 0.0482 \text{ cm}$$

With these equivalent dimensions for the entrance region, the dimensionless group required for profile estimation from the plot developed by Schlichting can be calculated.

$$\begin{aligned} 100\left(\frac{\mu}{\rho}\right)\left(\frac{x}{A^2 v_{ao}}\right) &= \frac{(1.8 \times 10^{-4} \text{ g/cm-sec})(0.0446 \text{ cm})}{(1.2 \times 10^{-5} \text{ g/cm}^3)(0.0482 \text{ cm})^2 v_o} \\ &= 296.8 \left(\frac{1}{v_{ao}}\right) \end{aligned}$$

where v_{ao} is the average velocity at the nozzle. For any given flow rate, v_{ao} can be calculated and the velocity profile can be estimated from the results presented by Schlichting.

$$R = 2.54 \text{ cm}$$

$$x = 0.0438 \text{ cm (half slit width)}$$

$$B = (120^\circ)(A) = 0.0526 \text{ cm}$$

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ESTIMATION OF NOZZLE ENTRANCE LENGTH
TO DETERMINE VELOCITY PROFILE

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9.3 Solution of Velocity Field Finite Difference Equations

As presented in Sect. 3, the equation of continuity and x- and y-direction components of the Navier-Stokes equation may be written in finite difference form as Eqs. (15) through (17), respectively.

$$\bar{v}_{3x} = \bar{v}_{2y} + \bar{v}_{1x} - \bar{v}_{4y} \quad (15)$$

$$\begin{aligned} \bar{v}_{ox}(\bar{v}_{3x} - \bar{v}_{1x}) + \bar{v}_{oy}(\bar{v}_{4x} - \bar{v}_{2x}) &= \frac{1}{2}[\bar{v}_{3x}^2 + \bar{v}_{3y}^2 - (\bar{v}_{1x}^2 + \bar{v}_{1y}^2)] \\ &+ \frac{2\nu}{v_{ao}H}[(\bar{v}_{3x} - 2\bar{v}_{ox} + \bar{v}_{1x}) + (\bar{v}_{4x} - 2\bar{v}_{ox} + \bar{v}_{2x})] \end{aligned} \quad (16)$$

$$\begin{aligned} \bar{v}_{ox}(\bar{v}_{3y} - \bar{v}_{1y}) + \bar{v}_{oy}(\bar{v}_{4y} - \bar{v}_{2y}) &= \frac{1}{2}[\bar{v}_{4x}^2 + \bar{v}_{4y}^2 - (\bar{v}_{2x}^2 + \bar{v}_{2y}^2)] \\ &+ \frac{2\nu}{v_{ao}H}[(\bar{v}_{3y} - 2\bar{v}_{oy} + \bar{v}_{1y}) + (\bar{v}_{4y} - 2\bar{v}_{oy} + \bar{v}_{2y})] \end{aligned} \quad (17)$$

If we solve for $\bar{v}_{ox}$ in Eq. (16) and for $\bar{v}_{oy}$ in Eq. (17),

$$\begin{aligned} \bar{v}_{ox} &= \frac{1}{\bar{v}_{3x} - \bar{v}_{1x} + \frac{8\nu}{v_{ao}H}} [\bar{v}_{oy}(\bar{v}_{2x} - \bar{v}_{4x}) + \frac{1}{2}(\bar{v}_{3x}^2 + \bar{v}_{3y}^2 - \bar{v}_{1x}^2 - \bar{v}_{1y}^2) \\ &+ \frac{2\nu}{v_{ao}H}(\bar{v}_{1x} + \bar{v}_{2x} + \bar{v}_{3x} + \bar{v}_{4x})] \end{aligned} \quad (30)$$

and

$$\begin{aligned} \bar{v}_{oy} &= \frac{1}{\bar{v}_{4y} - \bar{v}_{2y} + \frac{8\nu}{v_{ao}H}} [\bar{v}_{ox}(\bar{v}_{1y} - \bar{v}_{3y}) + \frac{1}{2}(\bar{v}_{4x}^2 + \bar{v}_{4y}^2 - \bar{v}_{2x}^2 - \bar{v}_{2y}^2) \\ &+ \frac{2\nu}{v_{ao}H}(\bar{v}_{1y} + \bar{v}_{2y} + \bar{v}_{3y} + \bar{v}_{4y})] \end{aligned} \quad (31)$$

Substituting Eq. (30) into Eq. (31) and Eq. (31) into Eq. (30), one finds

$$\begin{aligned}
[(\bar{v}_{3x} - \bar{v}_{1x}) + \frac{8v}{v_{ao}H}] \bar{v}_{ox} &= (\bar{v}_{2x} - \bar{v}_{4x}) \frac{1}{\bar{v}_{4y} - \bar{v}_{2y} + \frac{8v}{v_{ao}H}} [\bar{v}_{ox}(\bar{v}_{1y} - \bar{v}_{3y}) \\
&+ \frac{1}{2}(\bar{v}_{4x}^2 + \bar{v}_{4y}^2 - \bar{v}_{2x}^2 - \bar{v}_{2y}^2) + \frac{2v}{v_{ao}H}(\bar{v}_{1y} + \bar{v}_{2y} + \bar{v}_{3y} + \bar{v}_{4y})] \\
&+ \frac{1}{2}(\bar{v}_{3x}^2 + \bar{v}_{3y}^2 - \bar{v}_{1x}^2 - \bar{v}_{1y}^2) + \frac{2v}{v_{ao}H}(\bar{v}_{1x} + \bar{v}_{2x} + \bar{v}_{3x} + \bar{v}_{4x}) \quad (32)
\end{aligned}$$

and

$$\begin{aligned}
[(\bar{v}_{4y} - \bar{v}_{2y}) + \frac{8v}{v_{ao}H}] \bar{v}_{oy} &= (\bar{v}_{1y} - \bar{v}_{3y}) \frac{1}{\bar{v}_{3x} - \bar{v}_{1x} + \frac{8v}{v_{ao}H}} [\bar{v}_{oy}(\bar{v}_{2x} - \bar{v}_{4x}) \\
&+ \frac{1}{2}(\bar{v}_{3x}^2 + \bar{v}_{3y}^2 - \bar{v}_{1x}^2 - \bar{v}_{1y}^2) + \frac{2v}{v_{ao}H}(\bar{v}_{1x} + \bar{v}_{2x} + \bar{v}_{3x} + \bar{v}_{4x})] \\
&+ \frac{1}{2}(\bar{v}_{4x}^2 + \bar{v}_{4y}^2 - \bar{v}_{2x}^2 - \bar{v}_{2y}^2) + \frac{2v}{v_{ao}H}(\bar{v}_{1y} + \bar{v}_{2y} + \bar{v}_{3y} + \bar{v}_{4y}) \quad (33)
\end{aligned}$$

if v_{ox} and v_{oy} are solved,

$$\begin{aligned}
\bar{v}_{ox} &= \frac{1}{(\bar{v}_{3x} - \bar{v}_{1x}) + \frac{8v}{v_{ao}H} + \frac{(\bar{v}_{4x} - \bar{v}_{2x})(\bar{v}_{1y} - \bar{v}_{3y})}{\bar{v}_{4y} - \bar{v}_{2y} + \frac{8v}{v_{ao}H}}} \times \\
&\left[\frac{\bar{v}_{2x} - \bar{v}_{4x}}{\bar{v}_{4y} - \bar{v}_{2y} + \frac{8v}{v_{ao}H}} \left[\frac{1}{2}(\bar{v}_{4x}^2 + \bar{v}_{4y}^2 - \bar{v}_{2x}^2 - \bar{v}_{2y}^2) + \frac{2v}{v_{ao}H}(\bar{v}_{1y} + \bar{v}_{2y} + \bar{v}_{3y} + \bar{v}_{4y}) \right] \right. \\
&\left. + \frac{1}{2}(\bar{v}_{3x}^2 + \bar{v}_{3y}^2 - \bar{v}_{1x}^2 - \bar{v}_{1y}^2) + \frac{2v}{v_{ao}H}(\bar{v}_{1x} + \bar{v}_{2x} + \bar{v}_{3x} + \bar{v}_{4x}) \right] \quad (34)
\end{aligned}$$

and

$$\bar{v}_{oy} = \frac{1}{\bar{v}_{4y} - \bar{v}_{2y} + \frac{8v}{v_{ao}H} + \frac{(\bar{v}_{3y} - \bar{v}_{1y})(\bar{v}_{2x} - \bar{v}_{4x})}{\bar{v}_{3x} \bar{v}_{1x} + \frac{8v}{v_{ao}H}}}$$

$$\left[\frac{\bar{v}_{1y} - \bar{v}_{3y}}{\bar{v}_{3x} - \bar{v}_{1x} + \frac{8v}{v_{ao}H}} \left[\frac{1}{2}(\bar{v}_{3x}^2 + \bar{v}_{3y}^2 - \bar{v}_{1x}^2 - \bar{v}_{1y}^2) + \frac{2v}{v_{ao}H}(\bar{v}_{1x} + \bar{v}_{2x} + \bar{v}_{3x} + \bar{v}_{4x}) \right] \right.$$

$$\left. + \frac{1}{2}(\bar{v}_{4x}^2 + \bar{v}_{4y}^2 - \bar{v}_{2x}^2 - \bar{v}_{2y}^2) + \frac{2v}{v_{ao}H}(\bar{v}_{1y} + \bar{v}_{2y} + \bar{v}_{3y} + \bar{v}_{4y}) \right] \quad (35)$$

The continuity equation is a constraint which must be met. Therefore it will be forced into the two equations:

$$\bar{v}_{oy} = \frac{1}{\bar{v}_{4y} - \bar{v}_{2y} + \frac{8v}{v_{ao}H} + \frac{(\bar{v}_{3y} - \bar{v}_{1y})(\bar{v}_{2x} - \bar{v}_{4x})}{\bar{v}_{2y} - \bar{v}_{4y} + \frac{8v}{v_{ao}H}}} \left[\frac{\bar{v}_{1y} - \bar{v}_{3y}}{\bar{v}_{2y} - \bar{v}_{4y} + \frac{8v}{v_{ao}H}} \right.$$

$$\left[\frac{1}{2}[(\bar{v}_{2y} + \bar{v}_{1x} - \bar{v}_{4y})^2 + \bar{v}_{3y}^2 - \bar{v}_{1x}^2 - \bar{v}_{1y}^2] + \frac{2v}{v_{ao}H}(2\bar{v}_{1x} + \bar{v}_{2x} + \bar{v}_{2y} + \bar{v}_{4x} - \bar{v}_{4y}) \right]$$

$$\left. + \frac{1}{2}(\bar{v}_{4x}^2 + \bar{v}_{4y}^2 - \bar{v}_{2x}^2 - \bar{v}_{2y}^2) + \frac{2v}{v_{ao}H}(\bar{v}_{1y} + \bar{v}_{2y} + \bar{v}_{3y} + \bar{v}_{4y}) \right] \quad (36)$$

and

$$\bar{v}_{ox} = \frac{1}{(\bar{v}_{2y} - \bar{v}_{4y}) + \frac{8v}{v_{ao}H} + \frac{(\bar{v}_{4x} - \bar{v}_{2x})(\bar{v}_{1y} - \bar{v}_{3y})}{\bar{v}_{4y} - \bar{v}_{2y} + \frac{8v}{v_{ao}H}}} \left[\frac{\bar{v}_{2x} - \bar{v}_{4x}}{\bar{v}_{4y} - \bar{v}_{2y} + \frac{8v}{v_{ao}H}} \right. \times$$

$$\left[\frac{1}{2}(\bar{v}_{4x}^2 + \bar{v}_{4y}^2 - \bar{v}_{2x}^2 - \bar{v}_{2y}^2) + \frac{2v}{v_{ao}H}(\bar{v}_{1y} + \bar{v}_{2y} + \bar{v}_{3y} + \bar{v}_{4y}) \right]$$

$$\left. + \frac{1}{2}[(\bar{v}_{2y} + \bar{v}_{1x} - \bar{v}_{4y})^2 + \bar{v}_{3y}^2 - \bar{v}_{1x}^2 - \bar{v}_{1y}^2] + \frac{2v}{v_{ao}H}(2\bar{v}_{1x} + \bar{v}_{2x} + \bar{v}_{2y} + \bar{v}_{4x} - \bar{v}_{4y}) \right] \quad (37)$$

9.4 Computer Program

9.4.1 Description

The computer program performs one of three operations depending on the value of METH in the subprogram. If METH is equal to 1, subroutine ZERO is first called to zero the gas velocity field array. Then subroutine PROFIL is called to establish a velocity field at the nozzle exit grid points. This is accomplished by a linear interpolation between the ten data points defined in the data statement. These points were obtained by the method described in Appendix 9.2. After the nozzle exit velocity profile is established, the rest of the flow field is estimated in subroutine INITL. In this subroutine the field is initialized to the values assumed by Ranz and Wong, except that instead of setting the field between the jet opening and one-half slit-width away from the plate equal to one, the field is set equal to the velocity profile at the nozzle exit.

With an initial field now established, a point by point velocity calculation ensues. The main subprogram determines which point is to be chosen for evaluation by marching point by point in the y-direction and moving one unit in the x-direction when a boundary is contacted. At each point subroutine VELCON is called which performs the velocity calculation, and stores the worst deviation between a current and a previous value of the velocities in the entire grid. At the end of each set of grid iterations, this worst deviation is compared with a relative and absolute tolerance to determine whether convergence has been accomplished. If convergence has not been accomplished and the allowable number of iterations has not been exceeded, the grid iteration continues. If convergence is not accomplished within the allowed number of iterations, a partial list of velocities and coordinates is typed. (This option is also available if convergence is accomplished.) In any event, the velocity field is written onto a data file and the particle tracing subroutine, PRTCL, is called.

Subroutine PRTCL traces the path of particles originating from grid points located at the nozzle exit to the impaction surface. The iteration consists of evaluating the explicit equations for particle position and velocity over the dimensionless time interval DELT. At the end of each time interval, the gas velocity at the new particle position is evaluated by a linear interpolation between the four surrounding grid points. Iteration is continued until the particle is beyond the x-coordinate corresponding to the end of the plate, or the particle is within one half particle diameter of the wall (at which point it is presumed to be impacted and collected), or the velocity of the particle in the y-direction is "zero."

Points of origination are picked at an increasing number of grid units away from the jet centerline until a particle misses the plate. Then the golden section technique is employed between the last two points of origin to narrow the region from which the last particle impacts the plate. The golden section continues until the difference between the points of origin

between missed and impacted particles is within a specified tolerance. The collection efficiency is then calculated by dividing the x-coordinate of the last particle to hit the plate by the x-coordinate corresponding to half the slit-width. This entire particle tracing procedure may be performed for any particle diameter or range of particle diameters as specified in the data statement in this subroutine, and MINDP and MAXDP in the main subprogram. This completes the operations performed if the value of METH in the main subprogram is one.

If the value of METH in the main subprogram is two, the ZERO, PROFIL, and INITL subroutines are skipped, and a previously obtained array is further converged before particle tracing. If the value of METH is three, the previously obtained array is read and only particles are traced.

9.4.2 Variable Definition

DELT	time increment for integration of the particle motion equation
H	parameter relating half slit-width in cm to number of grid units (float, common), cm/grid unit
I	dummy variable indexing positive x-direction (integer), grid units
II	overall size of grid in x-direction (integer, common), grid units
IIII	array of seven x-coordinates for velocity field printout (integer), grid unit
II01	overall size of grid in x-direction minus one (integer), grid units
IPRINT	print switch for sample velocity field printout, =1 for printout, =2 for no printout
ISTORE	index specifying data file storage number (integer)
ISW	convergence switch, =1 if not all of the velocity components have converged, =2 if all of the velocity components have converged.
ISWL	=1 at the start of the velocity field calculation, =2 for convergence testing, =3 for normal operations
J	dummy variable indexing y-direction, grid units
JJ	overall size of grid in y or jet centerline direction (integer, common), grid unit
J1	dummy variable indexing y-direction from jet face, grid units
JJ1	y-coordinate for velocity field printout (integer), grid unit
LI	dummy i

LJ dummy J
 LJ1 dummy J1
 M iteration number
 MAXIT maximum allowable number of iterations
 MAXDP index for array "DRANGE" corresponding to the last particle diameter to be considered in subroutine PRTCL
 METH =1 if all calculations are to be performed, =2 if a stored velocity field is to be converged further before particle calculations, =3 if a stored velocity field is to be used only for particle calculations
 MINDP index for array "DRANGE" corresponding to the first particle diameter to be considered in the subroutine PRTCL
 MX initial of seven consecutive x-values for velocity field printout
 P half plate width, grid units
 P1 half plate width plus one, grid units
 S half slit width, grid units
 S1 half slit width plus one, grid units
 SP slit to plate distance, grid units
 SP1 slit to plate distance plus one, grid units
 S3 three times half slit width, grid units
 S31 three times the half slit width plus 1, grid units
 S32 three times the half slit width plus 2, grid units
 S41 four times the half slit width plus 1, grid units
 V velocity field array, 1st dimension = x-coordinate of grid point, 2nd dimension = y-coordinate of grid point, 3rd dimension = velocity component (=1 for x-component, =2 for y-component)
 VAO average jet exit speed, positive, cm/sec

Subroutine PROFIL

S1 half slit width plus one, grid units
 VELN velocity profile at jet outlet, grid units

VO dummy interpolated velocity
 X x-coordinate, grid units
 XS x-coordinates for VELN, grid units

Subroutine VELCON

A components of the y-velocity component calculation
 B components of the x-velocity component calculation
 CON storage of largest fractional difference between old and new velocity
 C1 convergence calculation for x-component of velocity
 C2 convergence calculation for y-component of velocity
 NU value of viscosity/density, g/cm-sec/g/cm^3
 VOX dummy x-component of velocity
 VOY dummy y-component of velocity

Subroutine PRTCL

DIAM particle diameter
 DRANGE array of particle diameters to be considered, microns
 DX1,DX2 difference between the particle and grid point x-coordinates for linear interpolation of gas velocity, grid units
 DY1,DY2 difference between the particle and grid point y-coordinates for linear interpolation of gas velocity, grid units
 IDIAM index of array DRANGE
 IP x-coordinate of grid point corresponding to particle origination from the slit, grid units
 PSI value of the impaction parameter, ϕ
 UX0 previous value of the x-component of particle velocity
 UX1 current value of the x-component of particle velocity
 UY0 previous value of the y-component of particle velocity
 UY1 current value of the y-component of particle velocity

VXY(1) interpolated value of the x-component of gas velocity at the particle position

VXY(2) interpolated value of the y-component of gas velocity at the particle position

X x-coordinate of particle position, grid units

X1 previous x-coordinate of particle position, grid units

X00,X01 interpolated values of the x-coordinate of grid points corresponding to particle originations from the slit, grid units

Y y-coordinate of particle position, grid units

Y1 previous value of y-coordinate of particle position, grid units

A listing of the computer program follows:

```

INTEGER SP, SPI, S, P, S31, S3, S32, S41, P1
DIMENSION I111(7)
COMMON /C(102,26,2), I1, JJ, SPI, SP, S, P, S41, VA0, H, ISV, ISV1
VA0=165.
MINDP=9
MAXDP=14
S=10
ISTOPE=10
METH=1
MAXIT=200
DELT=1./(6.*S)
H=0.04332/S
IPRINT=1
I1=10*S+2
JJ=9.5*S+1
P=6.7*S
P1=P+1
ISV1=1
ISV=1
S3=3*S
S31=3*S+1
S32=3*S+2
S41=4*S+1
I101=I1-1
SP=6*S
SPI=6*S+1
GO TO (1,2,2), METH
2 READ (ISTOPE,200) M,"
GO TO (100,100,3), METH
1 CALL ZEP0
CALL PROFIL
CALL INITL
M=0

```

```

100  DO 7 I=2, S41
      TYPE 5000, I
6000  FORMAT(I10)
      DO 5 J=3, SP
        LI=I
        LJ=J
        CALL "ELCON(LI, LJ)
        IF (I-3) 5, 10, 5
10      "(1, J, 2)="(3, J, 2)
        "(1, J, 1)=-"(3, J, 1)
5      CONTINUE
7      CONTINUE
      DO 16 I=S41, I101
        J=1
13      J1=SP1+(I-S41)*.577-J
        LI=I
        LJ1=J1
        CALL "ELCON(LI, LJ1)
        IF (I-PI) 4, 4, 6
4      IF (J1-3) 16, 16, 17
6      IF (I-I101) 11, 12, 11
12      "(11, J1, 1)="(1101, J1, 1)
        "(11, J1, 2)="(1101, J1, 2)
11      IF (J1-2) 17, 15, 17
15      "(1, 1, 1)="(1, 2, 1)
        "(1, 1, 2)="(1, 2, 2)
        GO TO 16
17      J=J+1
        GO TO 13
16      CONTINUE
        M=M+1
        IF (M-MAXIT) 998, 999, 999
993      ISM=2
        GO TO (100, 1000), ISM
999      TYPE 105, M
105      FORMAT (' CONVERGENCE NOT ACCOMPLISHED AFTER ', I4,
        ' ITERATIONS.')
        GO TO 2000
1000     TYPE 106, M
106      FORMAT (' CONVERGENCE ACCOMPLISHED AFTER ', I4,
        ' ITERATIONS.')
        GO TO (2000, 2000), IPRINT
2000     M=1
        TYPE 101
101      FORMAT (////)
        DO 20 MY=1, SP1
          TYPE 102
102      FORMAT (/)
          JJJ1=SP1-MY+1
          DO 21 IP=1, 7
            III1(IP)=MY+IP

```

```

21  CONTINUE
    TYPE 103, IIII(1),JJJ1,IIII(2),JJJ1,IIII(3),JJJ1,
!IIII(4),JJJ1,IIII(5),JJJ1,IIII(6),JJJ1,IIII(7),JJJ1
103  FORMAT (7(IX,13,' ',13,'* '))
    TYPE 104, '(K+L,JJJ1,1),L=1,7)
    TYPE 104, '(K+L,JJJ1,2),L=1,7)
104  FORMAT (7(IX,F7.3,2X))
20  CONTINUE
3000 OPEN (UNIT=1,STORE,ACCESS='APPEND')
    WRITE (10,200) 4,"
200  FORMAT (15,(F3.4))
3  CALL PRICL(DELT,MINDP,MAXDP)
    CALL EXIT
    END
    SWEPOUTLINE ZERO
    COMMON /C(102,96,2),11,JJ,SP1,SP,S,P,SA1,"A0,H,ISV,ISV1
    DO 1 I=1,11
    DO 2 J=1,JJ
    DO 3 K=1,2
    /C(1,J,K)=0.0
3  CONTINUE
2  CONTINUE
1  CONTINUE
    RETURN
    END

    SWEPOUTLINE PROFIL
    INTEGER SI,S,SP1
    DIMENSION XS(10),"FLN(10)
    COMMON /C(102,96,2),11,JJ,SP1,SP,S,P,SA1,"A0,H,ISV,ISV1
    DATA (XS(K),K=1,10),( "FLN(K),K=1,10)/0.0,0.35,0.4,0.51,0.6
!0.65,0.63,0.73,0.34,1.0,1.25,1.25,1.24,1.2,1.13,1.07,
!1.0,0.9,0.6,0.0/
    SI=S+1
    DO 1 I=1,SI
    X=(1-I.)/5
    DO 2 J=1,10
    IF (X-XS(J)) 4,3,2
3  /O="FLN(J)
    GO TO 5
2  CONTINUE
4  /O="(FLN(J)-FLN(J-1))*(X-XS(J-1))/(XS(J)-XS(J-1))+
!FLN(J-1)
5  /C(I+1,SP1,2)="/O
1  CONTINUE
    /C(1,SP1,2)="/C(3,SP1,2)
    RETURN
    END

```

```

SUBROUTINE INITL
  INTEGER S, SI, SPI, SP
  COMMON /C(102, 26, 2), I1, JJ, SPI, SP, S, P, S41, /A0, B, I SW, I SWI
  SI = S + 1
  DO 2 I = 1, SI
    DO 1 J = 3, SP
      IF (J - SI) 3, 3, 4
3     W(1, J, 1) = (I - 2.) / S
      W(1, J, 2) = (J - 2.) * W(1, SPI, 2) / S
      GO TO 1
4     W(1, J, 2) = W(1, SPI, 2)
1     CONTINUE
2     CONTINUE
    DO 7 I = SI, I1
      DO 6 J = 3, SI
        W(1, J, 1) = 1.
6       CONTINUE
7       CONTINUE
      RETURN
    END

```

```

SUBROUTINE WELCON(I, J)
  REAL W
  DIMENSION A(3), B(3)
  COMMON /C(102, 26, 2), I1, JJ, SPI, SP, S, P, S41, /A0, B, I SW, I SWI
  J1 = J + 1
  J01 = J - 1
  I1 = I + 1
  I01 = I - 1
  W = 0.1546
  A(1) = W(1, J1, 2) - W(1, J01, 2)
  A(2) = 3. * W / (H * A0)
  A(3) = (W(1, J01, 1) - W(1, J1, 1)) * (W(11, J, 2) - W(101, J, 2)) /
    (3. * W / (H * A0) + W(1, J01, 2) - W(1, J1, 2))
  A(4) = (W(101, J, 2) - W(11, J, 2)) / (3. * W / (A0 * H) + (W(1, J01, 2)
    - W(1, J1, 2)))
  A(5) = 1. / 2. * ((W(1, J01, 2) + W(101, J, 1) - W(1, J1, 2)) ** 2. +
    W(11, J, 2) ** 2. - (W(101, J, 1) ** 2. + W(101, J, 2) ** 2.))
  A(6) = 3. * W / (A0 * H) * (-W(1, J1, 2) + W(1, J01, 2) + 2. * W(101, J, 1) +
    W(1, J1, 1) + W(1, J01, 1))
  A(7) = 1. / 2. * (W(1, J1, 1) ** 2. + W(1, J1, 2) ** 2. - W(1, J01, 1) ** 2. -
    W(1, J01, 2) ** 2.)
  A(8) = 2 * W / (H * A0) * (W(11, J, 2) + W(101, J, 2) + W(1, J1, 2) +
    W(1, J01, 2))
  W07 = 1. / (A(1) + A(2) + A(3)) * (A(4) * (A(5) + A(6)) + A(7) + A(8))
  B(1) = -A(1)
  B(2) = A(2)
  B(3) = (W(1, J1, 1) - W(1, J01, 1)) * (W(101, J, 2) - W(11, J, 2)) /
    (3. * W / (H * A0) + W(1, J1, 2) - W(1, J01, 2))
  B(4) = (W(1, J01, 1) - W(1, J1, 1)) / (3. * W / (A0 * H) +
    W(1, J1, 2) - W(1, J01, 2))

```

```

      R(5)=A(7)
      R(6)=A(3)
      R(7)=A(5)
      R(8)=A(6)
      "0X=1./(R(1)+R(2)+R(3))*(R(4)*(R(5)+R(6))+R(7)+R(8))
      C1=ABS(" (1, J, 1) - "0X)/(ABS("0X)+1.E-07)
      C2=ABS(" (1, J, 2) - "0Y)/(ABS("0Y)+1.E-03)
      GO TO (2, 10, 10), ISV1
10    IF (CON-C1) 6, 6, 7
6     CON=C1
7     IF (CON-C2) 8, 9, 9
8     CON=C2
9     " (1, J, 1) = "0X
      " (1, J, 2) = "0Y
      GO TO (5, 2, 3), ISV1
2     IF (CON-1.E-01) 4, 5, 5
4     ISV=2
5     CON=0.
      ISV1=3
3     RETURN
      END

```

```

SUBROUTINE INITL
  INTEGER S, S1, SPI, SP
  COMMON " (102, 96, 2), 11, JJ, SPI, SP, S, P, S41, VA0, H, ISV, ISV1
  S1=S+1
  DO 2 I=1, S1
  DO 1 J=3, SP
  IF (J-S1) 3, 3, 4
3    " (1, J, 1) = (I-2.)/S
    " (1, J, 2) = (J-2.)*" (1, SPI, 2)/S
    GO TO 1
4    " (1, J, 2) = " (1, SPI, 2)
1    CONTINUE
2    CONTINUE
  DO 7 I=S1, 11
  DO 6 J=3, S1
    " (1, J, 1) = 1.
4    CONTINUE
7    CONTINUE
  RETURN
  END

SUBROUTINE PETCL(DELTA, MINDP, MAXDP)
  INTEGER SPI, SP, S, S41, S1, P
  DIMENSION "KY(2), DRANGE(14)
  COMMON " (102, 96, 2), 11, JJ, SPI, SP, S, P, S41, VA0, H, ISV, ISV1
  DATA (DRANGE(K), K=1, 14) / .36, .45, .57, .72, .9, 1.15, 1.45,
    1.8, 2.25, 2.85, 3.6, 4.5, 5.7, 7.2 /
  S1=S+1
  DO 1 IDIAM=MINDP, MAXDP
  DIAM=DRANGE(IDIAM)
  PSI=3400.*(1.0+0.16/DIAM)*VA0*(DIAM*1.E-04)**2.

```



```

DO 2 IP=3, 51
  WY1=W(IP, SP1, 2)
  WX1=0.
  XI=IP
  YI=SP1
  X=XI
  Y=YI
  PI=P+1
  WY0=WY1
  WXY(1)=0.
  WXY(2)=W(IP, SP1, 2)
3  IF (X-PI) 4, 1000, 1000
4  IF (Y-(0.5*1.E-04*DIAM/H+2.)) 2, 2, 5
5  IF (ABS(WY0)-0.00001) 1000, 6, 6
6  X=XI+2.*PSI*(WX1-WXY(1))*(1.-EXP(-DEL T/(2.*PSI)))+WXY(1)*
!DEL T
  Y=YI+2.*PSI*(WY1-WXY(2))*(1.-EXP(-DEL T/(2.*PSI)))+WXY(2)
!*DEL T
  XI=X
  YI=Y
  WX0=WX1
  WY0=WY1
  WX1=(WX0-WXY(1))*EXP(-DEL T/(2.*PSI))+WXY(1)
  WY1=(WY0-WXY(2))*EXP(-DEL T/(2.*PSI))+WXY(2)
  MX1=X
  MX2=MX1+1
  XI1=MX1
  XI2=MX2
  MY1=Y
  MY2=MY1+1
  YI1=MY1
  YI2=MY2
  DX1=X-XI1
  DX2=XI2-X
  DY1=Y-YI1
  DY2=YI2-Y
  DO 7 M=1, 2
    WXY(M)=((DX2*W(MX1, MY1, M)+DX1*W(MX2, MY1, M))*DY2
!+(DY2*W(MX1, MY1, M)+DY1*W(MX1, MY2, M))*DX2+
!(DX2*W(MX1, MY2, M)+DX1*W(MX2, MY2, M))*DY1+
!(DY2*W(MX2, MY1, M)+DY1*W(MX2, MY2, M))*DX1)/2.
7  CONTINUE
  GO TO 3
2  CONTINUE
1000 EFFCN7=(IP-3.)/5*100
  TYPE 101, DIAM, VAO, EFFCN7
101  FORMAT (/, ' THE COLLECTION EFFICIENCY OF THIS IMPACTION ',
! ' DEVICE, FOR PARTICLES OF ', /, I4.2, ' MICRONS ',
! ' DIAMETER, TRAVELING IN A JET OF AVERAGE OUTLET VELOCITY ',
! ' F4.1, ' CM/SEC, IS ', /, F5.1, ' PER CENT.', /)
1  CONTINUE
  RETURN
  END

```

```

SUBROUTINE PRTCL(DEL T,MINDP,MAXDP)
INTEGER SP1,SP,S,S41,S1,P
DIMENSION WXY(2),DRANGE(14)
COMMON W(102,96,2),II,JJ,SP1,SP,S,P,S41,VA0,H,IS4,ISW1
DATA (DRANGE(K),K=1,14)/.36,.45,.57,.72,.9,1.15,1.45,
!1.3,2.25,2.35,3.6,4.5,5.7,7.2/
S1=S+1
P1=P+1
DO 1 IDIAM=MINDP,MAXDP
DIA1=DRANGE(IDIAM)
PSI=3400.*(1.0+0.16/DIA1)*VA0*(DIA1*1.E-04)**2.
DO 2 IP=3,S1
X=IP
X01=IP
X00=IP-1.
WXY(2)=W(IP,SP1,2)
8 Y=SP1
W1=WXY(2)
WX1=0.
X1=X
Y1=Y
WY0=WY1
WXY(1)=0.
3 IF (X-P1) 4,1000,1000
4 IF (Y-(0.5*1.E-04*DIA1/H+2.)) 2,2,5
5 IF (ABS(WY0)-0.00001) 1000,6,6
6 X=X1+2.*PSI*(WX1-WXY(1))*(1.-EXP(-DEL T/(2.*PSI)))+WXY(1)*
!DEL T
Y=Y1+2.*PSI*(WY1-WXY(2))*(1.-EXP(-DEL T/(2.*PSI)))+WXY(2)
!*DEL T
X1=X
Y1=Y
WX0=WX1
WY0=WY1
WX1=(WX0-WXY(1))*EXP(-DEL T/(2.*PSI))+WXY(1)
WY1=(WY0-WXY(2))*EXP(-DEL T/(2.*PSI))+WXY(2)
MX1=X
MX2=MX1+1
XI1=MX1
XI2=MX2
MY1=Y
MY2=MY1+1
YI1=MY1
YI2=MY2
DX1=X-XI1
DX2=XI2-X
DY1=Y-YI1
DY2=YI2-Y
DO 7 M=1,2
WXY(M)=((DX2*W(MX1,MY1,M)+DX1*W(MX2,MY1,M))*DY2
!+(DY2*W(MX1,MY1,M)+DY1*W(MX1,MY2,M))*DX2+
!(DX2*W(MX1,MY2,M)+DX1*W(MX2,MY2,M))*DY1+
!(DY2*W(MX2,MY1,M)+DY1*W(MX2,MY2,M))*DX1)/2.

```

```

7      CONTINUE
      GO TO 3
2      CONTINUE
      IF (X01-S1) 11,12,12
12     EFFCNY=100.
      GO TO 3000
11     X00=X
      GO TO 9
1000   IP=S1
      X01=X
9      X=X00+(SQRT(S.)-1.)*(X10-X00)/2.
      IF (ABS(X00-X01)-0.05) 2000,2000,10
10     MX1=X
      XI1=MX1
      MX2=MX1+1
      XI2=MX2
      DX1=X-XI1
      DX2=XI2-X
      WXY(2)=DX2*(MX1,SP1,2)+DX1*(MX2,SP1,2)
      GO TO 8
2000   EFFCNY=((X01+X00)/2.-2.)/S*100
3000   TYPE 101, DIAM,VAO,EFFCNY
101    FORMAT (/, ' THE COLLECTION EFFICIENCY OF THIS IMPACTION ',
! 'DEVICE, FOR PARTICLES OF ',/,IX,F4.2,' MICRONS ',
! 'DIAMETER, TRAVELING IN A JET OF AVERAGE OUTLET VELOCITY ',
! 'F4.0,' CM/SEC, IS ',F5.1,' PER CENT.',/)
1      CONTINUE
      RETURN
      END

```

9.5 Experimental Jet Dimensions

The dimensions of the jet used in the experimental work are given in Fig. 9.

9.6 Location of Data

The original data are located in ORNL Databook A-7218-G, pp. 44-94. The databook and calculations are on file at the MIT School of Chemical Engineering Practice, Bldg. 3001, ORNL.

9.7 Nomenclature

A,A',B,B' distances employed to calculate equivalent slit width, cm

c correction factor for aerosol friction factors in non-laminar flow

A = 0.0876 cm

B = 0.3597 cm

C = 1.270 cm

D = 1.178 cm

E = 2.54 cm

$\alpha = 30^\circ$

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SCHOOL OF CHEMICAL ENGINEERING PRACTICE
AT
OAK RIDGE NATIONAL LABORATORY

EXPERIMENTAL JET DIMENSIONS

DATE 9-24-75	DRAWN BY FG	FILE NO. CEPS-X-215	FIG. 9
-----------------	----------------	------------------------	-----------

D_c	jet slit width, cm
D_p	aerosol particle diameter, cm
F	force, dynes
g	acceleration due to gravity, cm/sec^2
H	node spacing in finite difference equations, cm
m	aerosol particle mass, g
P	pressure
R	radius of curvature, cm
T	temperature, $^{\circ}\text{K}$
t	time
$\bar{t}$	dimensionless time variable, $v_{ao}t/D_c$
u	aerosol particle velocity
$\bar{u}$	dimensionless aerosol particle velocity, u/v_{ao}
v	gas velocity
$\bar{v}$	dimensionless gas velocity, v/v_{ao}
v_{ao}	average gas velocity at the nozzle mouth
x	position coordinate
$\bar{x}$	dimensionless position coordinate, x/D_c
y	position coordinate
$\bar{y}$	dimensionless position coordinate, y/D_c
ρ	gas density
ρ_p	aerosol particle density
μ	gas viscosity
η	efficiency of impaction
ψ	inertial impaction parameter, $C_D v_{ao} D_p^2 / 18 \mu D_c$

9.8 Literature References

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