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TURBULENT COAXIAL MIXING OF DISSIMILAR GASES AT NEARLY EQUAL STREAM VELOCITIES

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ABSTRACT

An analytical and experimental study is made of the isothermal turbulent mixing that ensues when one gas in injected coaxially into a stream of another gas that is moving in the same direction at a comparable velocity. The problem of turbulent coaxial mixing of dissimilar gases has been the subject of a number of recent studies. These investigations have resulted in a number of proposed formulations for the dependence of turbulent viscosity on geometry, flow, and physcial-property parameters. The various expressions for turbulent viscosity are compared in this paper on a consistent basis. It is shown that the different equations predict essentially the same eddy viscosity within certain ranges of stream velocity ratios and density ratios. Considerable divergence of results occurs, however, when a given equation is applied beyond the range of experimental conditions for which it has been verified.

Some of the proposed expressions include an axial dependence of the turbulent viscosity, others do not. Previously published data are compared with theory for three different assumed variations of eddy viscosity with axial position. It is shown that, for nearly equal stream velocities, the eddy viscosity can be taken as constant in both the radial and axial directions.

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The differences and similarities of the various analytical treatments to date have resulted, primarily, from attempts to include the case of equal stream velocities within the framework of Prandtl's original hypothesis for free turbulent flow. This phenomenological model predicts no turbulence if the two streams move at the same velocity. Experimental measurements have shown that this is not the case. This is not surprising, since, as has been suggested, some degree of initial turbulence will be present in the two streams. At nearly equal stream velocities, the effect of this initial turbulence should be most apparent.

The results of an experimental study of the turbulent coaxial flow of a bromine jet into an air stream are presented. It is shown that the initial turbulence in the two streams can be of significant importance when compared with that induced by differences in the stream velocities. Photographs of the bromine stream show that, for equal stream velocities, the flow changes from a laminar appearance to a turbulent one as the initial Reynolds number of the bromine stream is increased from 1840 to 3220. When honeycombs with 1/8 inch diameter cells that are 2 inches long are placed in both the air stream and the bromine stream, the turbulent appearance at the higher Reynolds number is greatly reduced. Photographs of the bromine stream for initial air-to-bromine velocity ratios of 0.85 and 1.52 indicate that the turbulence created by this velocity defect is much less than that initially present in the two streams.

It is concluded that the turbulence initially present in the two streams plays an important part in the turbulent coaxial mixing of dissimilar gases at nearly equal stream velocities. It is therefore probable

[redacted]

that simple, empirical modifications of Prandtl's expression for eddy viscosity do not adequately describe the mixing process, and that additional terms should be included to account for the initial turbulence present in the two streams.

INTRODUCTION

Turbulent shear flow has remained a subject of interest in the field of fluid mechanics for a considerable number of years. Free turbulence most commonly occurs in jet and wake flows. Most of the initial attention to jet flow was directed to the situation where an incompressible fluid issues into a quiescent environment of the same fluid. Considerable success was achieved by the application of phenomenological theories, notably Prandtl's mixing length hypothesis, and similarity solutions.[1]

A more complex situation arises when the medium into which the jet exhausts is not at rest and is not of the same material. Such a system has been the subject of a number of recent studies. These investigations have been prompted by interest in a gaseous-fueled nuclear rocket engine,[2] where a low-velocity fissionable gas is injected coaxially into a high velocity hydrogen propellant stream, and a supersonic combustor,[3] where high velocity hydrogen issues into a parallel stream of oxidizer that is flowing at a comparable velocity. Both situations involve the turbulent coaxial mixing of dissimilar gases.

Up to a point, the approaches to this problem have been the same. The diffusion equation and the Navier-Stokes momentum equations are written for isothermal, axisymmetric, boundary-layer flow, along with the continuity equation. This equation set is then applied to turbulent flow by assuming that the molecular transport coefficients can be replaced by or added to their turbulent counterparts. These equations are then solved by a transformation to a stream-function, axial-coordinate plane. All of the theoretical works have assumed that the turbulent transport coefficients are constant in the radial direction. An experimental study of hydrogen, helium, and argon jets issuing into an air stream indicates that this assumption is reasonably good; the eddy viscosity was found to decrease to 0.8 of the centerline value at the half-radius of the jet.[4]

To complete the analytical description of the flow field, it is necessary to make some algebraic statement as to the dependence of the eddy viscosity and the eddy diffusivity on pertinent geometry, flow, and physical-property parameters. It is in this regard that various approaches have been suggested. What is required is the equivalent of Prandtl's hypthesis, which stated that, in a region of free turbulence, the eddy diffusivity is proportional to the width of the mixing zone and to the difference between the maximum and minimum velocities across it. Two problems arise if this formulation is applied as stated. The first is that no turbulence is predicted for the case of equal stream velocities, although it has been observed in experimental studies. It has been demonstrated, however, that an eddy viscosity proportional to a velocity defect can be used to correlate turbulent coaxial mixing of dissimilar gases if the stream velocities are not equal.[5,6] A proposal has been made for the situation of nearly equal stream velocities to modify Prandtl's original hypothesis to include the difference in stream densities. One suggestion is to replace the velocity difference with a mass flux difference;[3] such a formulation has shown agreement with experimental data over the ranges investigated. This expression, however, is not altogether satisfactory, since it predicts no turbulence when the mass fluxes of the two streams are equal. An experimental study of this particular flow condition has shown that turbulence does exist for equal mass fluxes;[7] the author of reference 7 proposes an expression to eliminate this anomaly in which the eddy viscosity is taken to be proportional to the sum of the mass flux and the momentum flux. This expression is also shown to be in agreement with some experimental data.

The second problem that arises in attempting to apply Prandtl's free-turbulence expression to the coaxial mixing process results from the fact that it attempts to attribute all turbulence to the velocity difference between the two streams. The original equation, as well as all of the proposed modifications discussed above, requires that the eddy viscosity in the coaxial mixing region be proportional to some difference between the two streams. This does not account for any turbulence that is initially present in either of the two streams. It has been suggested that this "preturbulence" may be the dominant factor if the two streams are at nearly equal velocities.[8] The possible contribution of initial stream turbulence and boundary layers has also been mentioned in a number of the recent studies.[3,5,7] Experimental evidence that initial stream turbulence can affect the coaxial mixing process is reported in reference 9, where it was found that honeycomb flow straighteners significantly reduced the preturbulence. This is in accord with studies of the effect of grids on the eddy-diffusion coefficient in turbulent duct flow, where it has been found that grids appreciably reduce the scale of turbulence.[10]

These two aspects of the turbulent coaxial mixing of dissimilar gases have been investigated and are discussed herein. A number of expressions have been proposed for the eddy viscosity variation. Though the algebraic formulations appear to have significant differences, each expression has shown agreement with experimental data, at least for the range of data investigated in each case. These various relations for eddy viscosity are compared here on a consistent basis in order to disclose their similarities and differences. Previously published data are compared with theoretical calculations in order to determine the axial dependence of the eddy viscosity. The theoretical calculations are made with a computer program[2,11] that solves the axisymmetric boundary-layer equations with no similarity assumptions, and that incorporates arbitrary variations of eddy viscosity in the axial direction. The data are compared with the analysis for an eddy viscosity that increases, decreases, and is constant with axial position.

Results are also presented of an experimental study of the effect of preturbulence on the coaxial mixing process at nearly equal stream velocities. Photographs of a bromine stream exhausting into a surrounding air stream for various flow conditions are shown. The initial velocity ratios, air to bromine, were maintained between 0.988 and 1.009 to minimize the contribution of velocity defect to the free turbulence. Bromine Reynolds numbers were varied from 1840 to 3230. These flow conditions were repeated with 1/8-inch passage diameter honeycomb sections 2 inches thick in both the air and bromine streams at the injection point. In order to determine the relative contribution to turbulence of a velocity defect, initial velocity ratios were varied from 0.85 to 1.5 at a constant bromine Reynolds number of 2300.

EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 1 shows a schematic layout of the experimental apparatus, which consists of a vertical test section, metered air and bromine supplies, throttled vacuum exhaust, and electro-optical data instrumentation. The central feature of the apparatus is the rectangular vacuum-tight test section, which is 8 inches square in cross section by approximately 9 feet in height. Figure 2 shows the test section and some of the associated instrumentation. Two opposing faces of the test section consist of optical windows; through these is projected a collimated beam of white light that is intercepted by a photodetector on the opposite side. A narrow band-pass optical filter on the detector face passes monochromatic light at the peak of the bromine absorption band at 4150 angstroms. The light source and detector are rigidly mounted on a U-shaped frame to maintain alignment. The output of the detector provides a measure of the average bromine density along a given chord through the bromine stream.

The bromine boiler is seen at the right of figure 3; bromine flow is controlled by the power input to an internal quartz-jacketed pancake heater immersed in the bromine tank. The test section is operated at the vapor pressure of bromine at room temperature, about 4.5 psia. Thus, the heater supplies the heat of vaporization required to attain a desired flow. The monel boiler is coated inside with Teflon. Because of the extreme corrosiveness of bromine, only glass or Teflon is in contact with the vapor until it reaches the top of the test section. There it enteres a 1-inch-diameter monel tube from which it is injected into the air stream. Both gases flow from top to bottom through the test section.

Lucite tube bundles at the top and bottom of the test section eliminate any large-scale flow oscillations in the air stream. Air and bromine flow rates are measured with rotameters. The sizes of the test section and the bromine tube were chosen so as to provide operation at Reynolds numbers below and above 2000, as well as velocity ratios, air to bromine from 1.0 up to about 50.

The first step in running procedure is to set the desired air flow rate. This is done by use of an upstream-flow-control valve and a downstream valve that throttles to a vacuum exhaust system. After the desired air flow is established at the vapor pressure of bromine, the bromine flow is initiated by supplying power to the boiler. The bromine response is virtually instantaneous, since little heat loss is incurred by operation at room temperature. Typically, steady flow conditions can be achieved in 5 or 10 minutes.

THEORETICAL CONSIDERATIONS

The basic analytical procedure used here to compute turbulent coaxial velocity and concentration fields is described in references 2, 5, and 11, and only the pertinent features will be reiterated. The equation set is composed of the continuity, diffusion, and momentum equations written for isothermal, axisymmetric, boundary-layer flow. The bouyancy term is included, and no linearizing or similarity assumptions are made so that the results apply equally well near the jet origin. A von Mises transformation to a stream-function axial-position coordinate set is employed in the numerical solution. The ratio of eddy viscosity to molecular viscosity, $(\rho\epsilon/\mu)$, is assumed constant in the radial direction, and is varied in the axial direction according to the arbitrary function, $A + B\bar{z}^{C}$, where $\bar{z}$ is the axial distance from the jet origin. The turbulent transport coefficients, $\rho\epsilon$ and ϵ, are added to their molecular counterparts, μ and D_{12}, respectively. The eddy diffusivities for momentum and mass transport are assumed equal. The model of the coaxial flow field and the pertinent varables are shown in figure 3.

In order to compare the various expressions for eddy viscosity, they must be rewritten in the same form. From a study of air-bromine coaxial mixing, reference 5 obtains the following equation:

$$\frac{U\epsilon}{\mu} = 0.0172\left(\frac{U_e}{U_j} - 1\right)^{1/2} Re_j - 250 \tag{1}$$

For Reynolds numbers that are large with respect to the constant 250, equation (1) can be written in the form

$$\frac{(\rho\epsilon)_{¢}}{\rho_j U_j r_j}\ \frac{\rho_j}{\rho} = 0.187\left(\frac{U_e}{U_j} - 1\right)^{1/2} \tag{2}$$

In equation (2), $(\rho\epsilon)_{¢}$ is the centerline, or jet, value of the eddy viscosity.

Reference 3 suggests the following expression for eddy viscosity

$$(\rho\epsilon)_{¢} = 0.025\ r_{1/2}\ (\rho_e U_e - \rho_{¢} U_{¢}) \tag{3}$$

This can be written at the jet origin as

$$\frac{(\rho\epsilon)_{\not{c}}}{\rho_j U_j r_j} \frac{\rho_j}{\rho_e} = 0.025\left(\frac{U_e}{U_j} - \frac{\rho_j}{\rho_e}\right) \tag{4}$$

This expression has shown agreement with air-hydrogen data. For equal temperatures, the density ratio on the right side of equation (4) becomes the molecular weight ratio of hydrogen to air, 0.069. It should be noted here that the preceding expression produces an eddy viscosity ratio that varies in the axial direction, since both the centerline density and velocity are axial functions. For the purposes of this comparison, equation (4) is used to evaluate the eddy viscosity at the jet origin, where the jet density and velocity are at their initial values.

The expression proposed in reference 7 for the eddy viscosity is as follows:

$$\frac{(\rho\epsilon)_{\not{c}}}{\rho_j U_j r_j} = 0.025 \frac{r_{1/2}}{r_j}\left(\frac{\rho_e U_{\not{c}}}{\rho_j U_j} + \frac{\rho_e U_e^2}{\rho_j U_j^2}\right) \tag{5}$$

in a form similar to equations (2) and (4): This equation can be written at the jet origin

$$\frac{(\rho\epsilon)_{\not{c}}}{\rho_j U_j r_j} \frac{\rho_j}{\rho_e} = 0.025\left[1 + \left(\frac{U_e}{U_j}\right)^2\right] \tag{6}$$

where $(\rho\epsilon)_{\not{c}}$ is the value of the eddy viscosity in the jet stream at the injection point.

Equations (1), (3), and (5) have all been proposed to express the functional dependence of the turbulent viscosity $\rho\epsilon$. Obviously, they are not of the same form; yet each has been shown to agree with experimental data. By rewriting the equations in the forms given by equations (2), (4), and (6), it is possible to compare the various expressions on a consistent basis to see how similar or different they are.

In reference 5 it is suggested that a viscosity ratio of the two streams should be included in the eddy viscosity. In order to evaluate this idea, equations (2), (4), and (6) can be rewritten by adding the viscosity ratio to the left side of the equations, and multiplying the numerical coefficients on the right side by the actual values of the ratios of the gases used in the experiments related to each expression. By using the viscosity ratios of the gases studied by each of the investigators, equations (2), (4), and (6) can be written as follows:

$$\frac{(\rho\epsilon)_{⊄}}{\rho_j U_j r_j} \frac{\rho_j}{\rho_e} \frac{\mu_e}{\mu_j} = 0.228 \left(\frac{U_e}{U_j} - 1 \right)^{1/2} \tag{7}$$

$$\frac{(\rho\epsilon)_{⊄}}{\rho_j U_j r_j} \frac{\rho_j}{\rho_e} \frac{\mu_e}{\mu_j} = 0.051 \left(\frac{U_e}{U_j} - \frac{\rho_j}{\rho_e} \right) \tag{8}$$

$$\frac{(\rho\epsilon)_{⊄}}{\rho_j U_j r_j} \frac{\rho_j}{\rho_e} \frac{\mu_e}{\mu_j} = 0.051 \left[1 + \left(\frac{U_e}{U_j} \right)^2 \right] \tag{9a}$$

$$\frac{(\rho\epsilon)_{⊄}}{\rho_j U_j r_j} \frac{\rho_j}{\rho_e} \frac{\mu_e}{\mu_j} = 0.031 \left[1 + \left(\frac{U_e}{U_j} \right)^2 \right] \tag{9b}$$

Equations (9a) and (9b) are both rewritten forms of equation (6) with viscosity ratios of hydrogen-air and CO_2-air, respectively, since both of these systems were studied in reference 7.

DISCUSSION OF RESULTS

In reference 5 it was shown that good agreement between theory and experimental data was obtained by assuming that the ratio of the turbulent-to-laminar viscosity $\rho\epsilon/\mu$ was constant over the entire flow field. Since for the air-bromine system studied, the viscosity ratio was only 1.22, this assumption also results in an eddy viscosity $\rho\epsilon$ that is essentially constant. In references 3 and 7, the proposed expressions (eqs. (3) and (5)) yield an eddy viscosity that varies in the axial direction. To check the importance of an axial dependence of eddy viscosity, the data reported in reference 5 have been compared with the analysis of reference 11. The arbitrary variations of $\rho\epsilon/\mu$ considered are shown in figure 4. The constant value of 6 is the one reported in reference 5 as best representing the experimental data for an initial air-to-bromine velocity ratio of 1.25, a bromine Reynolds number of 870, and an air Reynolds number of 1720. The other two variations considered were a turbulent-to-laminar viscosity ratio that is proportional to $\bar{z}^{1/2}$ and one that is proportional to $\bar{z}^{-1/2}$. The coefficients shown for these two cases are those that best represented the data shown in figure 5. Figure 5(a) shows the comparison of the experimental data with theory for the three cases. The ordinate is the average bromine concentration normalized to the first data point. Figures 5(b) and 5(c) show similar comparisons for initial velocity ratios of 0.97 and 0.83.

These results indicate that, although an axial variation of the turbulent-to-laminar viscosity ratio does fit the data, it is not necessary. A constant value is adequate, if not better. This is in accord with the

the case of a circular jet issuing into a quiescent environment of the same fluid; for this situation, it has been established that the kinematic eddy viscosity is indeed constant over the entire flow field.[1]

Figure 6(a) shows a comparison of the various expressions for the turbulent viscosity as given by equations (2), (4), and (6). The data points on the curves from references 3 and 7 indicate the velocity ratios at which the analysis has been compared with experimental data. With the exception of the point at a velocity ratio of 2.8 (from ref. 3), the various expressions are in general agreement. This is quite remarkable, in view of the differences in the algebraic formulations, and the wide variations of the experimental conditions upon which they are based. The expressions of references 5 and 7 predict turbulent viscosities at the jet origin that are quite close; the data of reference 5 were obtained with an air-bromine system and jet Reynolds numbers from 255 to 3850, while the data of reference 7 were for a hydrogen-air and a CO_2-air system at jet Reynolds numbers of the order of 1 million. The limits of ±25 percent shown indicate the spread of the data of reference 5. It is of interest to note that the agreement between the expressions of references 5 and 7 would not exist at velocity ratios beyond about 3.5. The correlation of reference 7 predicts turbulent viscosities that are considerably in excess of those measured in reference 5, if the equation is applied much beyond the range in which it has been experimentally verified. This is due to the contribution of the momentum flux term in equation (5), which contains a squared velocity term.

Figure 6(b) shows a similar comparison except that the viscosity ratio of the two streams is included, as given by equations (7), (8), and (9). The trend is to move the expressions closer together, but the effect is slight, since the viscosities of the gases involved do not differ greatly.

The general conclusion suggested by figure 6 is that the modifications of Prandtl's original formulation that have been obtained by introducing mass and/or momentum fluxes have resulted in expressions that are more different in algebraic structure than in actual numerical fact.

Since considerable effort has been devoted to correlating the eddy viscosity in coaxial mixing, it is pertinent to inquire into how much of this turbulence is actually induced by differences between the two streams relative to that which is initially present. At nearly equal stream velocities the contribution of the preturbulence should be more readily detected. A series of test runs were made on a bromine jet exhausting into an air stream to investigate this effect. Photographs were taken of the bromine stream for a number of flow conditions, both with and without honeycomb sections in the two streams. Table 1 summarizes the conditions investigated.

Figure 7 shows the bromine flow for an initial velocity ratio of 1.009, a bromine Reynolds number of 1840, and an air Reynolds number of 2130. This clearly demonstrates that at nearly equal strem velocities, a segregated laminar-like flow pattern exists at low Reynolds numbers. Figure 8 shows the flow pattern for a velocity ratio of 0.988, a bromine

Reynolds number of 3230, and an air Reynolds number of 3660. Here the nature of the flow is markedly turbulent, though the velocity ratio is essentially unchanged. This shows that, for these flow conditions, turbulence can be induced in the coaxial mixing region by increasing the stream Reynolds numbers at constant velocity ratio.

To study the effect of upstream turbulence further, these flow conditions were repeated with honeycomb flow passages in both the air stream and the bromine stream at the injection point. An individual passage in the honeycomb was 1/8 inch in diameter and 2 inches in length. Thus, the Reynolds number of the bromine stream was reduced by a factor of 8 upon entering the honeycomb, while the air Reynolds number was reduced by a factor of 64.

Figure 9 illustrates the flow patterns at the same low Reynolds number (prior to the honeycomb sections) conditions as figure 7. This shows that the presence of the honeycombs did not add any significant degree of turbulence, since a smooth, segregated flow was again obtained. Figure 10 shows the nature of the flow when the Reynolds numbers of the flow are increased as before. Here the flow is turbulent, but the level of the turbulence is, qualitatively, much less. Comparison of figures 8 and 10, which are for identical flow conditions except for the honeycombs, shows that the honeycombs do significantly reduce the initial turbulence, though they do not eliminate it.

To assess the contribution of a stream velocity difference to turbulence relative to that initially present, the air stream velocity was varied while keeping the bromine stream constant. Figure 11 again shows the laminar-like flow pattern for a velocity ratio of 0.987, a bromine Reynolds number of 2300, and an air Reynolds number of 2600. Figure 12 shows the flow pattern when the air Reynolds number is decreased to 2240, producing a velocity ratio of 0.85. There is no significant change in the appearance of the flow. Figure 13 illustrates the flow pattern when the air flow is increased to a Reynolds number of 4010 and a velocity ratio of 1.52. Some flow disturbances are apparent, but the turbulence is considerably less severe than that present at a higher Reynolds number and a velocity ratio of 0.988.

These flow studies indicate that initial turbulence plays an important part in the nature of coaxial mixing of dissimilar gases, and at nearly equal stream velocities can dominate the situation. It is therefore unlikely that expressions which contain only differences of stream parameters will meet with general success and that additional terms will be required to account for the additional sources of turbulence present in the two streams.

CONCLUSIONS

A comparison has been made of various suggested expressions for the eddy viscosity in a turbulent coaxial flow system. Some arbitrary variations of the axial dependence of eddy viscosity have been used to compare theory with experiment, and an experimental study of the effect of initial stream turbulence on the mixing region has been conducted. For the range of conditions investigated, the following conclusions are indicated:

1. An axial variation of eddy viscosity does not improve the agreement of theory with experimental data that is obtained with a constant value.

2. Modifications of Prandtl's hypothesis for turbulent shear flow that introduce mass and or momentum fluxes rather than velocities produce expressions whose differences are more apparent than real. These various expressions predict essentially the same eddy viscosity when compared on a consistent basis, as long as they are only applied within the range of conditions for which they have been experimentally verified.

3. The initial turbulence present in the two streams contributes significantly to the coaxial mixing process, and can dominate the situation for nearly equal stream velocities. The presence of honeycomb sections immediately upstream of the injection point can reduce the turbulent mixing induced by this preturbulence.

NOMENCLATURE

A,B,C	constants
b	width of mixing region
C^*	normalized average bromine concentration
D_{12}	binary diffusion coefficient
Re	Reynolds number, $2rU\rho/\mu$
r	radial coordinate
$r_{1/2}$	half-radius
U	axial velocity component
z	axial coordinate
$\overline{z}$	dimensionless axial distance, z/r_j
ϵ	eddy diffusivity
$\rho\epsilon$	eddy viscosity

μ viscosity

ρ density

Subscripts:

℄ centerline

e external

j jet

REFERENCES

1. Schlichting, H., Boundary Layer Theory, 4th ed., New York: McGraw-Hill, 1960, chap. XXIII.

2. Ragsdale, R. G., and Weinstein, H., "On the Hydrodynamics of a Co-axial Flow Gaseous Reactor," Proceedings ARS/ANS/IAS Nuclear Propulsion Conference, TID 7653, pt. 1, pp. 82-88, August, 1962.

3. Ferri, A., Libby, P. A., and Zakkay, V., Theoretical and Experimental Investigation of Supersonic Combustion, pp. 55-118 in High Temperatures in Aeronautics, New York: Pergamon Press, 1962.

4. Zakkay, V., Krause, E., and Woo, S. D. L., Turbulent Transport Properties for Axisymmetric Heterogeneous Mixing, AIAA J., 1964, 2, (11), 1939-1947.

5. Ragsdale, R. G., Weinstein, H., and Lanzo, C. D., "Correlation of a Turbulent Air-Bromine Coaxial-Flow Experiment", NASA TN D-2121, February 1964.

6. Libby, P. A., Theoretical Analysis of Turbulent Mixing of Reactive Gases With Application to Supersonic Combustion of Hydrogen, ARS J., 1962, 32 (3), 388-396.

7. Alpinieri, L. J., Turbulent Mixing of Coaxial Jets, AIAA J., 1964, 2 (9), 1560-1567.

8. Abramovich, G. N., The Theory of Turbulent Jets, Cambridge, Mass.: M.I.T. Press, 1963, p. 153.

9. Curtet, R., and Ricou, R. P., On the Tendency to Self-Preservation in Axisymmetric Ducted Jets, J. Basic Engineering, Trans. ASME, Dec. 1964, 86 (4), 765-776.

10. Hinze, J. O., Turbulence, New York: McGraw-Hill, 1959, pp. 340-342.

11. Weinstein, H., and Todd, C. A., "A Numerical Solution of the Problem of Mixing of Laminar Coaxial Streams of Greatly Different Densities - Isothermal Case," NASA TN D-1534, February 1963.

TABLE I. - FLOW CONDITIONS FOR PRETURBULENCE STUDY

Figure	Run	Velocity ratio, U_e/U_j	Jet Reynolds number, Re_j	External Reynolds number, Re_e	Honeycombs	Jet velocity component, U_j, ft/sec	External velocity component, U_e, ft/sec
7	E1	1.009	1840	2130	No	2.896	2.921
8	E6	0.988	3230	3660	No	5.071	5.010
9	E25	1.009	1840	2130	Yes	2.896	2.921
10	E27	0.988	3230	3660	Yes	5.071	5.010
11	E3	0.987	2300	2600	No	3.632	3.587
12	E12	0.85	2300	2240	No	3.617	3.073
13	E11	1.52	2300	4010	No	3.617	5.494

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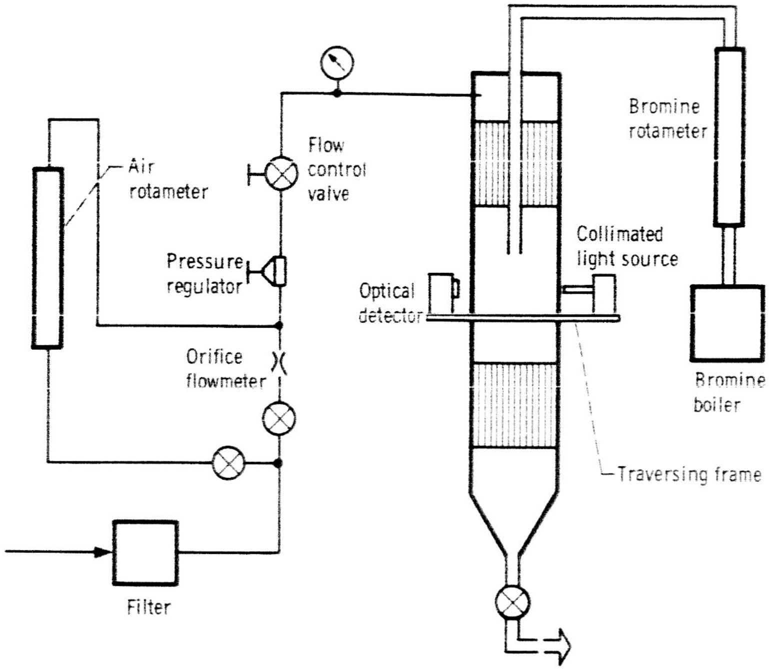

Figure 1. - Schematic drawing of air-bromine system.

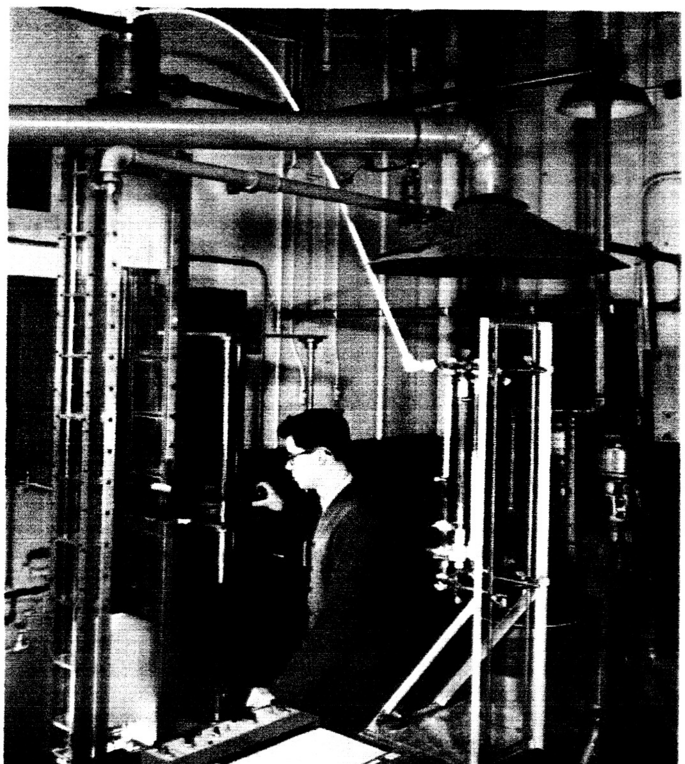
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Figure 2. - Experimental apparatus.

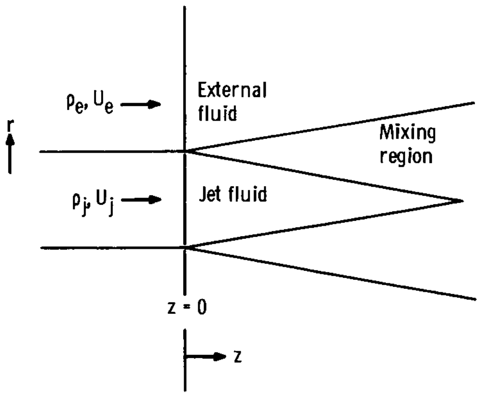

Figure 3. - Model of coaxial flow system.

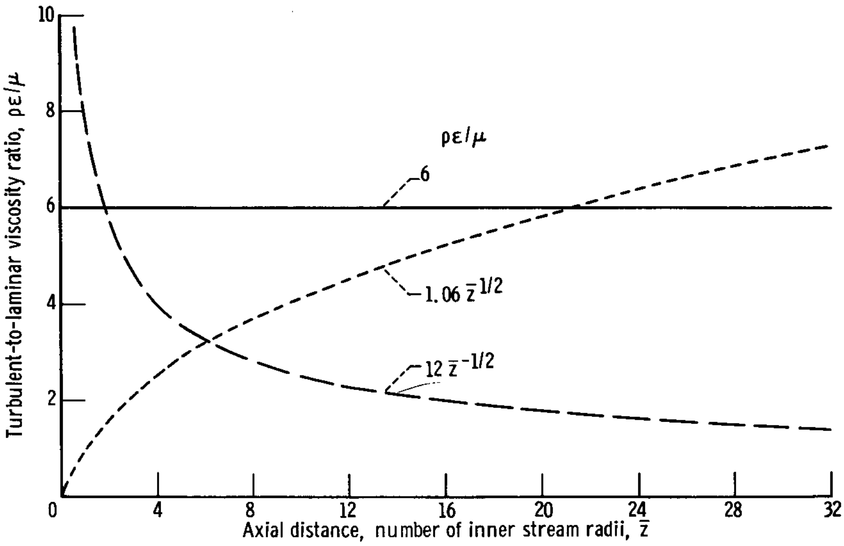

Figure 4. - Variations of $\rho\varepsilon/\mu$ used in data comparison for $U_e/U_j = 1.25$; $Re_j = 870$; $Re_e = 1720$.

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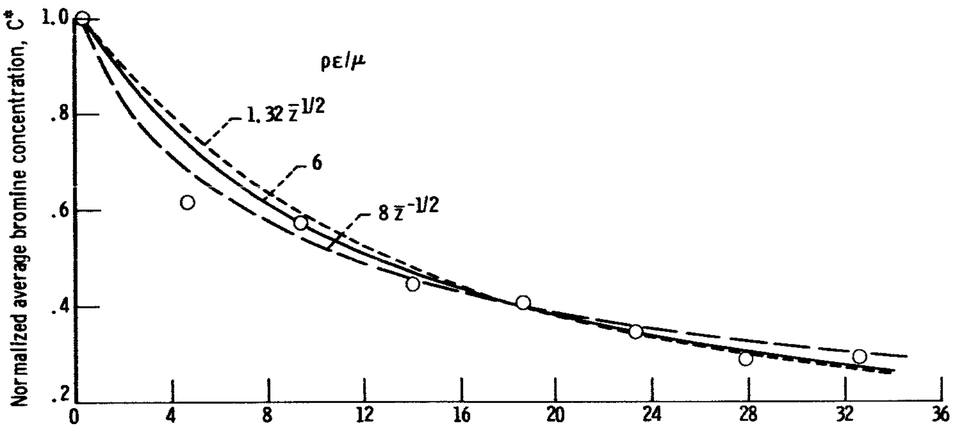
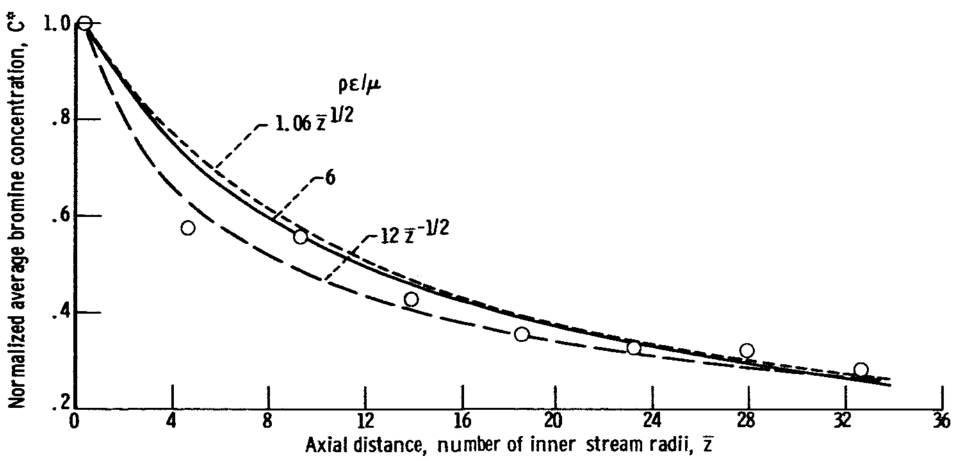


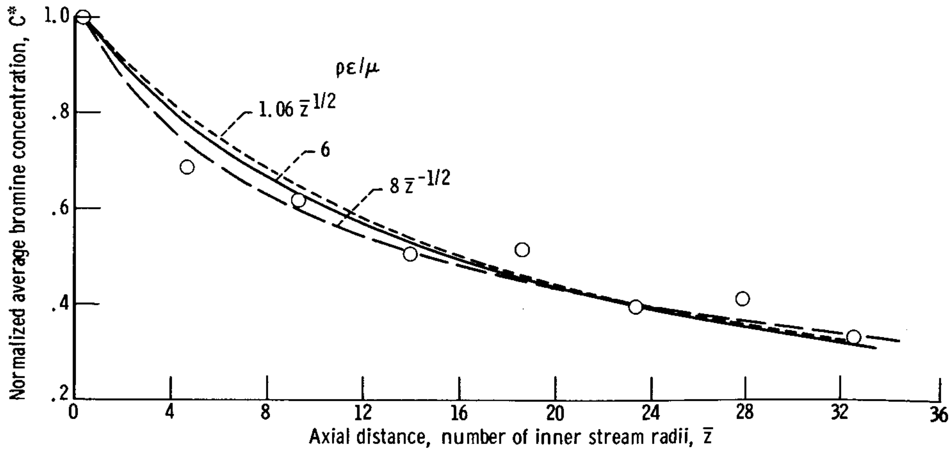
(a) $U_e/U_j = 1.25$; $Re_j = 870$; $Re_e = 1720$.

Figure 5. - Comparison of data and analysis.



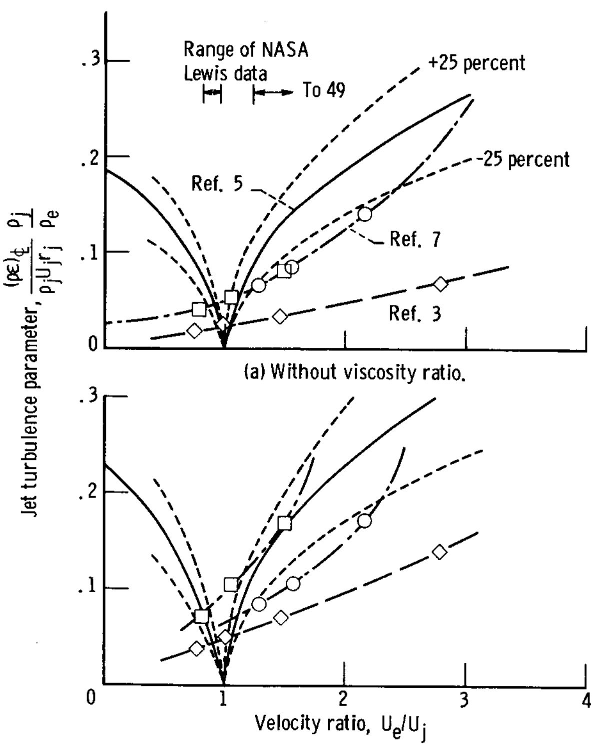
(b) $U_e/U_j = 0.97$; $Re_j = 870$; $Re_e = 1330$.

Figure 5. - Continued. Comparison of data and analysis.



(c) $U_e/U_j = 0.83$; $Re_j = 1030$; $Re_e = 1350$.

Figure 5. - Concluded. Comparison of data and analysis.



(a) Without viscosity ratio.

(b) With viscosity ratio.

Figure 6. - Comparison of turbulent viscosity formulations at jet origin.

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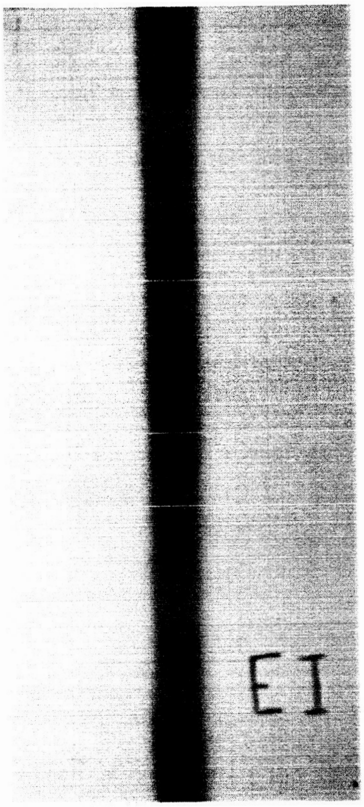

Figure 7. - Flow pattern for U_e/U_j = 1.009; Re_j = 1840; and Re_e = 2130.

Figure 8. - Flow pattern for U_e/U_j = 0.988; Re_j = 3230; and Re_e = 3660.

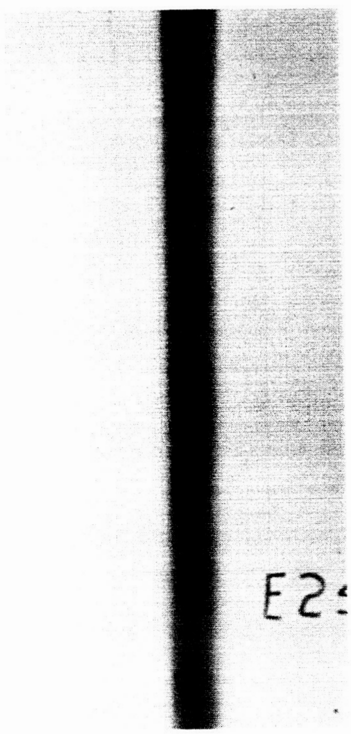

Figure 9. - Flow pattern for U_e/U_j = 1.009; Re_j = 1840; and Re_e = 2130.

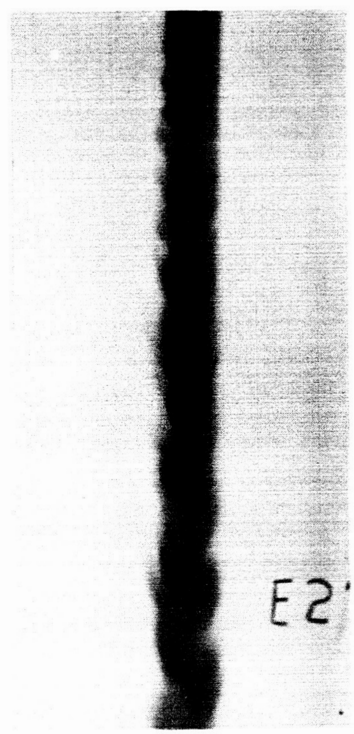

Figure 10. - Flow pattern for U_e/U_j = 0.988; Re_j = 3230; and Re_e = 3660.

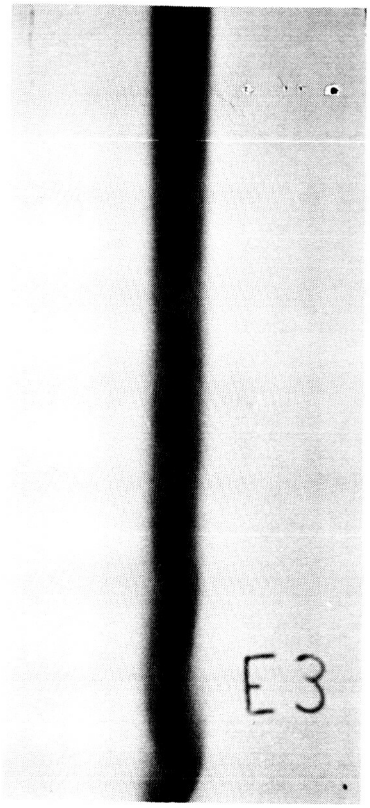

Figure 11. - Flow pattern for $U_e/U_j = 0.987$; $Re_j = 2300$; and $Re_e = 2600$.

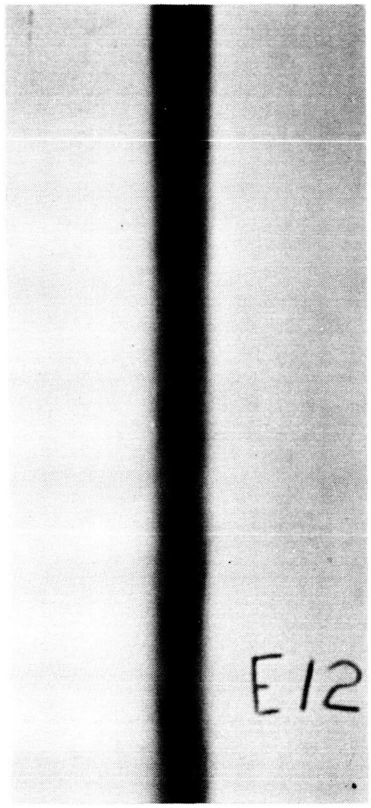

Figure 12. - Flow pattern for $U_e/U_j = 0.85$; $Re_j = 2300$; and $Re_e = 2240$.

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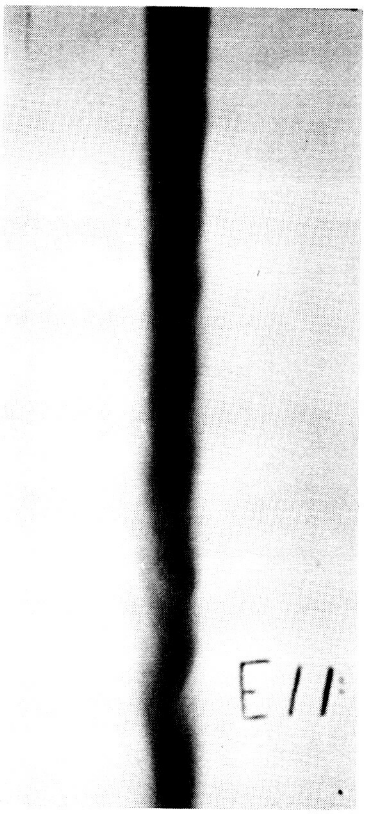

Figure 13. - Flow pattern for $U_e/U_j = 1.52$; $Re_j = 2300$; and $Re_e = 4010$.