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PHOTOGRAPHIC STUDY OF A BROMINE JET IN A COAXIAL AIRSTREAM

by Maynard F. Taylor and Charles C. Masser

Lewis Research Center
Cleveland, Ohio

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ABSTRACT

Photographs were taken of a bromine jet issuing into a coaxially flowing airstream. The bromine jet appeared laminar for jet velocities below 1.5 m/sec and airstream velocities below 2.1 m/sec. If either the jet or stream velocity exceeded the aforementioned velocity the bromine jet appeared nonlaminar. These velocities can be expressed as nondimensional parameters, jet Reynolds number and stream- to jet-velocity ratio. In terms of these parameters, the jet will have a laminar appearance if both the jet Reynolds number is less than about 2400 and the product of the stream- to jet-velocity ratio and the jet Reynolds number is less than about 3400. The investigation covered only the region from the injection point to five jet radii downstream.

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PHOTOGRAPHIC STUDY OF A BROMINE JET IN A COAXIAL AIRSTREAM

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SUMMARY

Photographs of a bromine jet injected into a coaxially flowing airstream are presented in this report. The bromine jet velocities varied from 0.32 to 2.65 meters per second, and the airstream varied from 0.5 to 20.6 meters per second. The stream- to jet-velocity ratio was varied from 0.4 to 32, and the difference between the stream and jet velocities varied from -1.6 to 20 meters per second. In the test chamber the ratio of the airstream density to bromine jet density was 0.18.

For jet velocities less than approximately 1.5 meters per second and airstream velocities less than approximately 2.1 meters per second, the bromine jet appeared laminar. If either the jet velocity was increased above about 1.5 meters per second or the airstream velocity was increased above about 2.1 meters per second, the bromine jet appeared nonlaminar. These velocities can be expressed as nondimensional parameters - jet Reynolds number and stream- to jet-velocity ratio. In terms of these parameters, the jet will have a laminar appearance if the jet Reynolds number is less than about 2400 and the product of the stream- to jet-velocity ratio and jet Reynolds number is less than about 3400. The investigation covered only the region from the jet injection point to five jet radii downstream.

INTRODUCTION

The fluid mechanics problem of a jet issuing into a coaxially flowing environment of a different fluid has not been as thoroughly studied as has the problem of a jet issuing into a quiescent environment of the same fluid. Subsonic coaxial jet mixing occurs in such practical instances as ejectors, afterburners, and combustion chambers as well as in plasma injection systems (ref. 1), supersonic combustors (ref. 2), and coaxial gaseous-fuel nuclear rocket engine concepts (ref. 3).

Most studies of coaxial jets have been limited to the case where the jet density is equal to the stream density and the jet velocity is greater than the stream velocity. Reference 4 presents a numerical solution for laminar coaxial streams with the ratios of jet to stream density and stream to jet velocity both as high as 100. Reference 5 is an extension of reference 4 to turbulent flow with experimental data for a bromine jet issuing into coaxially flowing air. This system gives a jet- to stream-density ratio of 5.5 and stream- to jet-velocity ratios up to 49. Good agreement between analysis and experiment was obtained by a trial and error selection of an eddy- to laminar-viscosity ratio to modify the laminar results. Reference 6 investigated the effect of introducing honeycombs into both the bromine injection tube and the airstream. The effect of varying the jet and stream Reynolds numbers simultaneously for a velocity ratio of 1 was also presented.

The present investigation was undertaken to study visually the effects of varying both the jet and stream velocities and the stream- to jet-velocity ratio. This study supplements the work of reference 5, which made no visual study, and reference 6, which made

TABLE I. - RANGE OF TEST CONDITIONS

	Airstream	Bromine jet
Static pressure at station 1, p_1, kN/m^2	300 to 375	17.9
Static pressure at station 2, p_2, kN/m^2	17.9	17.9
Average velocity at point of jet injection, V, m/sec	0.5 to 20.6	0.32 to 2.65
Average density at point of jet injection, ρ, kg/m^3	0.21	1.15
Average viscosity at point of jet injection, μ, $(\mu N)(sec)/m^2$	18.5	15.5
Average Reynolds number at point of jet injection, Re	120 to 5100	510 to 4300
Difference between average velocities at point of jet injection, $V_o - V_j$, m/sec	-1.6 to 20	
Ratio of average velocities at point of jet injection, V_o/V_j	0.4 to 32	
Ratio of average densities at point of jet injection, ρ_o/ρ_j	0.18	
Ratio of average viscosities at point of jet injection, μ_o/μ_j	1.2	

a visual study only for a velocity ratio of 1. References 5 and 6 investigated the flow for axial distances from 4.65 to 32 jet radii downstream of the jet injection point. The present study was limited to the region extending from the jet injection point to five jet radii downstream, a region which was not studied in references 5 and 6. This region will be referred to as the "near jet region."

The objective of the present investigation was to observe and photograph the physical appearance of the bromine jet in the near jet region for a range of bromine jet velocities and airstream velocities. No measurements were made in either the air or bromine streams. From the photographs the flow had either a "laminar" appearance (typified by a sharp, clearly defined, persistent boundary to the bromine jet) or a "nonlaminar" appearance (typified by a not clearly defined or undulating boundary of the bromine jet). The distortion of the bromine jet is discussed in terms of jet velocity, stream velocity, ratio of stream velocity to jet velocity, difference between stream and jet velocity, and the jet Reynolds number. The jet Reynolds number is based on the injection tube diameter and average velocity and properties at the injection point for the range of test conditions shown in table I.

SYMBOLS

D	inside diameter of jet injection tube
Fr	Froude number, V^2/gD
g	gravitational constant
Re_j	jet Reynolds number, $\rho_j V_j D/\mu_j$
Re_o	stream Reynolds number, $\rho_o V_o D/\mu_o$
V	velocity
ϵ^+	turbulence factor
ρ	density of gas
μ	absolute viscosity of gas

Subscripts:

j	bromine jet
o	outer airstream
1	station 1
2	station 2

EXPERIMENTAL APPARATUS

The experimental apparatus used in reference 6 was modified by the addition of a flow control valve upstream of the bromine rotameter for better control of the bromine flow. A schematic diagram of the system is shown in figure 1. The test chamber is operated at 17.9 kilonewtons per square meter absolute which is below the vapor pressure of bromine at room temperature. This pressure differential is the driving force for the bromine flow which is measured by a rotameter.

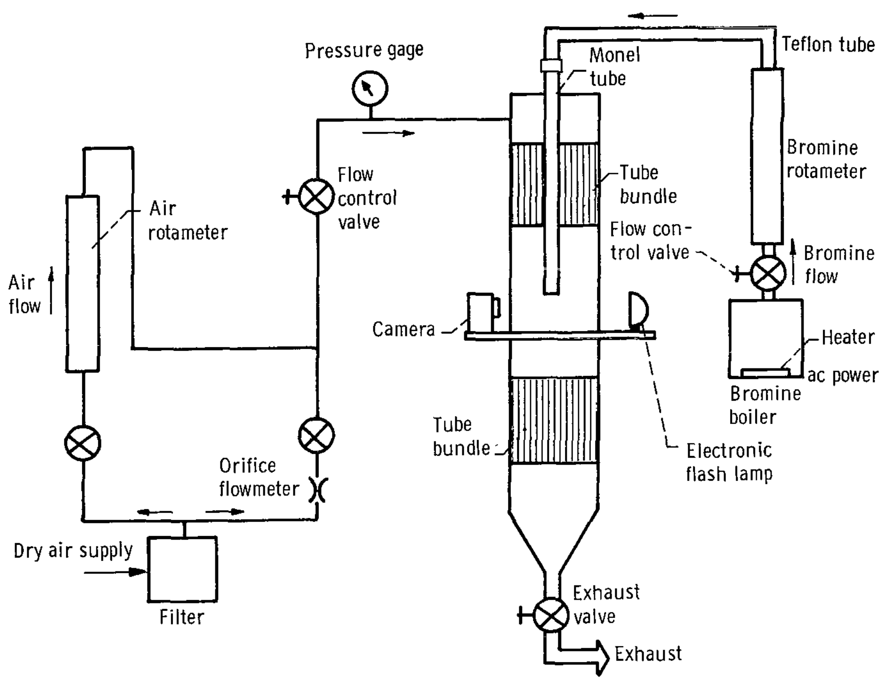


Figure 1. - Schematic drawing of air-bromine system.

The bromine reservoir is made of Monel and is coated on the inside with Teflon. The liquid bromine is kept at a constant temperature by supplying the heat of vaporization with a quartz-covered immersion heater. The extreme corrosiveness of bromine makes the use of Teflon and glass necessary for most of the bromine flow system. The only contact of the bromine with other materials is in the Monel tube which delivers the bromine to the air flowing in the test chamber. Dry air for the outer stream is supplied at a static pressure of 375 kilonewtons per square meter absolute to either the rotameter or the orifice (depending on the desired flow rate), and then through a flow control valve for airflow regulation to a plenum chamber. From the plenum, the air passed through a bank of three screens with a wire diameter of 0.053 millimeter and openings of 0.074 millimeter and a bundle of 1.3-centimeter inside-diameter tubes that are 30 centimeters long for the purpose of removing large scale turbulence. The static pressure drop through the screens and tube bundle was between 280 and 355 kilonewtons per square meter absolute depending on the mass flow rate of air. The important test section dimensions are listed in table II.

In jet mixing, the region upstream of the injection point can be important, and is therefore shown in more detail in figure 2. The bromine jet and outer airstream flow through the test chamber, through a second bundle of tubes, and then into an exhaust system.

Photographs are taken of the bromine jet issuing into the coaxially flowing airstream. The test chamber is backlighted with an electronic flash which has a color temperature of 6300 K and a duration of 1/500 of a second. The 10- by 13-centimeter film packs have an ASA rating of 320. The camera was approximately 90 centimeters from the bromine stream and 150 centimeters from the light source.

TABLE II. - TEST SECTION DIMENSIONS

Bromine tubes	Length, cm	110
	Inside diameter, cm	2.18
Air channel	Width, cm	20.3
	Depth, cm	20.3
Tube bundles	Tube length, cm	30
	Tube inside diameter, cm	1.3
Screens	Number of screens	3
	Wire diameter, mm	0.0053
	Flow opening size, mm	0.074

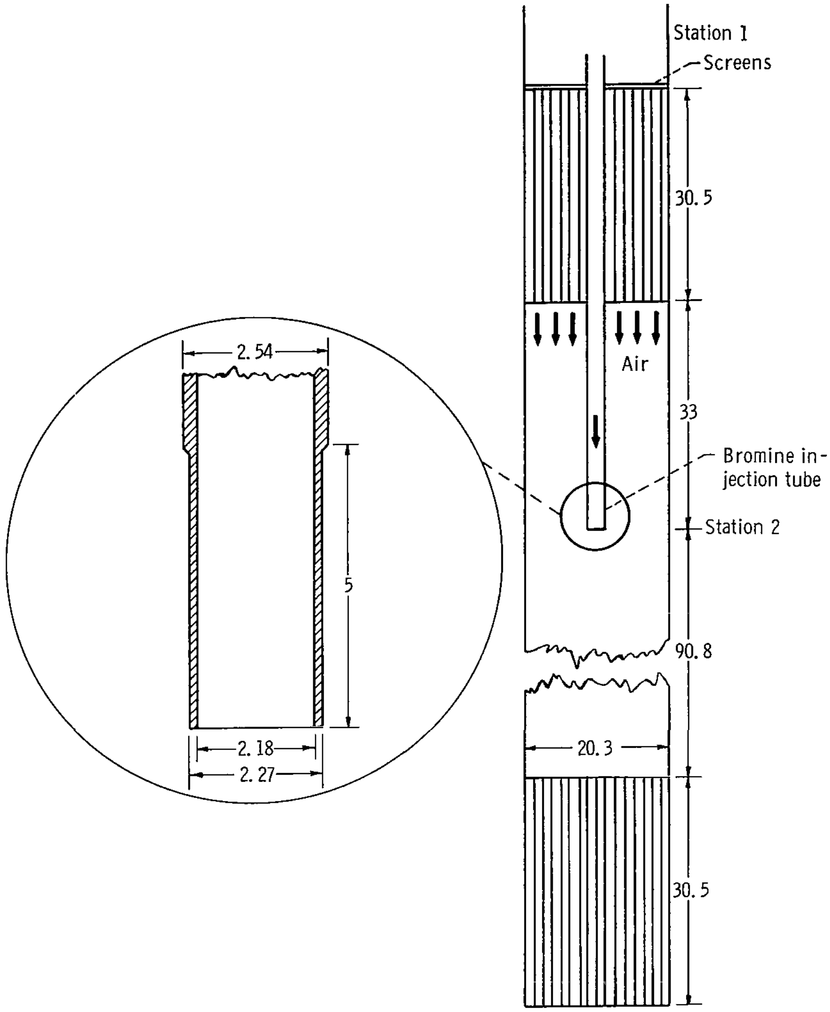


Figure 2. - Schematic drawing of test chamber. (All dimensions are in centimeters.)

DISCUSSION

The discussion of the photographs will be limited to an observed change in the appearance of the bromine jet and to the flow conditions at which the change occurs. The change seems to be due to the transition of the jet from laminar to nonlaminar flow. Not all of the possible causes for this change in flow have been investigated. For this report the region of interest (near jet region) extended from the jet injection point to a point five jet radii downstream.

For the flow to be considered laminar it had to have a laminar appearance throughout the near jet region. Both the bromine jet velocity V_j and the airstream velocity V_o

are average values calculated from the mass flow rates and conditions at the bromine jet injection point. Densities and viscosities are also for conditions at the jet injection point.

Figure 3 shows a number of photographs of the near jet region. The bromine jet issues into an airstream moving in the same direction through the test chamber. The average bromine velocity V_j is constant in each horizontal line of pictures and increases from 0.32 meter per second in the top line to 2.65 meters per second in the bottom line. In the vertical rows, the ratio of the average outer airstream velocity to the average bromine jet velocity V_o/V_j is constant. From figure 3, the bromine jet appears to become less laminar as either the outer stream velocity or the jet velocity is increased. The transition from laminar to nonlaminar flow appears to occur at a stream velocity between 1.27 and 2.55 meters per second at low jet velocities and at a jet velocity between 1.31 and 2.65 meters per second at low stream velocities.

Since the density of the bromine jet is greater than the density of the airstream, the jet can be accelerated by the force of gravity. For small jet velocities, this acceleration can be appreciable and thus result in an increase in the velocity and a decrease in the flow area downstream of the injection point. The ratio of the inertial force to the gravitational force is the Froude number, which is listed along with the jet velocity and jet Reynolds number in figure 3. The velocity of the bromine jet is also increased by the faster moving outer airstream.

The velocities of the airstream and the bromine jet for which the jet appears to be laminar in the photographs are shown as solid symbols in figure 4. The open symbols are for velocities at which the jet appears to be nonlaminar. From both figures 3 and 4 it is apparent that photographs of the jet are needed to fill the voids between 1.31 and 2.65 meters per second for the jet and 1.27 and 2.55 meters per second for the outer stream.

Figure 5(a) shows the effect of increasing the bromine jet velocity V_j while keeping the airstream velocity V_o between 0.5 and 1.7 meters per second. It can be seen that the bromine jet appears to change from laminar to nonlaminar at a jet velocity of about 1.5 meters per second. In figure 5(b), the bromine velocity V_j is maintained at values less than the 1.5 meters per second at which the jet appeared laminar in figure 5(a), and the stream velocity V_o is increased from 1.8 to 2.6 meters per second. The change in the appearance of the bromine jet with an increase in stream velocity V_o is more subtle than the change due to an increase in the bromine jet velocity V_j. The tendency of the flow to become wavy or unsteady first and then to break up is similar to the classical example of rising cigarette smoke.

The velocities from figures 5(a) and (b) are shown in figure 6, where the critical value for transition from laminar to nonlaminar flow can be seen to be about 1.5 meters per second for the jet velocity and about 2.1 meters per second for the stream velocity.

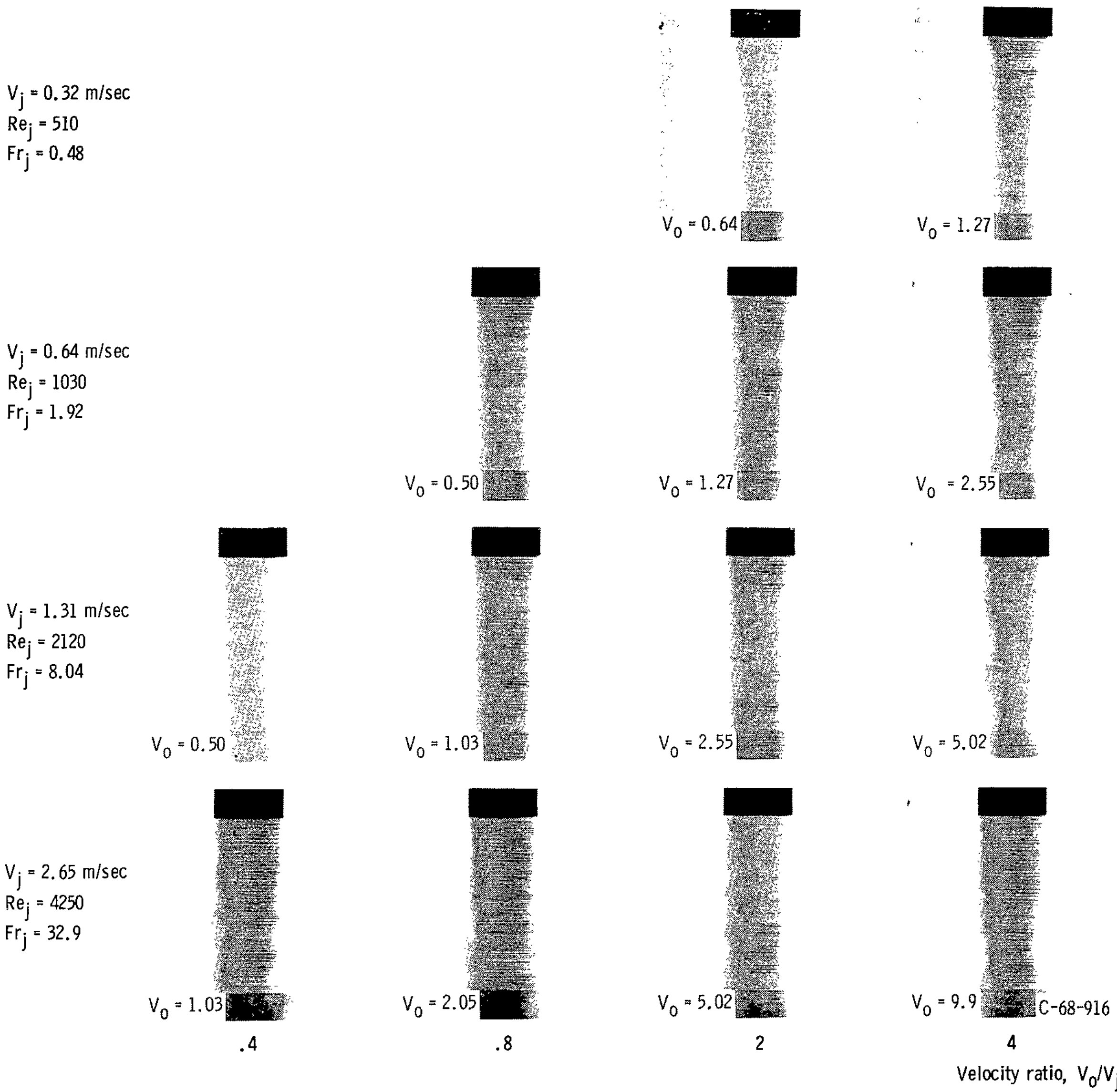
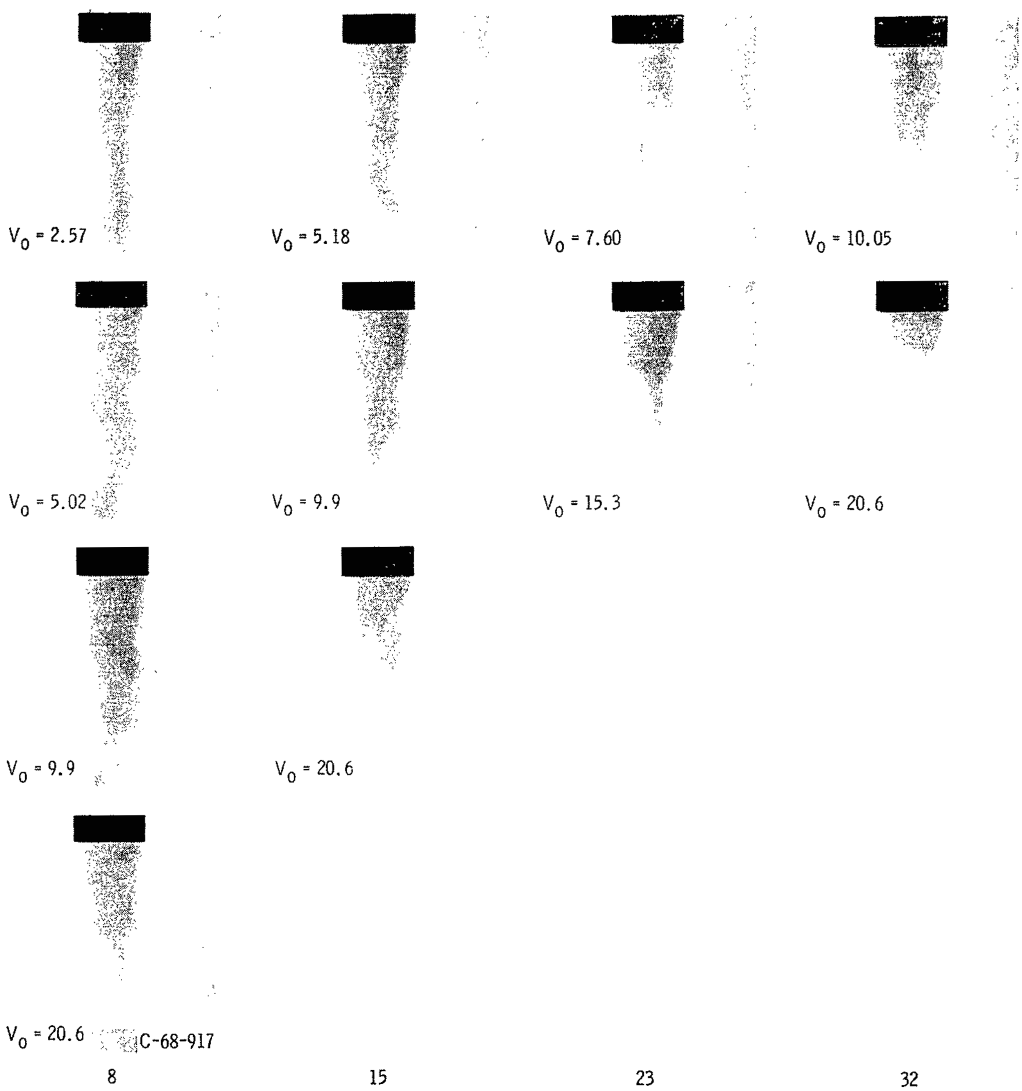


Figure 3. - Bromine jet issuing into a coaxially flowing



air-stream. Both jet and stream velocity are varied.

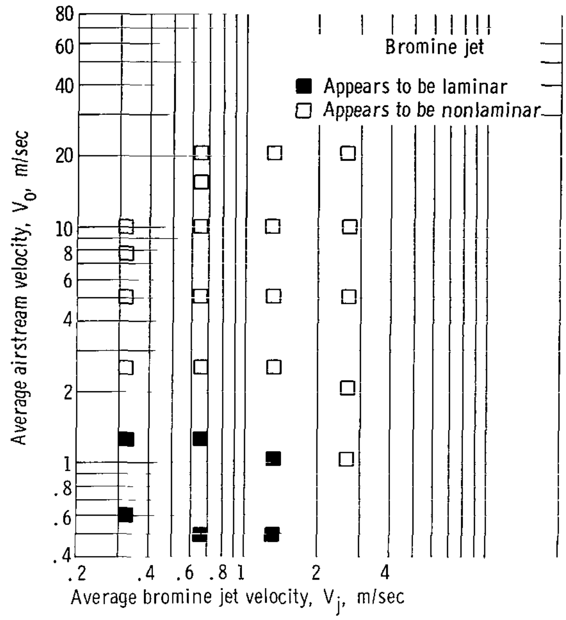


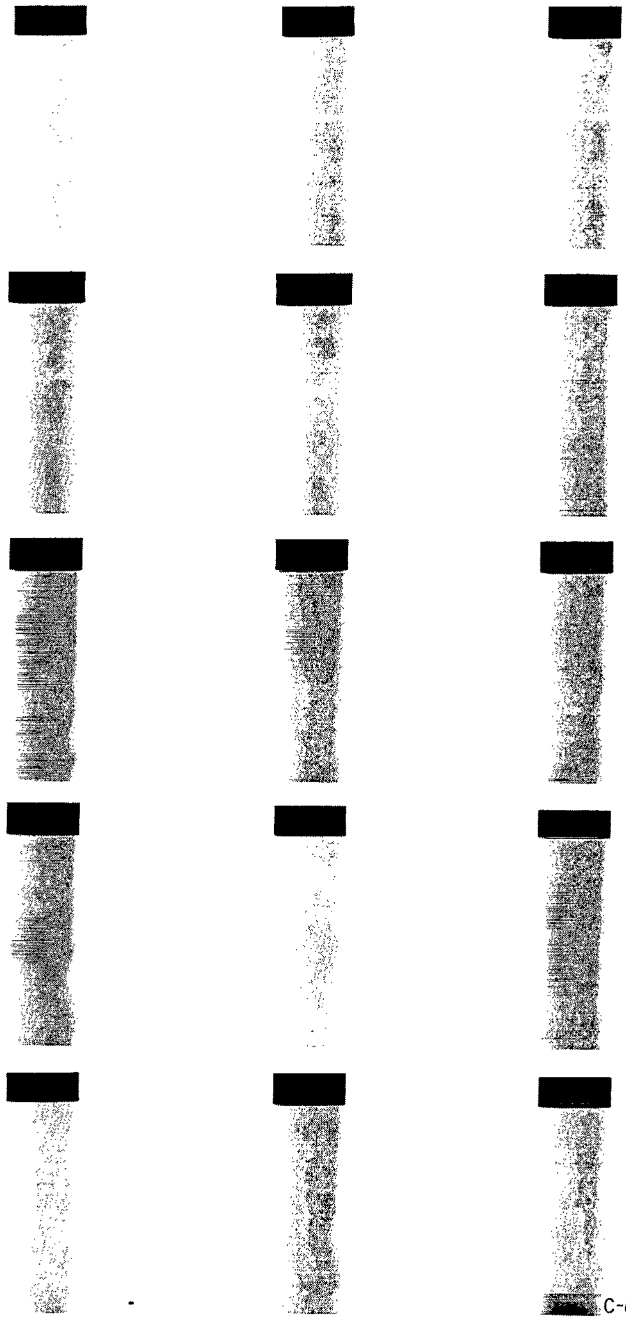
Figure 4. - Average bromine jet velocities and average air-stream velocities for photographs shown in figure 3.

It can be seen that the bromine jet can be made nonlaminar by increasing either the jet velocity V_j or the stream velocity V_o beyond the value for transition.

Because Reynolds number is usually used in describing flow through ducts, it seems logical to use it as a dimensionless parameter rather than the jet velocity. The jet Reynolds number is based on the jet injection tube diameter and the flow conditions at the point of injection. The jet velocity of 1.5 meters per second gives a jet Reynolds number of about 2400, which agrees closely with the critical Reynolds number for flow through a duct.

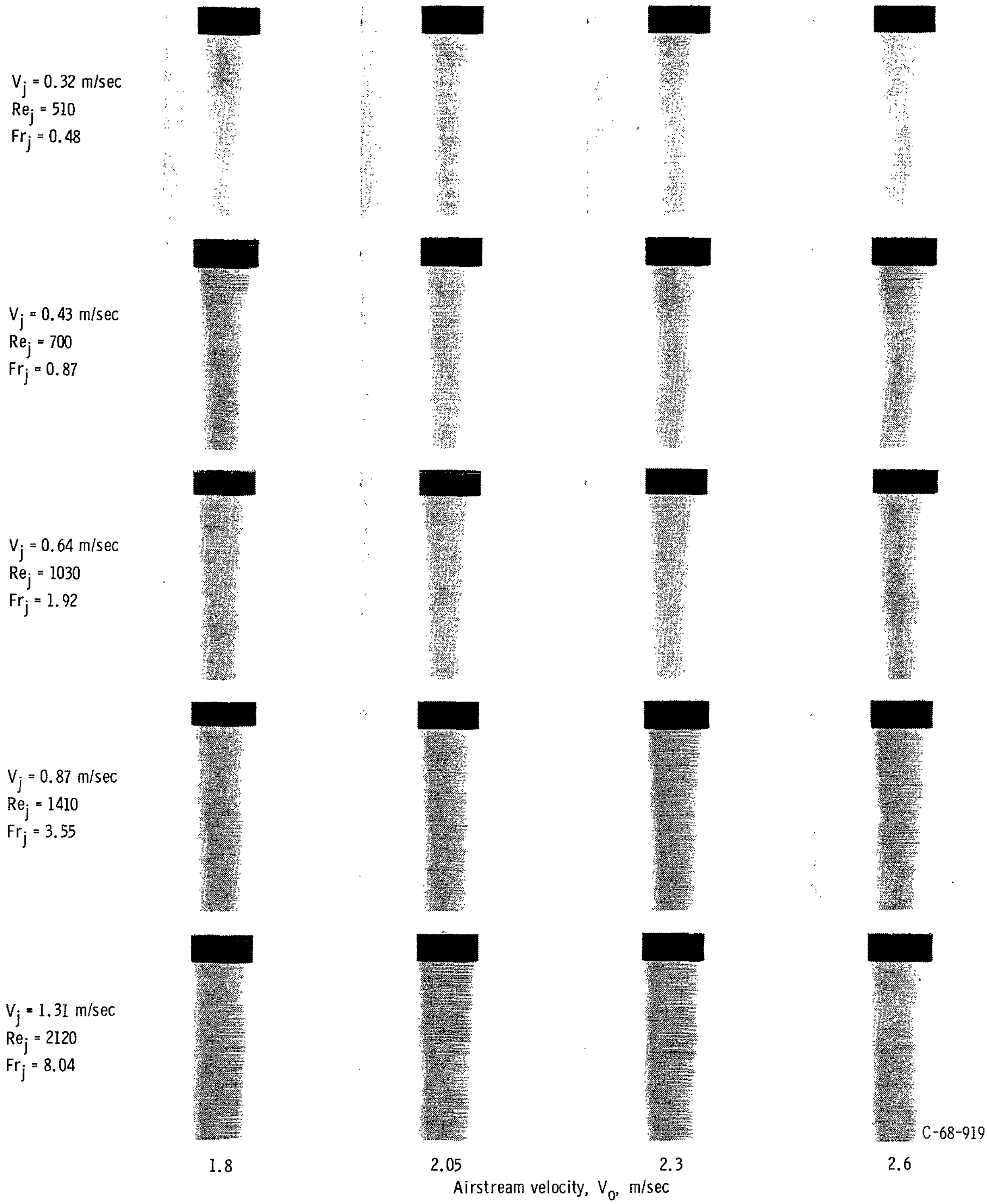
The stream velocity can be made nondimensional by dividing it by the jet velocity. It was found that for the conditions covered in this investigation the product of the jet Reynolds number and the velocity ratio V_o/V_j at which the appearance of jet changes from laminar to nonlaminar is nearly constant at approximately 3400. Figure 7(a) shows this transition velocity ratio as a function of the jet Reynolds number. For jet Reynolds number greater than about 2400 the flow appears to be nonlaminar for any velocity ratio.

Figure 7(b) shows the data of references 5 and 6 with the line for $V_o/V_j = 3400/Re_j$. Since no photographs are presented in reference 5, the criterion used here for whether the flow was laminar or turbulent was the value of the turbulence factor ϵ^+. In reference 5 the values for ϵ^+ varied from 0 to 6 and from 30 to 140. The runs with ϵ^+ from 0 to 6 were considered to be laminar ($\epsilon^+ \equiv 0$ for laminar flow) and the runs with an ϵ^+ from 30 to 140 were considered to be nonlaminar. Reference 6 presented photographs in which the flow appeared either laminar or nonlaminar. From figure 7(b) it can be seen



(a) Determination of critical jet velocity.

Figure 5. - Photographic determination of critical jet and stream velocities.



(b) Determination of critical stream velocity.

Figure 5. - Concluded.

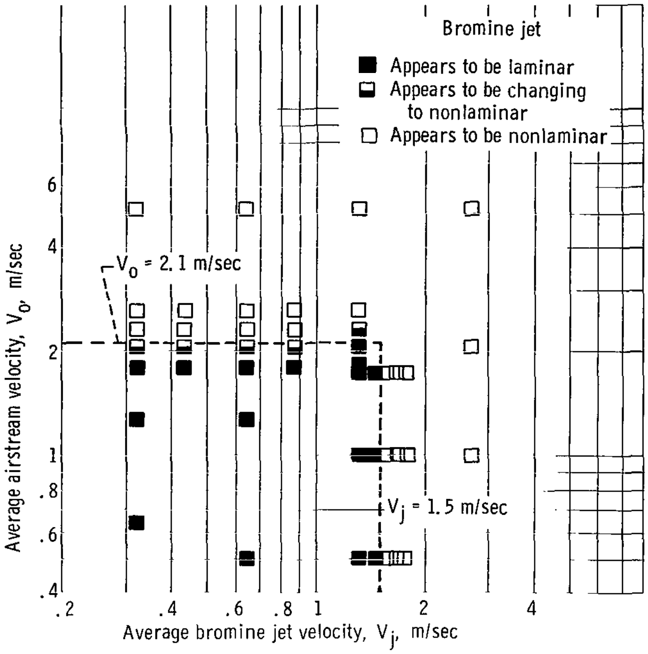
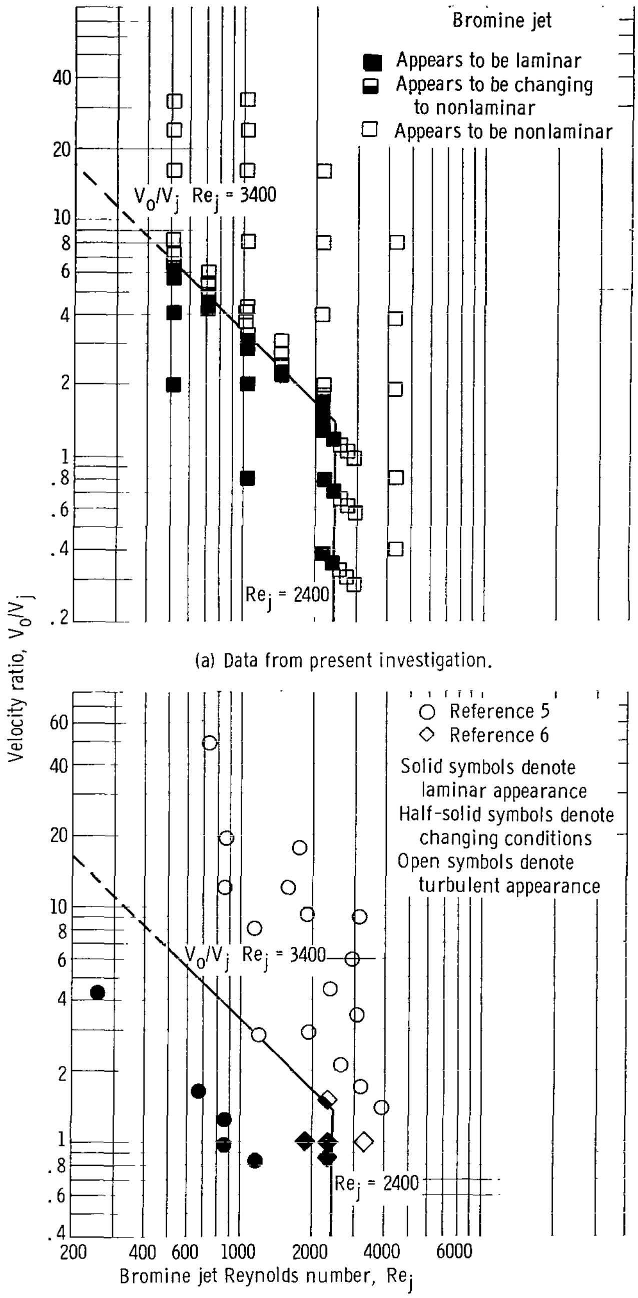


Figure 6. - Average bromine jet velocities and average air-stream velocities from photographs given in figures 3 and 5.

that unfortunately the velocity ratios V_o/V_j reported in references 5 and 6 are not close enough to the velocity ratios for transition either to confirm or contradict the relation between V_o/V_j and Re_j.

It should be emphasized that all of the data are for a bromine jet flowing coaxially downward with an airstream with both gases at room temperature. Further tests are necessary to define specifically the effect of varying temperature, viscosity, or density. Only the inside diameter of the bromine injector tube varied. It was 1.09 centimeters in reference 5, 2.37 centimeters in reference 6, and 2.18 centimeters in the present investigation.

The velocity difference $V_o - V_j$ is often used in coaxial flow studies. This velocity difference is usually made nondimensional by dividing it by the jet velocity V_j which reduces to $(V_o/V_j - 1)$. Figure 8 shows the variation of this dimensionless velocity difference as a function of the jet Reynolds number. For the range of conditions covered in this study, it is not clear whether velocity ratio or velocity difference is the better parameter.



(a) Data from present investigation.

(b) Data from references 5 and 6.

Figure 7. - Variation of velocity ratio with jet Reynolds number.

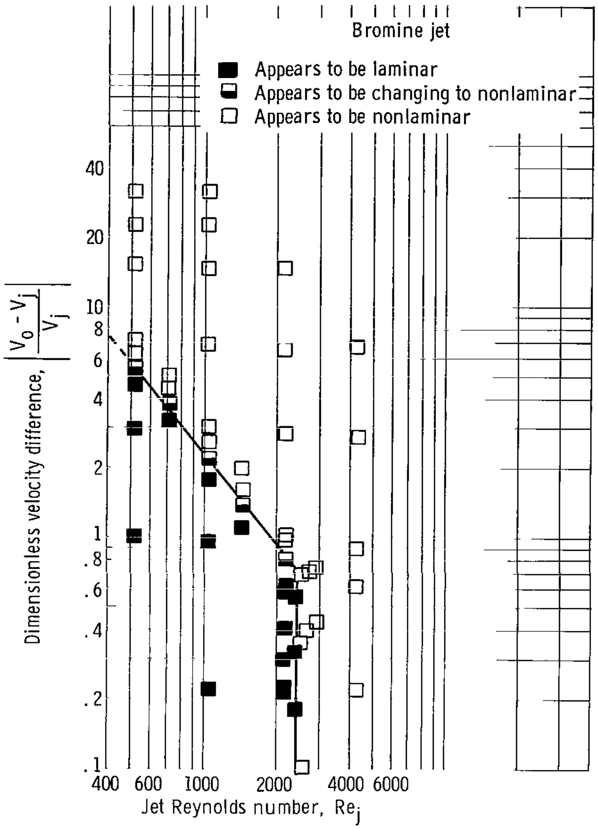


Figure 8. - Variation of dimensionless velocity difference with jet Reynolds number.

SUMMARY OF RESULTS

A photographic flow study was made of a bromine jet with velocities of 0.32 to 2.65 meters per second issuing into an airstream flowing coaxially with velocities between 0.5 and 20.6 meters per second. This results in ratios of stream velocity to jet velocity from 0.4 to 32, and differences between stream and jet velocity of -1.0 to 20 meters per second. The results of this study can be summarized as follows:

1. For airstream velocities below about 2.1 meters per second, there is a jet velocity of 1.5 meters per second at which the flow appears to change from laminar to nonlaminar. The jet Reynolds number, which is based on kinematic viscosity at the injection point, the jet injection tube diameter, and this transition velocity, has a value of about 2400.

2. For bromine velocities below about 1.5 meters per second there is an airstream velocity of 2.1 meters per second which causes the bromine jet to become nonlaminar.

3. In terms of nondimensional parameters, the two previous results can be combined into the following statement. The jet will have a laminar appearance if both of the following conditions are met:

(a) The jet Reynolds number is less than about 2400.

(b) The product of the stream- to jet-velocity ratio and the jet Reynolds number is less than about 3400.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 6, 1968,
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