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THE DISTRIBUTION OF AEROSOL PARTICLES DOWNSTREAM IN A TURBULENT FLUID JET (U)

by

Kathy I. Leary* and Stanley B. Mellsen

PCN No. 13E10

December 1982

* Chemistry Section Research Assistant, Summer 1982

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ABSTRACT

A mathematical model has been developed to predict the downstream distribution of particles in a fluid jet. The particles were initially assumed to be evenly dispersed over a cross-section of the circular jet, near the source of the jet, and, with computer-aided methods, the co-ordinates of the particles at a specified distance downstream were determined. The computer program was also built in such a manner that the paths of specific particles, from their initial upstream position to their final position downstream, could be completely followed. Some graphical results of these paths are presented for various particle sizes.

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NOTATION

$b_{1/2}$	half the width of a circular jet at half depth, cm
d	particle diameter, cm
D	jet diameter where particles are initially positioned in flow stream, cm
k	kinematic momentum of circular jet, $k = 2\pi\int_0^\infty u^2 y\,dy$
L	jet radius where particles are initially positioned in flow stream, cm
t	time, seconds
u	local fluid velocity, cm s^{-1}
u_x	axial component of fluid velocity, cm s^{-1}
u_y	radial component of fluid velocity, cm s^{-1}
U	center-line velocity of fluid at any distance downstream, cm s^{-1}
U_0	center-line fluid velocity at x_0, cm s^{-1}
x_0	axial distance from point source of jet where particles are initially positioned in flow stream, cm
x	co-ordinate of particle position parallel to center-line flow direction; axial co-ordinate, cm
y	co-ordinate of particle position perpendicular to center-line flow direction; radial co-ordinate, cm
σ	particle density, g cm^{-3}
μ	absolute viscosity of fluid, poise
ϱ	fluid density, g cm^{-3}
ε_0	virtual kinematic viscosity of turbulent flow, poise

The following are dimensionless:

C_D	drag coefficient for spheres
K	particle inertia parameter
Re	spherical particle slip Reynolds number
Re_0	spherical particle Reynolds number in free stream

NOTATION (Cont'd)

T	time tU/L
$\bar{u}_x$	axial component of fluid velocity u_x/U_0
$\bar{u}_y$	radial component of fluid velocity u_y/U_0
$\bar{v}_x$	$d\bar{x}/dT$, parallel component of particle velocity
$\bar{v}_y$	$d\bar{y}/dT$, transverse component of particle velocity
η	parameter used in calculation of fluid velocity
ϕ	parameter formed by combining Re_0 and K

LIST OF FIGURES

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DEFENCE RESEARCH ESTABLISHMENT SUFFIELD
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INTRODUCTION

Previous studies have been made (Mellsen, 1978 and 1979) involving streams of suspended particulates in such a way that impaction forces of airborne particles and collection efficiencies of specific samplers could be determined. The flow considered in the present study is of this same type; that is, it involves a fluid flow with suspended particles moving along with the flow. As a result, the same mathematical equations as were previously used may be used here to describe the motion of the particles in the fluid. In doing so, the velocity, as well as the position of each particle at any distance downstream can be determined.

The specific flow which is to be studied here is that of a turbulent circular jet with particles suspended across a cross-section of the jet. By developing a mathematical model, the radial and axial co-ordinates of the particles at a specific downstream distance will be determined, thus the actual particle distribution will be known. Also, the model is to be devised in such a fashion that the paths of particular particles may be completely followed from their initial upstream position to their final downstream position.

The information as revealed by this model will prove to be of some value from the chemical defence point of view in that it is of interest to know how particulate agents, i.e., irritants, such as CS and CR disperse in a flow field such as that described by a circular jet. The solution may also be applied to situations involving fluid-particle mixtures flowing from smoke stacks and/or exhaust pipes.

DEFINITION OF THE PROBLEM

When a jet leaves a small circular opening it causes surrounding fluid to be drawn in and mixed with the jet itself (Fig. 1). This results in an increase of volume of flow with distance from the orifice and a downstream cross-section of the flow field which is much larger than a cross-section nearer the source of the jet.

The problem to be considered here involves putting particles into a circular jet flow somewhere upstream and determining their positions downstream. We would like this situation to simulate a fluid-particle flow from a tube, with particles initially distributed across the mouth of the tube, however the mathematics describing the flow field assumes the jet as coming from a point source. In order to account for this, the particles are put in the flow, at the velocity of the flow, a short distance downstream from this issuing point. Their paths are then followed from this initial point onwards.

The distance from the source where the particles are initially distributed uniformly across the cross-section is defined by how much of the jet velocity profile is to be studied. It has been found that a distance, x_o of 5.896D from the point source encompasses the width of the jet at half depth (Schlichting, 1968). That is, for this x_o value the velocity of the particles which are located on the circumference of the circular cross-section will be one-half that of the center-line velocity (Fig. 2).

By increasing x_o, a smaller amount of the jet angle is covered and the velocity of the particles on the circumference will be more than one-half of the center-line velocity. When the value of x_o is less than that of 5.896D the opposite situation arises; a larger amount of the jet angle is covered and particle velocity on the circumference becomes smaller.

Thus, the basic problem is to choose an appropriate x_0 according to the portion of the jet angle to be studied, and thereby establish the starting point of the particle paths. Having done this, the paths are to be traced to a specified distance downstream where the co-ordinates of each particle are to be determined.

PARTICLE MOTION

The motion of an individual spherical particle has been found (Batchelor, 1967) to be defined by the following ordinary differential equations:

$$\frac{d\bar{v}_y}{dT} = \frac{C_D Re(\bar{u}_y - \bar{v}_y)}{24K} \qquad \text{(Eq. 1)}$$

$$\frac{d\bar{v}_x}{dT} = \frac{C_D Re(\bar{u}_x - \bar{v}_x)}{24K} \qquad \text{(Eq. 2)}$$

where $$Re = Re_0[(\bar{u}_y - \bar{v}_y)^2 + (\bar{u}_x - \bar{v}_x)^2]^{1/2} \qquad \text{(Eq. 3)}$$

$$K = \frac{\sigma d^2 U_0}{18\mu L} \quad \text{particle inertia parameter (Stokes number)} \qquad \text{(Eq. 4)}$$

$$Re_0 = \frac{U_0 d \varrho}{\mu} \quad \text{free stream Reynolds number} \qquad \text{(Eq. 5)}$$

The variables are defined on the notation pages at the beginning of this report and the basic geometry of the flow system is illustrated in Figure 1.

Both Equations 1 and 2 involve the term $C_D Re$. This presents a slight problem because C_D, the drag coefficient of the sphere, has been found to be a function of the Reynolds number Re. For example,

$$C_D = \frac{24}{Re}$$

for a situation involving Stokes flow. However, since both C_D and Re contain a velocity term it is more convenient to use

$$Re = \frac{C_D Re^2}{24}$$

when considering Stokes flow. This is because the velocity squared term contained in the denominator of the definition of C_D is cancelled by the velocity squared term in Re^2 and $C_D Re$ may then be found by dividing $C_D Re^2$ by Re.

As a result, the general expression becomes $Re = f(C_D Re^2)$ and in actual fact the drag coefficient is available in the form of explicit empirical equations. These equations, are (Davies, 1945):

$$Re = -\frac{C_D Re^2}{24}\ 2.3363 \times 10^{-4}(C_D Re^2)^2 + 2.0154 \times 10^{-6}(C_D Re^2)^3 - 6.9105 \times 10^{-9}(C_D Re^2)^4 \qquad \text{(Eq. 6)}$$

for $Re < 4$ or $C_D Re^2 < 140$

$$\log_{10} Re = -1.29536 + 9.86 \times 10^{-1}(\log_{10} C_D Re^2) - 4.6677 \times 10^{-2}(\log_{10} C_D Re^2)^2 + 1.1235 \times 10^{-3}(\log C_D Re^2)^3 \qquad \text{(Eq. 7)}$$

for $3 < Re < 10^4$, or $100 < C_D Re^2 < 4.5 \times 10^7$

The assumptions that must be made when using any of the equations which were introduced in this section include —

(a) negligible effects of gravity and/or electrostatic forces,

(b) monodisperse spherical particles with diameter very small as compared to the diameter of the initial upstream cross-sectional area, and

(c) free stream flow that is steady, incompressible and irrotational.

THE TURBULENT CIRCULAR JET

The velocity components of a turbulent circular jet have been defined (Schlichting, 1968) as:

$$\left.\begin{aligned} u_x &= \frac{3}{8\pi}\,\frac{k}{\varepsilon_0 x}\,\frac{1}{(1 + \frac{1}{4}\eta^2)^2} \\ u_y &= \frac{1}{4}\sqrt{\frac{3}{\pi}}\,\frac{\sqrt{k}}{x}\,\frac{\eta - \frac{1}{4}\eta^2}{(1 + \frac{1}{4}\eta^2)^2} \\ \text{where}\quad \eta &= \frac{1}{4}\sqrt{\frac{3}{\pi}}\,\frac{\sqrt{k}}{\varepsilon_0}\,\frac{y}{x} \end{aligned}\right\} \qquad \text{(Eq. 8)}$$

The curve which results from these equations has been found to agree quite favorably with the first theoretical consideration of a circular jet as done by W. Tollmien and the experimental results of H. Reichardt (Figure 24.8, Schlichting).

In applying Equations 8 to the problem considered here it is necessary to find numerical values for particular constants such as the empirical constant, $\sqrt{k}/\varepsilon_0$, and/or the constant kinematic momentum, k. In order to do this, the theory as presented (Schlichting) must be employed to modify the equations of u_x and u_y to more suitable forms. These modifications are now to be introduced.

Due to measurements obtained by H. Reichardt, half the jet width at half the depth of the velocity distribution at any point x is given by $b_{1/2} = 0.0848x$. This is actually half the width of the jet at the point where, for each distribution, the minimum velocity in the x direction is one-half of the maximum velocity which occurs.

According to Schlichting, the point at which the fluid velocity is one-half the maximum fluid velocity, $\eta = 1.286$ and $b_{1/2} = 5.27x\ \varepsilon_0/\sqrt{k}$. By equating these two expressions of $b_{1/2}$, the result is

$$\frac{\varepsilon_0}{\sqrt{k}} = 0.0161$$

so that $\sqrt{k}/\varepsilon_0$, which occurs in u_x and η, is 1/0.0161.

The equations we now have are:

$$u_x = \frac{3}{8\pi x}\left(\frac{1}{0.0161}\right)\frac{1}{(1 + \frac{1}{4}\eta^2)^2}\sqrt{k}$$

$$u_y = \frac{1}{4}\sqrt{\frac{3}{\pi}}\,\frac{1}{x}\,\frac{\eta - \frac{1}{4}\eta^2}{(1 + \frac{1}{4}\eta^2)^2}\sqrt{k}$$

$$\eta = \frac{1}{4}\sqrt{\frac{3}{\pi}}\left(\frac{1}{0.0161}\right)\frac{y}{x}$$

It can be seen that for any co-ordinate consisting of an x and y value, η can be found and the only unknown quantity left to be determined is $\sqrt{k}$ found in u_x and u_y.

It has been derived from substitution that

$$\sqrt{k} = 1.59 b_{1/2} U$$

or $$\sqrt{k} = 1.59(0.0848x)U = 0.1348xU$$

where U is the center-line velocity at any distance x. Not knowing this value, it appears that it would be more convenient to express $\sqrt{k}$ in terms of U_0 — the velocity of the fluid at x_0, where x_0 is the distance downstream from the issuing point of the jet that is considered the starting point of the solid particles.

It is known that for a free turbulent circular jet the center-line velocity U is proportional to x^{-1} therefore

$$U = \frac{c}{x}$$

and $$U_0 = \frac{c}{x_0}$$ where c is an arbitrary constant.

By obtaining an expression for x_0, then, knowing U_0, the constant can be found as can the appropriate value of U for any x.

Assuming the situation as illustrated in Figure 2, then $b_{1/2} = 0.5D$. Also, $b_{1/2} = 0.0848x_0$ as was previously introduced. Thus

$$x_0 = \frac{0.5D}{0.0848} = 5.896D \qquad \text{(Eq. 9)}$$

and $$c = 5.896DU_0 \quad .$$

The velocity U at any downstream distance x may now be expressed in terms of U_0, D and x:

$$U = \frac{5.896DU_0}{x}$$

and the simplified expression for $\sqrt{k}$ becomes

$$\sqrt{k} = 0.795DU_0 \quad .$$

By substituting this into u_x and u_y, the resulting fluid velocity components are:

$$u_x = \frac{3}{8\pi x}\left(\frac{1}{0.0161}\right)\frac{1}{(1 + \frac{1}{4}\eta^2)^2}(0.795DU_0)$$

$$u_y = \frac{1}{4}\sqrt{\frac{3}{\pi}}\,\frac{1}{x}\,\frac{\eta - \frac{1}{4}\eta^2}{(1 + \frac{1}{4}\eta^2)^2}\,(0.795\,D U_0)$$

Thus, for any constants D and U_0 (which are analogous to OD and UF of the computer program used to solve the problem), and for any x and y co-ordinate, η may be calculated as well as can u_x and u_y.

Each fluid velocity component was normalized in the solution to the center-line fluid velocity which prevailed at x_0. This was done so that the initial velocity in the x direction of the fluid at the center, and thus the center particle, was always 1.0. All other velocities could easily be compared to this value.

Finally, as an overall conclusion to these previous substitutions and derivations, the normalized equations which were actually used to find the velocity components of a turbulent circular jet for the situation of this problem are:

$$\bar{u}_x = \frac{u_x}{U_0} = \frac{3}{8\pi x}\left(\frac{1}{0.0161}\right)\frac{1}{(1 + \frac{1}{4}\eta^2)^2}\,(0.795\,D)$$

$$\bar{u}_y = \frac{u_y}{U_0} = \frac{1}{4}\sqrt{\frac{3}{\pi}}\,\frac{1}{x}\,\frac{\eta - \frac{1}{4}\eta^2}{(1 + \frac{1}{4}\eta^2)^2}\,(0.795\,D) \qquad \text{(Eq. 10)}$$

where, as before

$$\eta = \frac{1}{4}\sqrt{\frac{3}{\pi}}\left(\frac{1}{0.0161}\right)\frac{y}{x}\,.$$

COMPUTER METHODS OF SOLUTION

The computer program which was built to solve the problem considered here consists of various subprograms incorporated into the main program itself. Each of these subprograms are briefly described in the program listing and the whole program is documented in such a way that the step-by-step procedure may be quite easily followed. Refer to the Appendix for a listing of the program and a sample solution.

A total of fourteen constants are to be supplied by the user and these are read in as input data. Each of these variables, as well as most of the others used throughout the program are described at the beginning of the listing so that they may be easily referred to while running the program.

In order to establish the initial upsream starting point, a constant AF is to be read in and used in the statement XZ = 5.896*OD/RADZ*AF. The value of AF provided by the user depends upon the angle of the jet velocity profile to be studied. With AF = 1.0 the jet encompasses the jet width at half the depth of the profile. See Figure 2 for an illustration of the situation resulting when AF = 1.0 and refer to the previous section entitled "Definition of the Problem" for a more complete description of this value of x_0. When AF is less than 1.0, then a different value of x_0 results and a wider portion of the velocity profile is covered; when AF is greater than 1.0, a smaller jet angle than that at half depth is covered. Thus by varying the input value of AF different portions of the jet velocity profile may be studied according to the user's preference.

One of the most important subroutines which was built into the solution program is that of SUBROUTINE SBM22. As is described in the listing, this uses the fourth-order Runge Kutta method to integrate a specified number of ordinary differential equations. In this case, the ordinary differential equations which are to be solved by SUBROUTINE SBM22 are

$$\frac{d\bar{v}_x}{dT}, \frac{d\bar{v}_y}{dT}, \frac{d\bar{x}}{dT}, \frac{d\bar{y}}{dT}$$

which are analogous to DG(1), DG(2), DG(3) and DG(4) respectively of the computer program. By integrating these equations, the velocity and position of the particle is obtained (note that DG(1) and DG(2) represent Equations 1 and 2).

The values of Re and K of Equations 1 and 2 are easily found for each new step by direct substitution of previously determined values into Equations 3, 4 and 5. However, the value of CDRE is found by the subprogram FUNCTION CDRE. This is done by calculating, for each step, the numerical solution of the definitive empirical equations (Eqs. 6 and 7). By using Newton's method for finding the zero of a function, these numerical solutions are determined and the value of CDRE can be obtained.

This subprogram, FUNCTION CDRE, presents the only visible error of the whole program. The procedure used involves an iterative process which is terminated only when a certain condition is met, namely, that

$$\left| \frac{X_{k+1} - X_k}{X_{k+1}} \right| < \varepsilon$$

where ε is any small number. When this condition is not met then a message of NO CONVERGENCE is printed by the computer and the value of CDRE is taken to be what was previously stored there. Although the number of iterations (100) is quite high, there are some situations where the initial estimate doesn't converge and the message is printed out. In these cases, the true value of CDRE is, in fact, not what it is taken to be and a small amount of error is introduced into the calculations by assuming an incorrect value. However, since the actual computed values of CDRE change very little from one time increment to the next, then this error is assumed to be negligible and the message may be, for practical purposes, ignored.

The program was written for a large number of diverse situations however one limitation which was discovered is that the smallest particle diameter which could be input is 20 μ. At a diameter of 10 μ, an overflow problem in the computer calculations resulted so no solution could be obtained. Other limitations of the program have not yet been discovered.

As a small addition to the solution, the average number of particles per unit area (cm^2) at the initial cross-section is computed, as it also is at the cross-section downstream. It may be noted that the upstream concentration is in fact the actual number of particles per square centimeter since they (the particles) are uniformly distributed over the cross-section. However, upon reaching the downstream distance, the particles will no longer be uniformly dispersed and the resulting concentration represents an average of particles per square centimeter.

RESULTS AND DISCUSSION

A sample solution for one set of input data is shown after the program listing in the Appendix. Many more calculations were made using this program to produce the graphical results shown in Figures 3 to 7.

The plots of Figures 3, 4 and 5 are those of the actual particle paths for particle diameters of 100 μ, 50 μ and 20 μ. It can be seen that the downstream distribution does not vary much with particle size, however, the larger particulates tended to become distributed a bit further away from the center of the flow. Even though the difference is small it indicates that the larger particles were less inclined to be influenced by the surrounding fluid which is drawn in as the jet spans out downstream. If this is the case, the momentum of these larger particles would cause them to flow out and away from the center more than the smaller particles and as a result, they would have greater y co-ordinates. It must be noted that these graphs were plotted for a value of AF equal to 0.3217 which was choosen so that most of the velocity profile was covered (this was determined for v_y of the outside particle equal to 0.0 at the initial position).

There are no experimental results available to compare with the mathematical results presented in Figures 3, 4 and 5. Since the model contains many assumptions, including steady, irrotational flow and the starting location of the particles, the results should be tested by experiment to establish their validity. Some errors, however, could possibly have been introduced into the solution by computer round-off but these are assumed to be negligible.

The graphs of Figures 6 and 7 are families of curves showing the radial co-ordinate of the outside particle as a function of the inertia parameter K. (The outside particles are those which are located on the circumference of any circular cross-sectional area of the jet which engulfs all particles.) These curves are plotted for a series of values of ϕ, a dimensionless parameter independent of particle size and equal to Re_0^2/K.

Figure 6 shows the results for AF = 1.0 which means that all of the particles are assumed to be distributed across the width of the jet at half the depth of the velocity profile. At this point, as was previously mentioned, the initial velocities of the outside particles (in the x direction) are one-half the velocity of the center particle. Figure 7 shows the results for AF = 0.5 which covers a wider portion of the jet angle than when AF = 1.0. At this angle, the velocities of the outside particles are found to be about 0.14 times that of the center particle thus confirming that a wider portion of the profile is indeed covered.

In these two figures each curve was fitted by eye through several data points obtained by applying the computer program to various particle diameters. As a result, by knowing the particles' free stream Reynolds number Re_0 and the inertia parameter K then by studying the appropriate curve, the radial co-ordinates of the outside particles at a specific distance downstream may be estimated. Also, for any value of ϕ which falls between those plotted in the figures, the method of interpolation provides a means of approximating the downstream radial co-ordinate.

As a last point to note, the results as given in the Appendix indicate that although both the particles and the fluid have the same initial velocity, the velocity of the fluid tends to decrease faster than the particles as they are observed downstream. This can be explained by considering the effect of the fluid on the particles in the following way:

> In the presence of a fluid which is continually decreasing in velocity, as is the case here, particles moving in the same direction as the fluid will have a drag force acted upon them. Although the particles will begin to slow down very quickly they will still have a greater velocity than the fluid because of the inertia effects which they experience. As the distance downstream is increased however, the difference between particle velocity and fluid velocity is narrowed (refer to columns of VX′ and UX′ of the solution given in the Appendix). This is due to the fact that the fluid velocity is changing more slowly as the downstream distance is increased.

CONCLUSIONS

In some situations it may be of interest to know how particulates disperse in a fluid-particle circular jet. As an attempt to find some answers a mathematical model has been developed which predicts the distribution of particles, by specifying their radial and axial co-ordinates, at any distance downstream. This model also enables the paths of specific particles to be completely followed from their initial upstream position to their downstream position.

A computer program was written to provide quick and easy solutions to this mathematical model. Also, the computer solution was devised in such a manner that a wide variety of flow situations can be considered; this depends only on the data which is provided as input by the user. However, the output of this program should be validated by experimental data since the model contains many assumptions.

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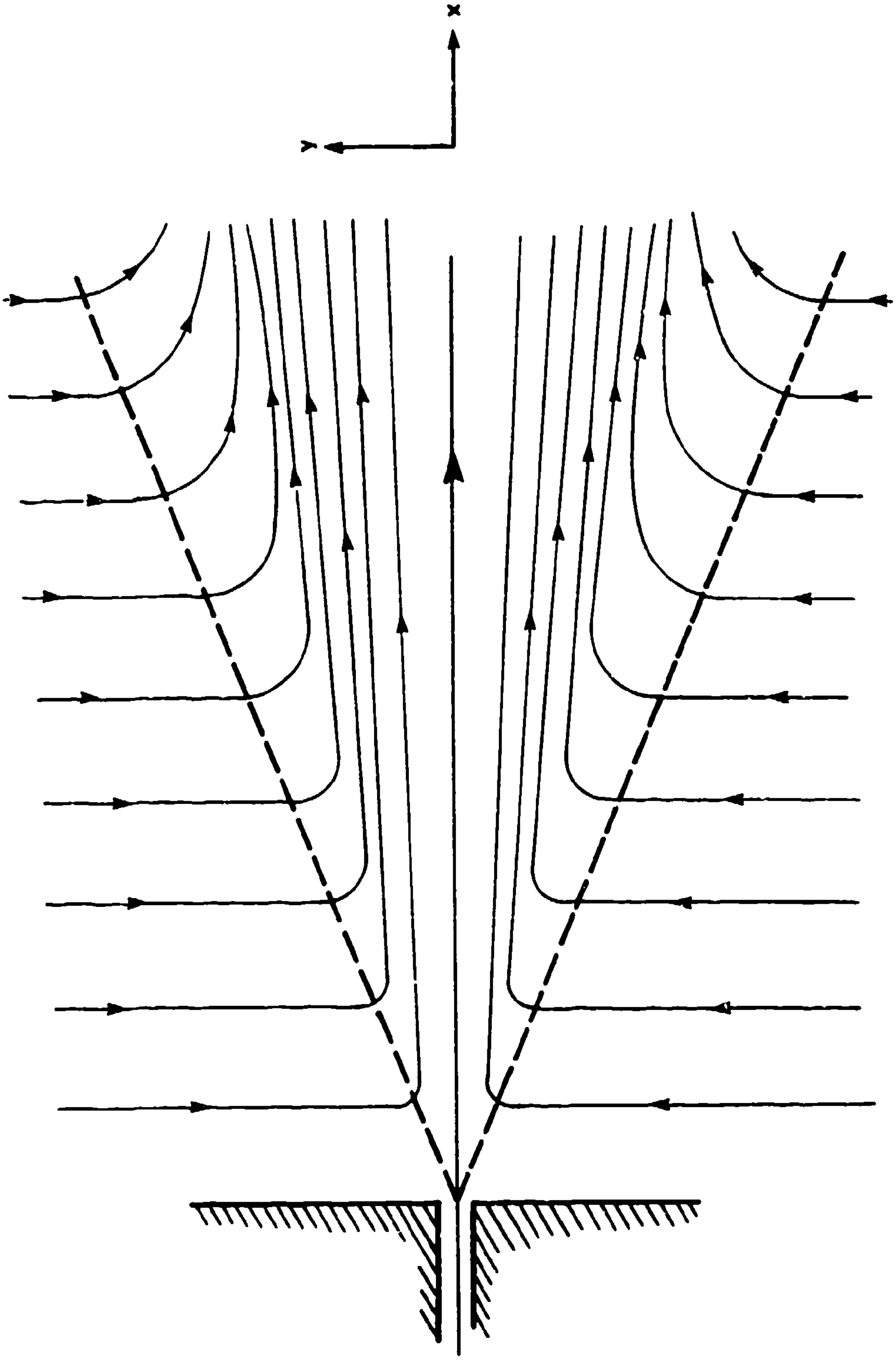

Figure 1. Co-ordinate System for a Circular, Turbulent Free Jet, Illustrating the Pattern of Streamlines.

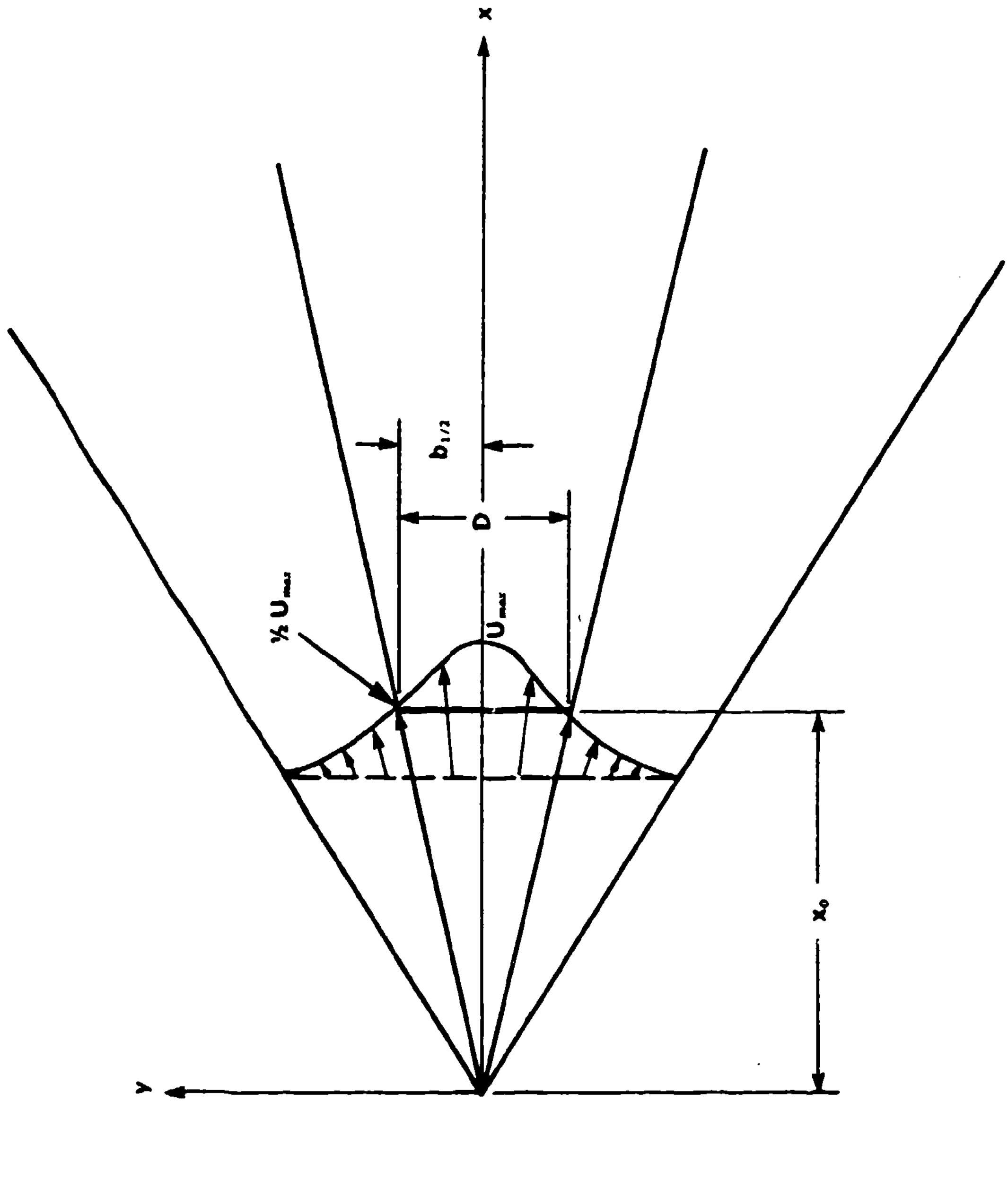

Figure 2. Illustrating the Idea of x_o with Respect to $b_{1/2}$ and the Jet Diameter D to be Studied.

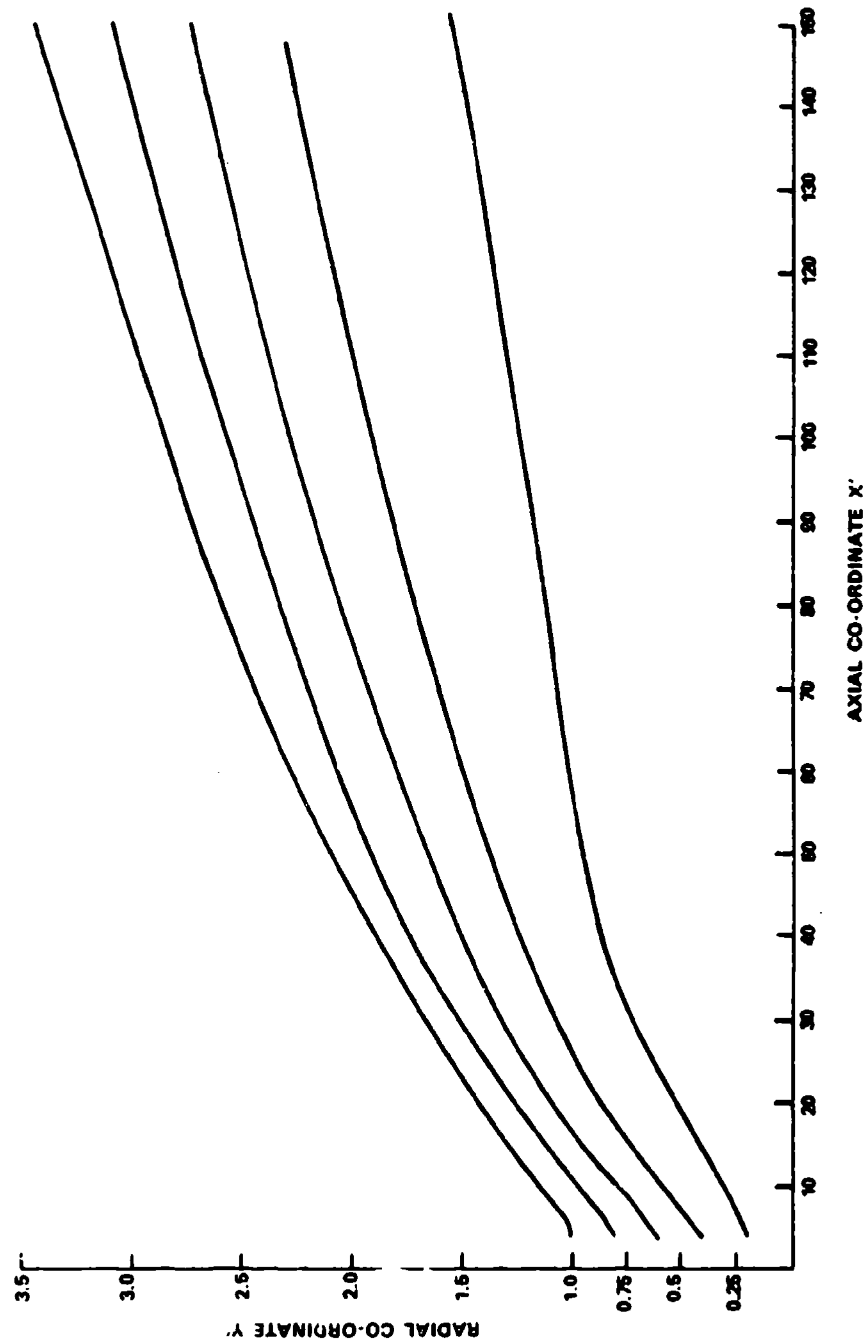

Figure 3. PATHS OF THE PARTICLES IN THE FLUID, FOR A PARTICLE DIAMETER OF 100 μ.

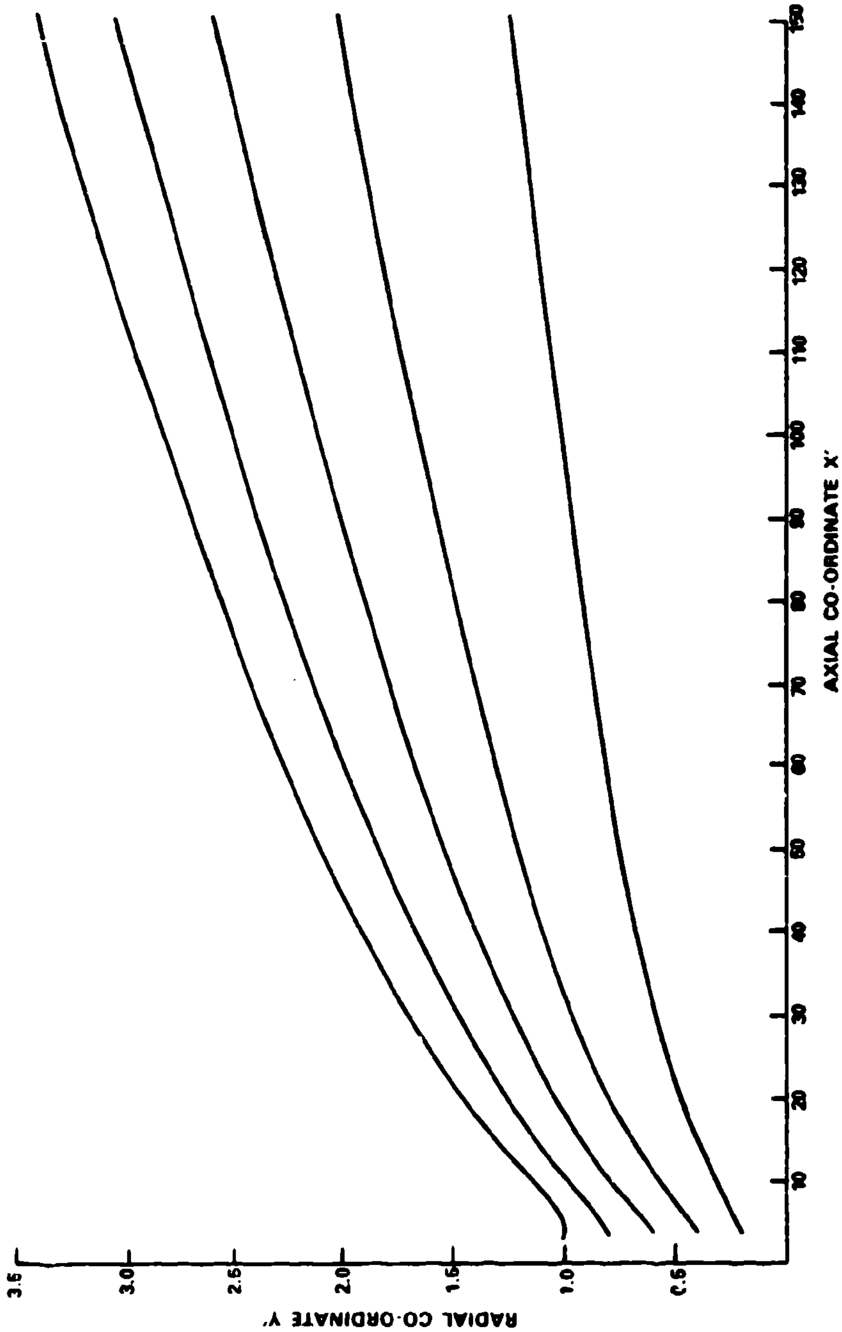

Figure 1. PATHS OF THE PARTICLES IN THE FLUID, FOR A PARTICLE DIAMETER OF 50 μ.

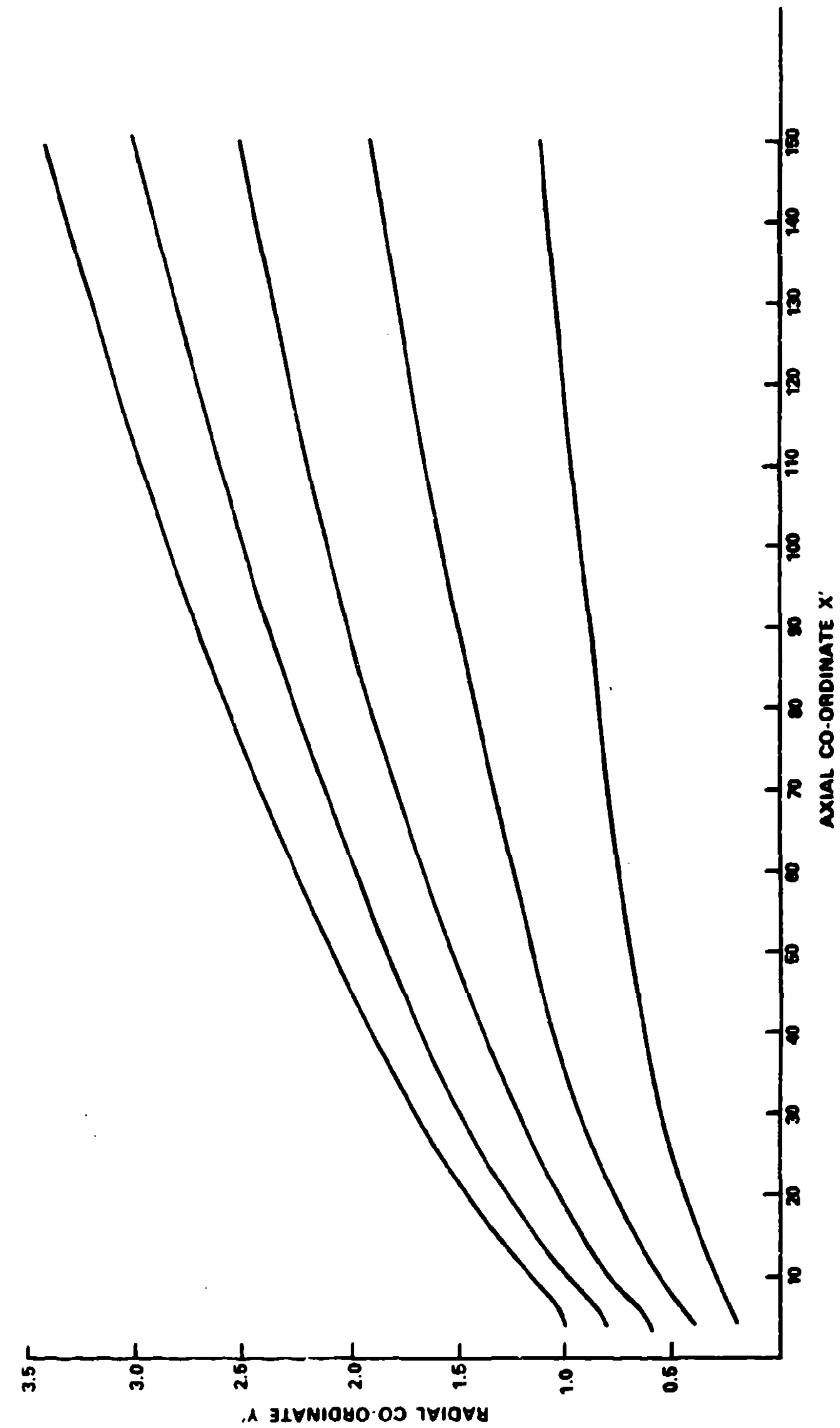

Figure 5. PATHS OF THE PARTICLES IN THE FLUID, FOR A PARTICLE DIAMETER OF 20 μ.

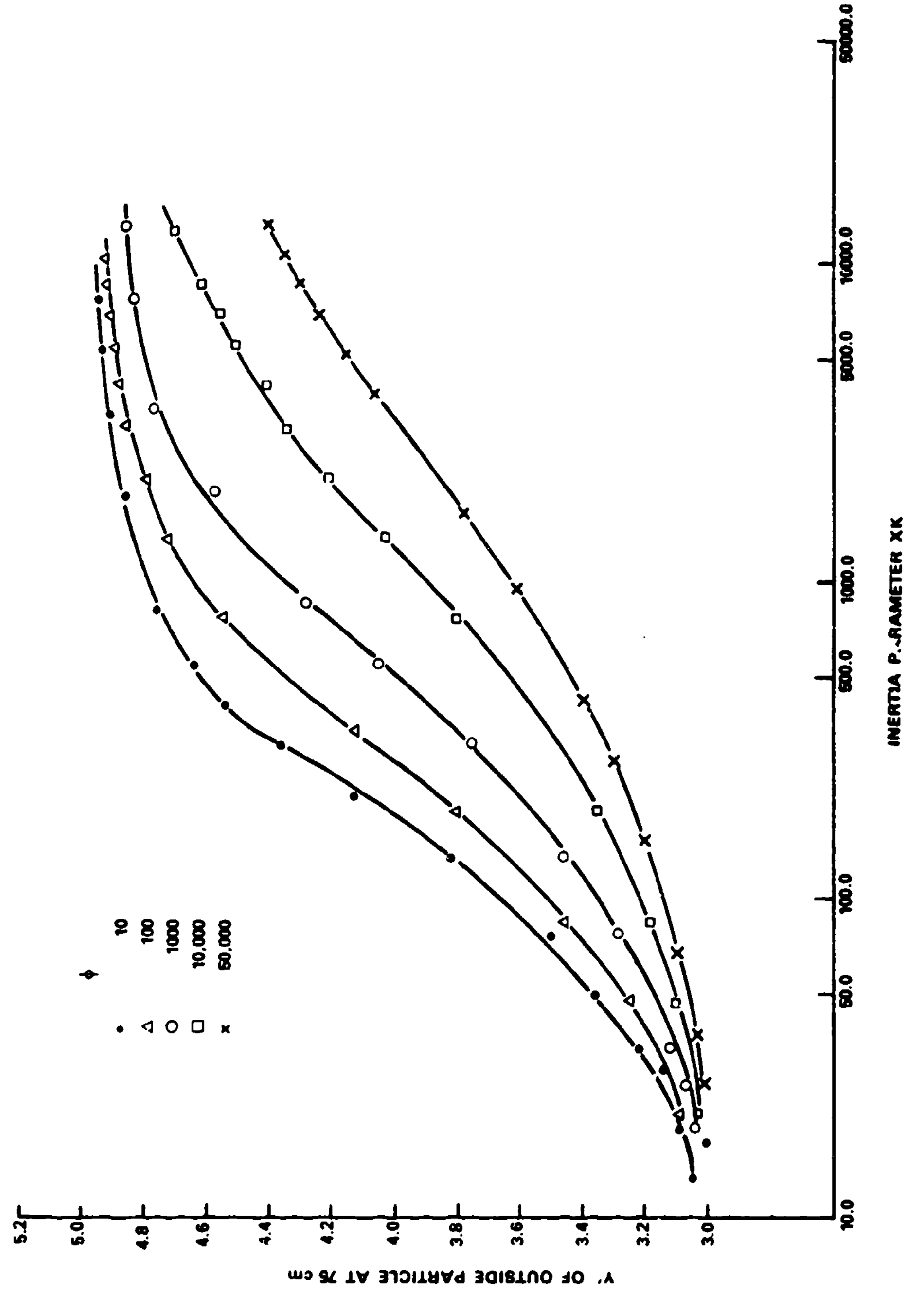

Figure 6. Calculated Radial Co-ordinate of Outside Particle as a Function of its Inertia Parameter, for the Jet Width Resulting when AF = 1.0

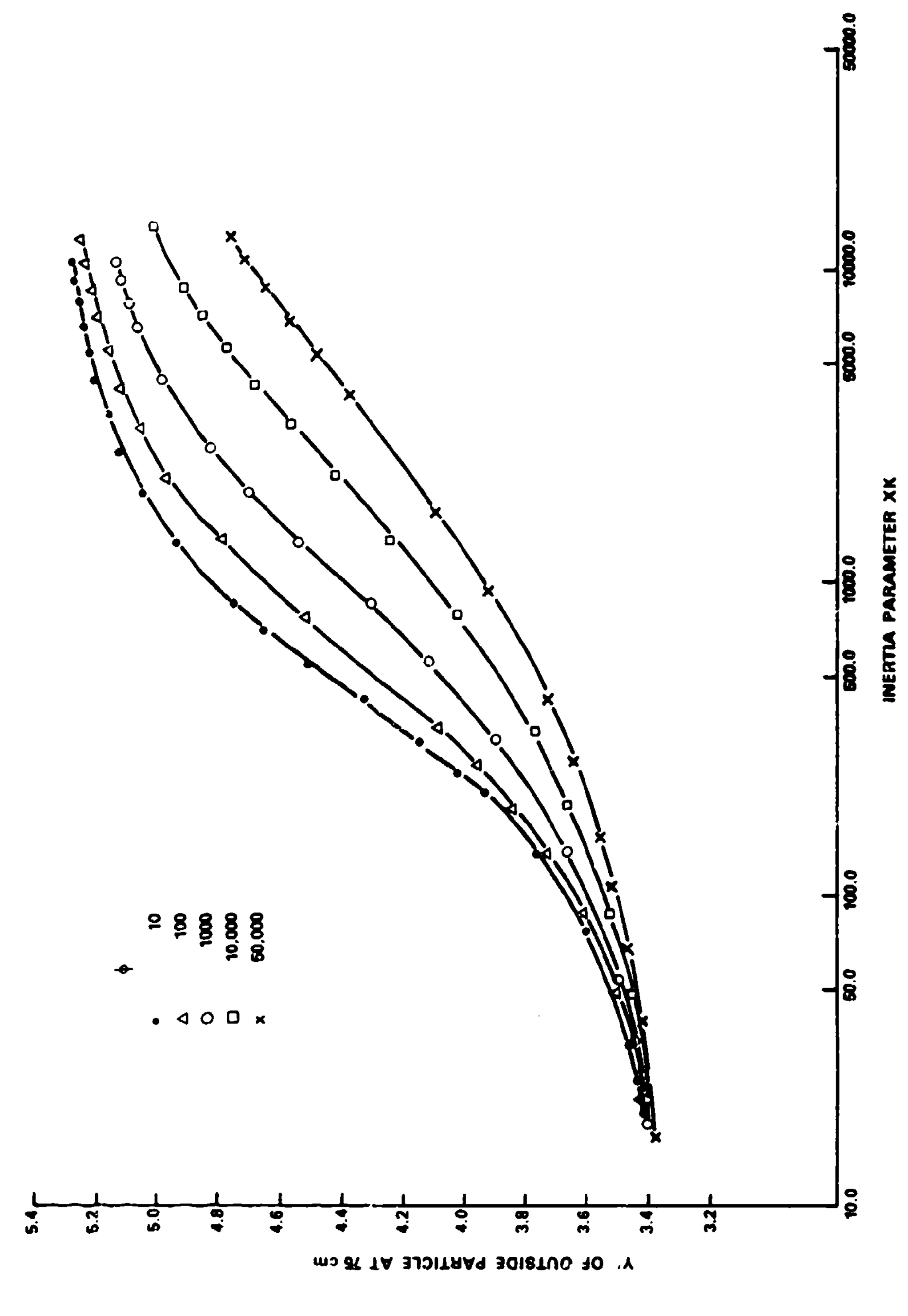

Figure 7. Calculated Radial Co-ordinate of Outside Particle as a Function of its Inertia Parameter, for the Jet Width Resulting when AF = 0.5

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C                        TRIBUTION OF PARTICLES IN A CIRCULAR JET STREAM00013099
C                                                                       00014099
C**** LIST VARIABLES TO BE USED:                                        00020032
C        AF - FACTOR WHICH CONTROLS HOW MUCH OF THE FLUIDS' VELOCITY PRO- 00021099
C             FILE WILL BE STUDIED (AF=1.0 INDICATES A JET STREAM WHOSE   00022099
C             WIDTH COVERS THE WIDTH OF THE VELOCITY PROFILE AT HALF DEPTH00023099
C        AMAXD - DOWNSTREAM DISTANCE AT WHICH PARTICLE DISTRIBUTION IS TO 00024099
C             BE DETERMINED, CM                                           00025099
C        AMAXN - DOWNSTREAM DISTANCE AT WHICH PARTICLE DISTRIBUTION IS TO 00026099
C             BE DETERMINED, NORMALIZED TO RADZ, CM                       00027099
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C        AREA - CROSS-SECTIONAL AREA WHICH ENGULFS FINAL DISTRIBUTION OF  00029099
C             PARTICLES, CMXCM                                            00029199
C        AREAZ - CROSS-SECTIONAL AREA WHICH ENGULFS INITIAL UPSTREAM DIS- 00029299
C             TRIBUTION OF PARTICLES, CMXCM                               00029399
C        CON - AVERAGE NUMBER OF PARTICLES PER UNIT AREA FINALLY DISTRI- 00029499
C             BUTED AT AMAXD                                              00029599
C        CONZ - AVERAGE NUMBER OF PARTICLES PER UNIT AREA INITIALLY DIS- 00029699
C             TRIBUTED AT XZ                                              00029799
C        DBP - DISTANCE BETWEEN EACH PARTICLE AT XZ, CM                   00029899
C        DTAU - DIMENSIONLESS TIME INCREMENT AFTER WHICH PARTICLE VELO-   00029999
C             CITY AND POSITION IS FOUND                                  00030099
C        G(1) - VX, VELOCITY OF PARTICLE IN AXIAL DIRECTION, CM/S         00030199
C        G(2) - VY, VELOCITY OF PARTICLE IN RADIAL DIRECTION, CM/S        00030299
C        G(3) - X CO-ORDINATE, AXIAL DISTANCE DOWNSTREAM FROM ISSUING     00030399
C             POINT OF JET, CM                                            00030499
C        G(4) - Y CO-ORDINATE, RADIAL DISTANCE FROM CENTER-LINE OF JET, CM00030599
C        IFUP - FREQUENCY OF PRINTOUT OF RESULTS FOR SPECIFIC PARTICLES   00030699
C             CHOOSEN                                                     00030799
C        IHTPL - HALF OF TOTAL NUMBER OF PARTICLES PER LINE, INCLUDING    00030899
C             CENTER PARTICLE(SEE ITPL)                                   00030999
C        ITP - TOTAL NUMBER OF PARTICLES PER CROSS-SECTION OF JET         00031099
C        ITPL - TOTAL PARTICLES PER LINE ACROSS JET STREAM (VERTICALLY,   00031199
C             HORIZONTALLY, DIAGONALLY). ASSUMED TO BE AN ODD NUMBER      00031299
C        N1, N2 - TWO PARTICLES CHOOSEN BY USER WHICH HAVE THEIR VELOCITY 00031399
C             AND POSITION, AFTER EACH DTAU, COMPLETELY OUTPUT BY PROGRAM 00031499
C        NI - NUMBER OF LINES OF PARTICLES IN CROSS-SECTION OF JET        00031599
C        NUP - PARTICLE NUMBER (PARTICLE AT CENTER OF STREAM IS NUMBER 1) 00031699
C        OD - DIAMETER OF JET WHERE PARTICLES ARE INITIALLY POSITIONED IN 00031799
C             FLOW STREAM, CM                                             00031899
C        PD - PARTICLE DIAMETER, CM                                       00031999
C        RAD - RADIUS OF CROSS-SECTIONAL AREA WHICH ENGULFS FINAL DISTRI- 00032099
C             BUTION OF PARTICLES, CM                                     00032199
C        RADZ - RADIUS OF CROSS-SECTIONAL AREA WHICH ENGULFS INITIAL UP-  00032299
C             STREAM DISTRIBUTION OF PARTICLES, CM                        00032399
C        REZ - SPHERICAL PARTICLE REYNOLDS NUMBER IN FREE STREAM          00032499
C        RHO - FLUID DENSITY, G/CC                                        00032599
C        SIGMA - PARTICLE DENSITY, G/CC                                   00032699
C        TAU - CUMULATIVE NORMALIZED TIME                                 00032799
C        UF - CENTER-LINE VELOCITY OF JET, CM/S                           00032899
C        UX - VELOCITY OF FLUID IN AXIAL DIRECTION, CM/S                  00032999
C        UY - VELOCITY OF FLUID IN RADIAL DIRECTION, CM/S                 00033099
C        XK - PARTICLE INERTIAL PARAMETER                                 00033199
C        XMU - ABSOLUTE VISCOSITY OF FLUID, POISE                         00033299
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          C     XZ = AXIAL DISTANCE FROM ISSUING POINT OF JET WHERE PARTICLES   00033399
          C          ARE INITIALLY POSITIONED IN FLOW STREAM, CM                00033499
          C     YZ = RADIAL DISTANCE FROM CENTER-LINE OF JET WHERE EACH PARTICLE 00033599
          C          IS INITIALLY POSITIONED, CM                                00033699
          C                                                                     00034019
ISN 0002        WRITE(6,10)                                                     00040005
ISN 0003     10 FORMAT(1H1,20X,'THE DISTRIBUTION OF PARTICLES IN A CIRCULAR JET DO00050028
               1WNSTREAM FROM A JET OPENING'/21X,77('*'))                       00060029
          C                                                                     00070019
ISN 0004        READ(5,*) UO,PO,RHO,SIGMA,XMU,UF,AF                             00080085
          C                                                                     00100019
ISN 0005        REZ=RHO*PO*UF/XMU                                               00110005
ISN 0006        XK=SIGMA*PO**2*UF/(9.0*XMU*UO)                                  00120005
          C                                                                     00130019
ISN 0007        WRITE(6,30)UO,PO,RHO,SIGMA,XMU,UF,REZ,XK,AF                     00140092
ISN 0008     30 FORMAT(///,' THE PHYSICAL PARAMETERS OF THE FLOW STREAM ARE:'/40X,00150030
               1' UO     =  ',F10.4/40X,' PO     =  ',F10.6/40X,' RHO    =  ',F10.6/ 00160030
               140X,' SIGMA =  ',F10.6/40X,' XMU    =  ',F10.7/40X,' UF     =  ', 00170030
               1F11.4/40X,' REZ    =  ',F10.5/40X,' XK     =  ',F10.4/40X,' AF     = 00171099
               1  ',F6.4)                                                       00172099
          C                                                                     00180019
ISN 0009        READ(5,*) AMAXO,DTAU,ITPL,NL,N1,N2,IFOP                         00190099
          C                                                                     00200019
ISN 0010        PI=3.14159265                                                   00210051
ISN 0011        RADZ=UO/2.0                                                     00221054
ISN 0012        AZ=5.896*UO/RADZ*AF                                             00222099
ISN 0013        DBP=1.0/((ITPL-1)/2.0)                                          00230099
ISN 0014        AMAXN=AMAXO/RADZ                                                00231099
          C                                                                     00240019
          C**** CALCULATE TOTAL PARTICLES AND THE INITIAL PARTICLE DENSITY.     00250032
ISN 0015        AREAZ=PI*RADZ**2                                                00270008
ISN 0016        ITP=ITPL*NL-(NL-1)                                              00280022
ISN 0017        CONZ=ITP/AREAZ                                                  00290022
          C                                                                     00300019
ISN 0018        WRITE(6,50) ITPL,NL,ITP,N1,N2,DBP,AMAXO,AMAXN,DTAU,IFOP,XZ     00310099
ISN 0019     50 FORMAT(/,' THE NECESSARY DATA FOR THIS RUN IS '/40X,' ITPL   =  ', 00311030
               1I3,/40X,' NL     =  ',I3/40X,' ITP    =  ',I3/40X,' N1     =  ',I3/4000312030
               1X,' N2     =  ',I3/40X,' DBP    =  ',F6.5/40X,' AMAXO  =  ',F9.3/40X,00313099
               1' AMAXN  =  ',F9.3/40X,' DTAU   =  ',F7.4/40X,' IFOP   =  ',I3/40X, 00314099
               1' XZ     =  ',F10.5)                                            00314199
          C                                                                     00314231
          C**** PREPARE OUTPUT TABLE.                                           00314354
ISN 0020        WRITE(6,55)                                                     00314454
ISN 0021     55 FORMAT(1H1,40X,'THE COMPLETE SOLUTION OF CHOSEN PARTICLES'/40X, 00314585
               1' ',41('-')//58X,' AND'/58X,' ---'//20X,' THE CO-ORDINATES AND VEL00314685
               1OCITY OF ALL PARTICLES AT THE REQUIRED DISTANCE DOWNSTREAM'/20X, 00314786
               1' ',82('-')//15X,92H (ALL VALUES ARE NORMALIZED: TAU=TU/R,X'=X/R,Y00314889
               1'=Y/R,VX'=VX/UF,VY'=VY/UF,UX'=UX/UF,UY'=UY/UF)////13X,' TAU',10X, 00314999
               12HX',10X,2HY',10X,3HVX',10X,3HVY',10X,3HUX',10X,3HUY',10X,'CONE'/ 00315099
               1' ',13X,3(1H_),2(10X,2(1H_)),4(10X,3(1H_)),10X,4(1H_)/' ',13X, 00315199
               13(1H_),2(10X,2(1H_)),4(10X,3(1H_)),10X,4(1H_))                 00315299
          C                                                                     00315354
          C**** CALCULATE THE AVERAGE NUMBER OF PARTICLES IN A SPECIFIC AREA    00315499
          C**** DOWNSTREAM BY CALLING SUBROUTINE K1.                            00315532
ISN 0022        CALL K1(OD,ITPL,ITP,XZ,DBP,DTAU,REZ,XK,N1,N2,AMAXN,IFOP,UF,PI,CON,00315699
               1        AF,AMAXO,RADZ)                                          00315799
          C                                                                     00315899
          C**** OUTPUT THE RESULTS.                                             00315932
ISN 0023        WRITE(6,60) CONZ,AMAXO,CON                                      00316099
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LEVEL 2.3 (FX06)              MAIN              OS/360  FORTRAN H EXTENDED              DATE 82.238/12.55.42        PAGE   3
   ISN 0024          60 FORMAT(//,' THE INITIAL CONCENTRATION OF PARTICLES IS   ',F10.6// 00316131
                        1' THE AVERAGE CONCENTRATION OF PARTICLES, A DISTANCE OF ',F6.2,' D00316299
                        1OWNSTREAM IS ',F10.6)                                                 00316399
                  C                                                                            00316431
   ISN 0025              STOP                                                                  00317031
   ISN 0026              END                                                                   00318031
*OPTIONS IN EFFECT*NAME(MAIN) NOOPTIMIZE LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT NOGOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I)
*STATISTICS*     SOURCE STATEMENTS =       25, PROGRAM SIZE =      2214, SUBPROGRAM NAME =  MAIN
*STATISTICS*  NO DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                        892K BYTES OF CORE NOT USED
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LEVEL 2.3 (FAUG)                    OS/360  FORTRAN H EXTENDED            DATE 82.238/12.55.42         PAGE    1
REQUESTED OPTIONS: NODECK,NOLIST,OPT(0)
OPTIONS IN EFFECT: NAME(MAIN) NOOPTIMIZE LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT NOGOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I)
                C                                                                     00319031
                C                                                                     00319131
ISN 0002              SUBROUTINE K1(OD,ITPL,ITP,XZ,DBP,DTAU,REZ,XK,N1,N2,AMAXN,IFOP,  00319299
                     1            OF,PI,CON,AF,AMAXD,RAD7)                            00319399
                C**** THIS SUBROUTINE WILL CALCULATE THE AVERAGE NUMBER OF PARTICLES PER00319499
                C**** UNIT AREA AT A SPECIFIED DISTANCE DOWNSTREAM FROM THE CIRCULAR   00319532
                C**** OPENING. THE PROCEDURE USES SUBROUTINE MSBM28 WHICH IS RE-       00319632
                C**** SPONSIBLE FOR COMPUTING PARTICLE VELOCITY AND POSITION FOR VARI- 00319799
                C**** OUS TIME INCREMENTS ALONG THE PATH OF THE PARTICLE, WHICH IS     00319832
                C**** NECESSARY TO FIND THE DOWNSTREAM CONCENTRATION.                  00319932
                C                                                                     00320031
ISN 0003              DIMENSION G(4)                                                  00320131
ISN 0004              IHTPL=(ITPL+1)/2                                                00320231
ISN 0005              YZ=-DBP                                                         00320378
                C                                                                     00320431
                C**** STEPWISE INTEGRATION FOLLOWING THE POSITION OF EACH PARTICLE.    00320532
                C**** (PARTICLE 1 IS AT VERY CENTER OF STREAM.)                        00320632
ISN 0006              DO 50 NOP=1,IHTPL                                               00320731
                C**** SET AND PRINT INITIAL CONDITIONS.                                00320899
ISN 0007              TAU=0.0                                                         00320931
ISN 0008              YZ=YZ+DBP                                                       00321078
ISN 0009              G(3)=XZ                                                         00321131
ISN 0010              G(4)=YZ                                                         00321278
ISN 0011              ANEU=1.0/4.0*SQRT(3.0/PI)*1.0/0.0161*G(4)/G(3)                  00321371
ISN 0012              UX=3.0/(8.0*PI*G(3))*1.0/0.0161*1.0/((1.0+1.0/4.0*ANEU**2)**2)  00321480
                     1    *0.7948*(OD/RAD7)*AF                                        00321599
ISN 0013              UY=1.0/4.0*SQRT(3.0/PI)*1.0/G(3)*(ANEU-1.0/4.0*ANEU**2)/        00321671
                     1    ((1.0+1.0/4.0*ANEU**2)**2)*0.7948*(OD/RAD7)*AF              00321799
ISN 0014              G(1)=UX                                                         00321845
ISN 0015              G(2)=UY                                                         00321945
ISN 0016              WRITE(6,25)NOP,TAU,G(3),G(4),G(1),G(2),UX,UY                    00322099
ISN 0017           25 FORMAT(/,' PARTICLE ',I3/' ',12('*')/' THE INITIAL CONDITIONS OF T00322199
                     1HIS PARTICLE ARE:'/10X,F8.2,5X,F8.3,5(5X,F8.6))                 00322299
                C**** CALL ON SUBROUTINE MSBM28 TO FIND PARTICLES VELOCITY AND POSITION.00322399
ISN 0018              CALL MSBM28(G,TAU,DTAU,XK,OD,REZ,UX,UY,NOP,N1,N2,AMAXN,IFOP,PI,AF,00322499
                     1            AMAXD,RAD7)                                         00322599
ISN 0019           50 CONTINUE                                                        00322631
                C                                                                     00322731
                C**** AFTER ALL PARTICLES HAVE REACHED THE REQUIRED DISTANCE DOWN-     00322832
                C**** STREAM, FIND THE CIRCULAR AREA WHICH ENGULFS THEM, AND CAL-      00322932
                C**** CULATE THE AVERAGE NUMBER OF PARTICLES IN THAT AREA.             00323099
ISN 0020              RAD=G(4)                                                        00323133
ISN 0021              AREA= PI*RAD**2                                                 00323231
ISN 0022              CON=ITP/AREA                                                    00323331
ISN 0023              RETURN                                                          00323431
ISN 0024              END                                                             00323531
*OPTIONS IN EFFECT*NAME(MAIN) NOOPTIMIZE LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT NOGOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I)
*STATISTICS*     SOURCE STATEMENTS =       23, PROGRAM SIZE =      1536, SUBPROGRAM NAME =    K1
*STATISTICS*  NO DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                   492K BYTES OF CORE NOT USED
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LEVEL 2.3 (FAUG)                            OS/360  FORTRAN H EXTENDED              DATE 82.238/12.55.42        PAGE   1
REQUESTED OPTIONS: NODECK,NOLIST,OPT(0)
OPTIONS IN EFFECT: NAME(MAIN) NOOPTIMIZE LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT NOGOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I)

                  C                                                                       00323634
                  C                                                                       00323734
  ISN 0002              SUBROUTINE MSBM28(G,TAU,DTAU,XK,OD,REZ,UX,UY,NOP,N1,N2,AMAXN,IFOP,00323899
                       1                PI,AF,AMAXD,RADZ)                                  00323999
                  C**** THIS SUBROUTINE CALCULATES (FOR HALF THE PARTICLES OF ONE LINE).  00324099
                  C**** PARTICLE POSITION, PARTICLE VELOCITY AND FLUID VELOCITY FOR EACH  00324199
                  C**** INCREMENT OF TIME AND OUTPUTS THE VALUES AT A DISTANCE OF AMAXD   00324299
                  C**** (THE MAXIMUM DOWNSTREAM DISTANCE). IN DOING THIS, THE DISTRIBUTION00324399
                  C**** OF THE PARTICLES AT ANY VALUE OF AMAXD CAN BE DETERMINED SINCE THE00324499
                  C**** CO-ORDINATES (BOTH AXIAL AND RADIAL DISTANCES) ARE KNOWN.         00324599
                  C**** FOR THE SPECIFIC PARTICLES TO BE STUDIED, THE POSITION AND THE    00324699
                  C**** VELOCITY OF BOTH THE PARTICLE AND THE FLUID, AT THIS POSITION, ARE00324799
                  C**** OUTPUT ACCORDING TO THE FREQUENCY AS STORED IN IFOP. THIS ALLOWS  00324899
                  C**** CHOSEN PARTICLES TO BE COMPLETELY STUDIED FROM THE CIRCULAR OPEN- 00324999
                  C**** ING RIGHT TO THE MAXIMUM DOWNSTREAM DISTANCE.                     00325099
                  C                                                                       00325134
  ISN 0003              DIMENSION G(4),DG(4)                                              00325249
  ISN 0004              NSTEP=0                                                           00325334
  ISN 0005              M=0                                                               00325434
                  C                                                                       00325534
  ISN 0006            8 M=M+1                                                             00325634
                  C**** CALL OF RUNGE KUTTA SUBROUTINE.                                   00325734
  ISN 0007              CALL SMM22(4,G,DG,TAU,DTAU,IRUNG,M)                               00325834
                  C                                                                       00325934
  ISN 0008              IF (IRUNG-1) 10,9,10                                              00326034
  ISN 0009            9 RE=REZ*((UY-G(2))**2+(UX-G(1))**2)**0.5                           00326135
                  C**** CALCULATE PRODUCT OF CD AND RE NECESSARY FOR O.D.E.S              00326235
  ISN 0010              XCORE=CORE(RE)                                                    00326335
                  C**** EVALUATE O.D.E.S OF PARTICLE MOTION.                              00326435
  ISN 0011              DG(1)=(XCORE/(24.0*XK))*(UX-G(1))                                 00326535
  ISN 0012              DG(2)=(XCORE/(24.0*XK))*(UY-G(2))                                 00326635
  ISN 0013              DG(3)=G(1)                                                        00326735
  ISN 0014              DG(4)=G(2)                                                        00326835
  ISN 0015              GO TO 8                                                           00326935
  ISN 0016           10 CONTINUE                                                          00327035
  ISN 0017              M=0                                                               00327135
                  C                                                                       00327235
                  C**** CALCULATE FLUID VELOCITY AT PARTICLE POSITION.                    00327335
  ISN 0018              ANEU=1.0/4.0*SQRT(3.0/PI)*1.0/0.0161*G(4)/G(3)                    00327435
  ISN 0019              UX=3.0/(8.0*PI*G(3))*1.0/0.0161*1.0/((1.0+1.0/4.0*ANEU**2)**2)    00327580
                       1        *0.7948*(OD/RADZ)*AF                                      00327699
  ISN 0020              UY=1.0/4.0*SQRT(3.0/PI)*1.0/G(3)*(ANEU-1.0/4.0*ANEU**3)/          00327735
                       1        ((1.0+1.0/4.0*ANEU**2)**2)*0.7958*(OD/RADZ)*AF            00327899
                  C                                                                       00327935
                  C**** PRINT COMPLETE SOLUTION OF SPECIFIC PARTICLES CHOOSEN.            00328335
  ISN 0021              IF ((NOP.NE.N1).AND.(NOP.NE.N2)) GO TO 25                         00328460
  ISN 0023              NSTEP=NSTEP+1                                                     00328535
  ISN 0024              IF (NSTEP-IFOP) 25,18,25                                          00328635
  ISN 0025           18 CONTINUE                                                          00328735
  ISN 0026              NSTEP=0                                                           00328835
  ISN 0027              WRITE(6,50) TAU,G(3),G(4),G(1),G(2),UX,UY,XCORE                   00328999
  ISN 0028           50 FORMAT(10X,F8.2,5X,F8.3,5(5X,F8.6),6X,F6.3)                       00329099
                  C                                                                       00329135
                  C**** INTEGRATE ACROSS ANOTHER STEP IF REQUIRED.                        00329235
  ISN 0029           25 IF (G(3).LT.AMAXN) GO TO 8                                        00329399
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                  C                                                                        00329435
                  C**** UPON REACHING REQUIRED DISTANCE DOWNSTREAM,PRINT EXACT             00329535
                  C**** COORDINATES AND VELOCITY OF PARTICLE.                              00329635
   ISN 0031             WRITE(6,80)XMAXD,TAU,G(3),G(4),G(1),G(2),UX,UY                     00329799
   ISN 0032          80 FORMAT(' THE FINAL CONDITIONS, AT A DISTANCE OF ',F6.2,' DOWNSTREA00329886
                       1M, ARE:'/10X,F8.2,5X,F8.3,5(5X,F8.6)/' ',105('_')/)                00329999
                  C                                                                        00330035
   ISN 0033             RETURN                                                             00330135
   ISN 0034             END                                                                00330235
*OPTIONS IN EFFECT*NAME(MAIN) NOOPTIMIZE LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT NOGOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I)
*STATISTICS*     SOURCE STATEMENTS =       33, PROGRAM SIZE =      1760, SUBPROGRAM NAME =MSOM28
*STATISTICS*  NO  DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                      488K BYTES OF CORE NOT USED
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SM 1077

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REQUESTED OPTIONS: NODECK,NOLIST,OPT(0)
OPTIONS IN EFFECT: NAME(MAIN) NOOPTIMIZE LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT NOGOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I)
                   C
                   C
      ISN 0002           SUBROUTINE SBM22(N,Y,F,X,H,IRUNG,M)
                   C**** THIS SUBROUTINE USES THE FOURTH-ORDER RUNGE KUTTA METHOD TO
                   C**** INTEGRATE N FIRST-ORDER ORDINARY DIFFERENTIAL EQUATIONS, ACROSS
                   C**** ONE STEP OF LENGTH H IN THE INDEPENDENT VARIABLE X. IN THIS
                   C**** CASE, THE O.D.E.S TO BE SOLVED ARE THOSE DESCRIBING THE MOTION
                   C**** OF A PARTICLE IN A FLUID.
                   C
      ISN 0003           DIMENSION PHI(50),SAVY(50),Y(50),F(50)
                   C
      ISN 0004           GO TO (2,3,4,5,6), M
                   C
                   C**** PASS 1
      ISN 0005         2 IRUNG=1
      ISN 0006           RETURN
                   C
                   C**** PASS 2
      ISN 0007         3 DO 22 J=1,N
      ISN 0008           SAVY(J)=Y(J)
      ISN 0009           PHI(J)=F(J)
      ISN 0010        22 Y(J)=SAVY(J)+0.5*H*F(J)
      ISN 0011           X=X+0.5*H
      ISN 0012           IRUNG=1
      ISN 0013           RETURN
                   C
                   C**** PASS 3
      ISN 0014         4 DO 33 J=1,N
      ISN 0015           PHI(J)=PHI(J)+2.0*F(J)
      ISN 0016        33 Y(J)=SAVY(J)+0.5*H*F(J)
      ISN 0017           IRUNG=1
      ISN 0018           RETURN
                   C
                   C**** PASS 4
      ISN 0019         5 DO 44 J=1,N
      ISN 0020           PHI(J)=PHI(J)+2.0*F(J)
      ISN 0021        44 Y(J)=SAVY(J)+H*F(J)
      ISN 0022           X=X+0.5*H
      ISN 0023           IRUNG=1
      ISN 0024           RETURN
                   C
                   C**** PASS 5
      ISN 0025         6 DO 55 J=1,N
      ISN 0026        55 Y(J)=SAVY(J)+(PHI(J)+F(J))*H/6.0
      ISN 0027           IRUNG=2
      ISN 0028           RETURN
                   C
      ISN 0029           END
*OPTIONS IN EFFECT*NAME(MAIN) NOOPTIMIZE LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT NOGOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I)
*STATISTICS*   SOURCE STATEMENTS =       28, PROGRAM SIZE =      1600, SUBPROGRAM NAME = SBM22
*STATISTICS*  NO DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                      492K BYTES OF CORE NOT USED
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SM 1077

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LEVEL 2.3 (FAUG)                  OS/360  FORTRAN H EXTENDED              DATE 82.238/12.55.43        PAGE   1
REQUESTED OPTIONS: NODECK,NOLIST,OPT(0)
OPTIONS IN EFFECT: NAME(MAIN) NOOPTIMIZE LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT NOGOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I)
                C                                                                      00336538
                C                                                                      00336638
   ISN 0002           FUNCTION CDRE(RE)                                                00336799
                C**** THIS FUNCTION COMPUTES THE PRODUCT OF DRAG COEFFICIENT AND       00336838
                C**** REYNOLDS NUMBER FOR A SPHERE, WHICH IS NECESSARY FOR THE         00336938
                C**** EQUATIONS OF MOTION OF THE PARTICLES.                            00337038
                C                                                                      00337138
                C**** CONSTANT COEFFICIENTS.                                           00337238
   ISN 0003           A1=1.0/24.0                                                      00337338
   ISN 0004           A2=-2.3363*1.E-04                                                00337439
   ISN 0005           A3=2.0154*1.E-06                                                 00337599
   ISN 0006           A4=-6.9105*1.E-09                                                00337638
   ISN 0007           B0=-1.29536                                                      00337738
   ISN 0008           B1=9.86*1.E-01                                                   00337838
   ISN 0009           B2=-4.6677*1.E-02                                                00337938
   ISN 0010           B3=1.1235*1.E-03                                                 00338038
                C                                                                      00338138
                C**** CHOOSE THE APPROPRIATE POLYNOMIAL.                               00338238
   ISN 0011           IF(RE-4.0) 2,7,7                                                 00338338
                C                                                                      00338438
                C**** INITIAL ESTIMATE FOR ONE POLYNOMIAL.                             00338538
   ISN 0012         2 IF(RE-0.001) 3,4,4                                               00338638
   ISN 0013         3 CDRE=24.0                                                        00338738
   ISN 0014           GO TO 30                                                         00338838
                C                                                                      00338938
   ISN 0015         4 X=24.0*RE                                                        00339038
                C                                                                      00339138
                C**** BEGIN NEWTON METHOD ITERATION (MAXIMUM ITERATION TIMES=100)      00339299
   ISN 0016           DO 6 ITER =1,100                                                 00339399
   ISN 0017           FX=A1*X+A2*X**2+A3*X**3+A4*X**4-RE                               00339438
   ISN 0018           FPX=A1+2.0*A2*X+3.0*A3*X**2+4.0*A4*X**3                          00339538
   ISN 0019           DELX=FX/FPX                                                      00339638
   ISN 0020           X=X-DELX                                                         00339738
                C**** CHECK FOR CONVERGENCE.                                           00339838
   ISN 0021           EPS=1.E-06                                                       00339938
   ISN 0022           IF(ABS(DELX/X)-EPS) 5,5,6                                        00340038
   ISN 0023         5 CDRE=X/RE                                                        00340138
   ISN 0024           GO TO 30                                                         00340238
   ISN 0025         6 CONTINUE                                                         00340340
   ISN 0026           GO TO 29                                                         00340440
                C                                                                      00340538
                C**** INITIAL ESTIMATE FOR OTHER POLYNOMIAL.                           00340638
   ISN 0027         7 CD=1.0                                                           00340738
   ISN 0028           ELOG=0.4342944819032S2                                           00340838
   ISN 0029           X=ALOG(CD*RE**2)*ELOG                                            00340938
                C**** BEGIN NEWTON METHOD ITERATION (MAXIMUM ITERATION TIMES=100)      00341099
   ISN 0030           DO 24 ITER=1,100                                                 00341199
   ISN 0031           FX=B0+B1*X+B2*X**2+B3*X**3-ALOG(RE)*ELOG                         00341238
   ISN 0032           FPX=B1+2.0*B2*X+3.0*B3*X**2                                      00341338
   ISN 0033           DELX=FX/FPX                                                      00341438
   ISN 0034           X=X-DELX                                                         00341538
                C**** CHECK FOR CONVERGENCE.                                           00341638
   ISN 0035           EPS=1.E-06                                                       00341738
   ISN 0036           IF(ABS(DELX/X)-EPS) 22,22,24                                     00341840
   ISN 0037        22 CDRE=10.0**X/RE                                                  00341938
```

```
LEVEL 2.3 (FXU6)              CORE              OS/360  FORTRAN H EXTENDED              DATE 82.238/12.55.43        PAGE   2
   ISN 0038          GO TO 30                                                                    00342038
   ISN 0039       20 CONTINUE                                                                    00342140
              C                                                                                  00342238
   ISN 0040       29 WRITE(6,202)                                                                00342338
   ISN 0041      202 FORMAT(' NO CONVERGENCE')                                                   00342438
              C                                                                                  00342538
   ISN 0042       30 RETURN                                                                      00342639
   ISN 0043          END                                                                         00342738
*OPTIONS IN EFFECT*NAME(MAIN) NOOPTIMIZE LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT NOGOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I)
*STATISTICS*     SOURCE STATEMENTS =       42, PROGRAM SIZE =     1250, SUBPROGRAM NAME =  CORE
*STATISTICS*  NO  DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                        492K BYTES OF CORE NOT USED

*STATISTICS*  NO  DIAGNOSTICS THIS STEP
```

```
THE DISTRIBUTION OF PARTICLES IN A CIRCULAR JET DOWNSTREAM FROM A JET OPENING
******************************************************************************

THE PHYSICAL PARAMETERS OF THE FLOW STREAM ARE:
                              UD     =     1.0000
                              PD     =    0.010000
                              RHO    =    0.011213
                              SIGMA  =    1.000000
                              XMU    =   0.0001789
                              UF     =     700.0000
                              REZ    =    47.46225
                              XR     =     43.4756
                              AF     =   1.0000
THE NECESSARY DATA FOR THIS RUN IS
                              ITPL   =   11
                              NL     =    5
                              ITP    =   51
                              N1     =    1
                              N2     =    6
                              DBP    =  .20000
                              AMAXD  =     75.000
                              AMAXN  =    150.000
                              DTAU   =   1.0000
                              IFOP   =   25
                              XZ     =    11.79200
```

THE COMPLETE SOLUTION OF CHOSEN PARTICLES

AND

THE CO-ORDINATES AND VELOCITY OF ALL PARTICLES AT THE REQUIRED DISTANCE DOWNSTREAM

(ALL VALUES ARE NORMALIZED: TAU=TU/R, X'=X/R, Y'=Y/R, VX'=VX/UF, VY'=VY/UF, UX'=UX/UF, UY'=UY/UF)

PARTICLE 1

THE INITIAL CONDITIONS OF THIS PARTICLE ARE:

TAU	X'	Y'	VX'	VY'	UX'	UY'	CORE
0.0	11.792	0.0	0.999437	0.0	0.999439	0.0	
25.00	35.102	0.0	0.658894	0.0	0.356030	0.0	48.245
50.00	46.181	0.0	0.419317	0.0	0.255201	0.0	39.953
75.00	55.114	0.0	0.308299	0.0	0.213837	0.0	34.803
100.00	62.022	0.0	0.249825	0.0	0.190016	0.0	31.225
125.00	67.768	0.0	0.214116	0.0	0.173856	0.0	29.678
150.00	72.828	0.0	0.190605	0.0	0.161824	0.0	28.323
175.00	77.375	0.0	0.174056	0.0	0.152314	0.0	27.333
200.00	81.565	0.0	0.161666	0.0	0.144490	0.0	26.646
225.00	85.480	0.0	0.151924	0.0	0.137872	0.0	26.165
250.00	89.176	0.0	0.143973	0.0	0.132159	0.0	25.818
275.00	92.689	0.0	0.137296	0.0	0.127150	0.0	25.558
300.00	96.048	0.0	0.131566	0.0	0.122703	0.0	25.358
325.00	99.273	0.0	0.126563	0.0	0.118717	0.0	25.200
350.00	102.380	0.0	0.122135	0.0	0.115113	0.0	25.073
375.00	105.383	0.0	0.118173	0.0	0.111833	0.0	24.967
400.00	108.292	0.0	0.114597	0.0	0.108830	0.0	24.879
425.00	111.115	0.0	0.111345	0.0	0.106064	0.0	24.803
450.00	113.861	0.0	0.108367	0.0	0.103507	0.0	24.739
475.00	116.535	0.0	0.105627	0.0	0.101131	0.0	24.683
500.00	119.144	0.0	0.103092	0.0	0.098917	0.0	24.634
525.00	121.691	0.0	0.100739	0.0	0.096847	0.0	24.590
550.00	124.181	0.0	0.098545	0.0	0.094904	0.0	24.552
575.00	126.619	0.0	0.096493	0.0	0.093077	0.0	24.517
600.00	129.007	0.0	0.094567	0.0	0.091355	0.0	24.486
625.00	131.348	0.0	0.092756	0.0	0.089726	0.0	24.458
650.00	133.645	0.0	0.091048	0.0	0.088184	0.0	24.433
675.00	135.901	0.0	0.089433	0.0	0.086720	0.0	24.410
700.00	138.117	0.0	0.087904	0.0	0.085 29	0.0	24.389
725.00	140.296	0.0	0.086452	0.0	0.084004	0.0	24.370
750.00	142.440	0.0	0.085071	0.0	0.082739	0.0	24.352
775.00	144.550	0.0	0.083756	0.0	0.081531	0.0	24.336
800.00	146.628	0.0	0.082501	0.0	0.080376	0.0	24.321
825.00	148.675	0.0	0.081302	0.0	0.079269	0.0	24.307

THE FINAL CONDITIONS, AT A DISTANCE OF 75.00 DOWNSTREAM, ARE:

TAU	X'	Y'	VX'	VY'	UX'	UY'
842.00	150.050	0.0	0.080517	0.0	0.078583	0.0

PARTICLE 2

THE INITIAL CONDITIONS OF THIS PARTICLE ARE:

TAU	X'	Y'	VX'	VY'	UX'	UY'
0.0	11.792	0.200000	0.967187	0.007674	0.967187	0.007674

THE FINAL CONDITIONS, AT A DISTANCE OF 75.00 DOWNSTREAM, ARE:

TAU	X'	Y'	VX'	VY'	UX'	UY'
849.00	150.034	0.835381	0.080225	0.000321	0.078272	0.000213

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PARTICLE [illegible]
****

THE INITIAL CONDITIONS OF THIS PARTICLE ARE:

0.0	11.792	0.400000	0.879127	0.012992	0.879127	0.012992

THE FINAL CONDITIONS, AT A DISTANCE OF 75.00 DOWNSTREAM, ARE:

868.00	150.001	1.569998	0.079985	0.000404 --	0.022567	-0.000390 --

PARTICLE 4
****

THE INITIAL CONDITIONS OF THIS PARTICLE ARE:

0.0	11.792	0.600000	0.757000	0.015541	0.757000	0.015541

NO CONVERGENCE
THE FINAL CONDITIONS, AT A DISTANCE OF 75.00 DOWNSTREAM, ARE:

897.00	150.043	2.208954	0.078443	0.000552 ---	0.024621	-0.000531 -

PARTICLE 5
****

THE INITIAL CONDITIONS OF THIS PARTICLE ARE:

0.0	11.792	0.800000	0.624623	0.015735	0.624623	0.015735

NO CONVERGENCE
THE FINAL CONDITIONS, AT A DISTANCE OF 75.00 DOWNSTREAM, ARE:

932.00	150.051	2.765120	0.077300	0.000670 ---	0.025560	-0.000648 --

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PARTICLE 6
****

THE INITIAL CONDITIONS OF THIS PARTICLE ARE:

0.0	11.792	1.000000	0.499895	0.014377	0.499895	0.014377	
25.00	23.911	1.334849	0.454636	0.012175	0.353537	0.007800	34.707
50.00	34.194	1.600122	0.366863	0.008776	0.271816	0.005231	34.546
75.00	42.522	1.787936	0.301441	0.006434	0.228324	0.004035	32.068
100.00	49.437	1.928933	0.254631	0.004955	0.201523	0.003350	30.765
125.00	55.370	2.039995	0.221953	0.003998	0.183114	0.002902	29.522
150.00	60.613	2.131449	0.198713	0.003360	0.169455	0.002582	28.381
175.00	65.356	2.209559	0.181555	0.002915	0.158750	0.002339	27.485
200.00	69.723	2.278148	0.168361	0.002589	0.150026	0.002147	26.821
225.00	73.795	2.339621	0.157845	0.002340	0.142711	0.001990	26.332
250.00	77.630	2.395574	0.149213	0.002144	0.136446	0.001859	25.965
275.00	81.267	2.447102	0.141952	0.001984	0.130990	0.001747	25.686
300.00	84.736	2.494988	0.135739	0.001851	0.126175	0.001650	25.467
325.00	88.060	2.539817	0.130325	0.001739	0.121881	0.001565	25.293
350.00	91.257	2.582033	0.125550	0.001642	0.118017	0.001490	25.152
375.00	94.342	2.621984	0.121298	0.001557	0.114513	0.001428	25.035
400.00	97.325	2.659944	0.117465	0.001482	0.111315	0.001363	24.938
425.00	100.218	2.696141	0.113994	0.001416	0.108379	0.001309	24.855
450.00	103.027	2.730763	0.110826	0.001356	0.105672	0.001260	24.784
475.00	105.761	2.763966	0.107918	0.001302	0.103163	0.001214	24.723
500.00	108.424	2.795879	0.105237	0.001253	0.100830	0.001173	24.669
525.00	111.024	2.826622	0.102752	0.001208	0.098653	0.001135	24.622
550.00	113.563	2.856290	0.100440	0.001167	0.096614	0.001099	24.580
575.00	116.047	2.884970	0.098283	0.001129	0.094699	0.001066	24.543
600.00	118.478	2.912732	0.096262	0.001094	0.092897	0.001035	24.510
625.00	120.860	2.939650	0.094365	0.001061	0.091196	0.001007	24.480
650.00	123.197	2.965777	0.092578	0.001031	0.089586	0.000980	24.453
675.00	125.490	2.991171	0.090891	0.001002	0.088061	0.000955	24.428
700.00	127.742	3.015875	0.089295	0.000975	0.086612	0.000931	24.406
725.00	129.955	3.039935	0.087782	0.000950	0.085234	0.000908	24.385
750.00	132.131	3.063396	0.086345	0.000927	0.083921	0.000887	24.366
775.00	134.272	3.086273	0.084978	0.000905	0.082668	0.000867	24.349
800.00	136.380	3.108612	0.083675	0.000884	0.081470	0.000848	24.333
825.00	138.456	3.130441	0.082431	0.000864	0.080323	0.000830	24.318
850.00	140.502	3.151785	0.081242	0.000845	0.079225	0.000813	24.304
875.00	142.518	3.172668	0.080104	0.000827	[illegible]	0.000797	24.292
900.00	144.507	3.193114	0.079013	0.000810	[illegible]	0.000781	24.280
925.00	146.469	3.213144	0.077966	0.000794	[illegible]	0.000766	24.269
950.00	148.405	3.232778	0.076961	0.000778	[illegible]	0.000752	24.258

THE FINAL CONDITIONS, AT A DISTANCE OF 75.00 DOWNSTREAM, ARE:

971.00	150.012	3.268978	0.076166	0.000766 ---	[illegible]	-0.000740 --

THE INITIAL CONCENTRATION OF PARTICLES IS 64.935196

THE AVERAGE CONCENTRATION OF PARTICLES, A DISTANCE OF 75.00 DOWNSTREAM IS 1.537895

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This Sheet Security Classification

DOCUMENT CONTROL DATA – R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

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11. SUPPLEMENTARY NOTES	12. SPONSORING ACTIVITY

13. ABSTRACT

A mathematical model has been developed to predict the downstream distribution of particles in a fluid jet. The particles were initially assumed to be evenly dispersed over a cross-section of the circular jet, near the source of the jet, and, with computer-aided methods, the co-ordinates of the particles at a specified distance downstream were determined. The computer program was also built in such a manner that the paths of specific particles, from their initial upstream position to their final position downstream, could be completely followed. Some graphical results of these paths are presented for various particle sizes.

(U)

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KEY WORDS

Aerosol

Turbulent Jet

Particulate Dissemination

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