NASA TECHNICAL NOTE

NASA TN D-5209

c. 1

NASA TN D-5209

PHOTOGRAPHIC STUDY OF A BROMINE JET FLOWING IN A COAXIAL AIRSTREAM AND IMPINGING ON A STAGNATION SURFACE

by Charles C. Masser and Maynard F. Taylor

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1969

PHOTOGRAPHIC STUDY OF A BROMINE JET FLOWING IN A COAXIAL AIRSTREAM AND IMPINGING ON A STAGNATION SURFACE

By Charles C. Masser and Maynard F. Taylor

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

ABSTRACT

A photographic study is made of a bromine jet issuing into a coaxially flowing airstream and impinging on a stagnation surface. The objective is to determine if the amount of bromine in the near jet region can be increased by the insertion of a stagnation surface in the jet. The diameter, shape and distance of the stagnation surface from the bromine injection point was varied. Several cases showed that a stagnation surface did slightly reduce the erratic behavior of the jet, and in other cases slightly increased the amount of bromine in the near jet region. However, no substantial increase of bromine in the near jet region was found by using a stagnation surface.

PHOTOGRAPHIC STUDY OF A BROMINE JET FLOWING IN A COAXIAL AIRSTREAM AND IMPINGING ON A STAGNATION SURFACE

by Charles C. Masser and Maynard F. Taylor

Lewis Research Center

SUMMARY

A photographic study was made of a bromine jet issuing into a coaxially flowing airstream and impinging on a stagnation surface. The objective of the study is to determine if the amount of bromine in the near jet region can be increased by the insertion of a stagnation surface in the jet. Photographs were taken of the bromine jet with and without the presence of a stagnation surface. Bromine jet velocities varied from 0.3 to 2.67 meters per second and airstream velocities varied from 0.5 to 20.6 meters per second. The diameter of the flat stagnation surface varied from 1, 1.5, to 2 times the diameter of the bromine injection tube. The distance of the flat stagnation surface from the bromine injection tube varied from the 1 to 2.5 jet diameters. Three shapes of stagnation surfaces, flat, concave, and convex, were studied.

It was found there was no substantial increase of bromine in the near jet region by using a stagnation surface. Also, the presence of a stagnation surface did not greatly influence the parameters at which the jet appears to change from laminar to nonlaminar. The transition from laminar to nonlaminar appearance occurred whenever the jet Reynolds number was greater than 2500 or the product of velocity ratio and jet Reynolds number was greater than 4000. Small effects were observed with stagnation surfaces, and they are as follows:

1. For flat stagnation surfaces held at a constant 2 jet diameters from the bromine injection tube, the upstream mixing appears never to decrease as the stagnation surface diameter increases. In fact, at velocity ratios of 4 or more, the upstream jet boundary becomes more erratic.

2. For a flat stagnation surface equal in diameter to the bromine tube, the jet boundary appears to be less erratic as the stagnation surface is moved from 2 to 1 jet diameter downstream of the jet injection point. Also at a velocity ratio of 32 there appears to be a slight increase in the amount of bromine in the near jet region as the stagnation surface is moved closer to the bromine injection point.

3. For various shaped stagnation surfaces equal in diameter to the bromine tube and held at a constant 2 jet diameters from the bromine tube, the upstream interaction does appear to be affected. Of the three types of surfaces, flat, concave, and convex, the convex surface appears to cause a less erratic nature to the bromine jet boundary. And at a velocity ratio of 32 there appears to be a larger amount of bromine in the near jet region.

INTRODUCTION

The fluid mechanics of a jet issuing into a coaxially flowing environment of a different fluid has not been as thoroughly studied as has a jet issuing into a quiescent environment of the same fluid. Subsonic coaxial jet mixing occurs in such practical instances as injectors, 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.

Weinstein and Todd (ref. 4) presents a numerical solution for laminar coaxial streams. Ratios of jet-to-stream density and stream-to-jet velocites both as high as 100 were investigated. Ragsdale, Weinstein, and Lanzo (ref. 5) modified the numerical solutions of reference 4 to include turbulent flow. Experimental data for a bromine jet issuing into coaxially flowing air are also presented. This bromine-air 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. Ragsdale and Edwards (ref. 6) visually investigated the effect of introducing honeycombs into both the bromine injection tube and the airstream. This was done for a velocity ratio of 1 at two different stream and jet velocities.

Taylor and Masser (ref. 7) visually studied the effects of varying both the jet and stream velocities and the stream-to-jet velocity ratios. The study of Taylor and Masser (ref. 7) supplements the work of Ragsdale, et al. (ref. 5), which made no visual study, and Ragsdale and Edwards (ref. 6), which made a visual study only for a velocity ratio of 1. Taylor and Masser (ref. 7) also limited their study to the region from the jet injection tube to 2.5 jet diameters downstream. This near jet region is important in the coaxial gas-core nuclear rocket concept since the cavity is less than 2 jet diameters in length.

In the gas core nuclear rocket concept a central core of slow-moving reacting gaseous fuel radiates its energy to the faster-moving coaxially flowing hydrogen propellant. However, the faster-moving propellant accelerates the fuel and mixes with it. This mixing results in a smaller fuel density than desired for nuclear criticality. Therefore, a minimum amount of mixing is desired between the fuel and propellant.

To simulate mixing in the gas-core nuclear rocket, bromine gas was chosen to represent the fuel jet and air to represent the propellant stream. The bromine gas allowed the experiment to be visually examined and photographed. The air-bromine density ratio (0.18) is also approximately the same as the uranium-hydrogen density ratio predicted in the gas-core rocket. One suggestion for increasing the amount of bromine in the near jet region over that observed by Taylor and Masser (ref. 7) is to place a stagnation surface near the injection point.

The objective of the present investigation is to determine if the amount of bromine in the near jet region can be increased by the insertion of a stagnation surface in the jet. Photographs of the bromine jet were taken with and without the presence of a stagnation surface. Discussion will center around the observed change in shape of the bromine jet boundary with and without the stagnation surface. The stagnation surface varies in shape, diameter, and distance from the bromine injection point. Also the jet and airstream velocities are varied for any given stagnation surface. No measurements were taken in either the air or bromine streams. The bromine jet and airstream are discussed in terms of jet velocity, stream velocity, ratio of stream velocity to jet velocity, and 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.

TABLE I. - RANGE OF TEST CONDITIONS

	Airstream	Bromine jet
Static pressure at station 1, p_1, kN/m^2 (psia)	300 to 375 (43.5 to 54.4)	17.9 (2.6)
Static pressure at station 2, p_2, kN/m^2 (psia)	17.9 (2.6)	17.9 (2.6)
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	----	510 to 4300
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	

SYMBOLS

D	inside diameter of jet injection tube
Re_j	jet Reynolds number, $\rho_j V_j D/\mu_j$
V	velocity
ρ	density of gas
μ	absolute viscosity of gas

Subscripts:

j	bromine jet
o	outer airstream

EXPERIMENTAL APPARATUS

The experimental apparatus used in this study is the same as that used by Taylor and Masser (ref. 7) except for the insertion of a stagnation surface downstream of the bromine jet injection point. A schematic diagram of the system is shown in figure 1. The

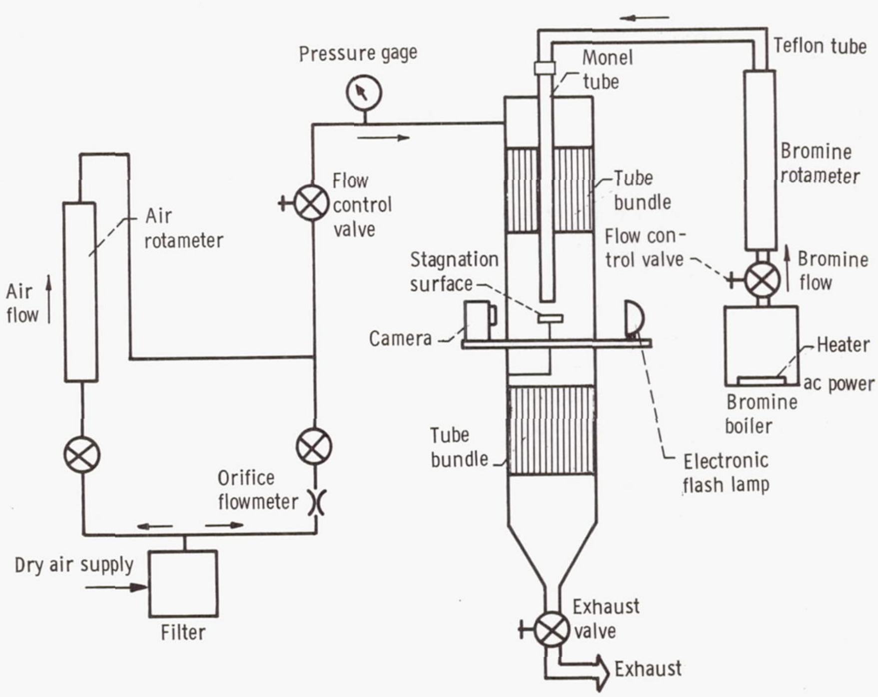


Figure 1. - Schematic drawing of air-bromine system.

test chamber is operated at 17.9 kilonewtons per square meter absolute (2.6 psia) 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.

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 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 (54.4 psia) to either the air rotameter or the orifice (depending if small or large airflow is desired), and then through a flow control valve for airflow regulation to a plenum chamber. From the plenum the air passes through a bank of three screens with a wire diameter of 0.053 millimeter and openings of 0.074 millimeter and through a bundle of 1.3 centimeter-inside-diameter

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	3
Wire diameter, mm	0.0053
Flow opening size, mm	0.074

tubes that are 30 centimeters long. The purpose is to remove large-scale turbulence. The static pressure drop through the screens and tube bundle is 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 coaxial flowing jets, the region upstream of the injection point can be important, and is therefore shown in more detail in figure 2. No effort has been made in this study to vary the conditions upstream of the injection point. The bromine jet leaves the monel tube and impinges on the stagnation surface and mixes with the airstream. The bromine

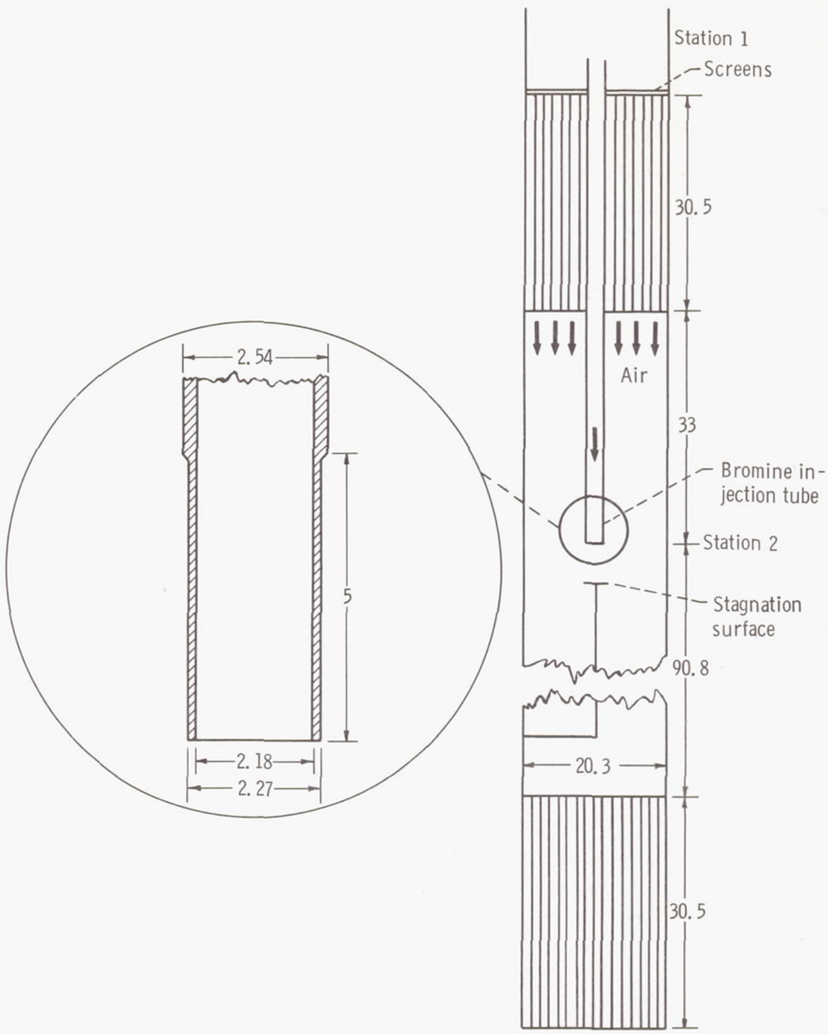


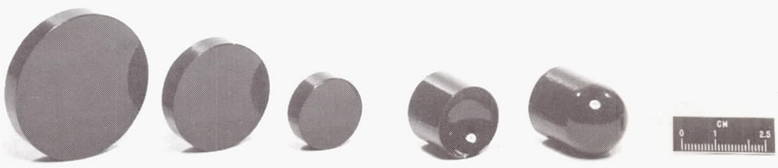
Figure 2. - Schematic drawing of test chamber. (All dimensions are in centimeters.)

and air mixture flows through the rest of the test section, 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 and impinging on the stagnation surface. The test chamber is backlighted with an electronic flash which has a color temperature of 6300 K and a duration of 1/500 second. The 10- by 12.5-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.

STAGNATION SURFACES

The stagnation surfaces used in this study are shown in figure 3. There are three types of stagnation surfaces, flat, concave, and convex. Only one size of concave and convex surfaces was used. The diameter of these two are the same and equal to the diameter of the bromine injection tube. The flat circular plates had diameters of 1, 1.5, and 2 times the diameter of the bromine injection tube.



C-68-2051

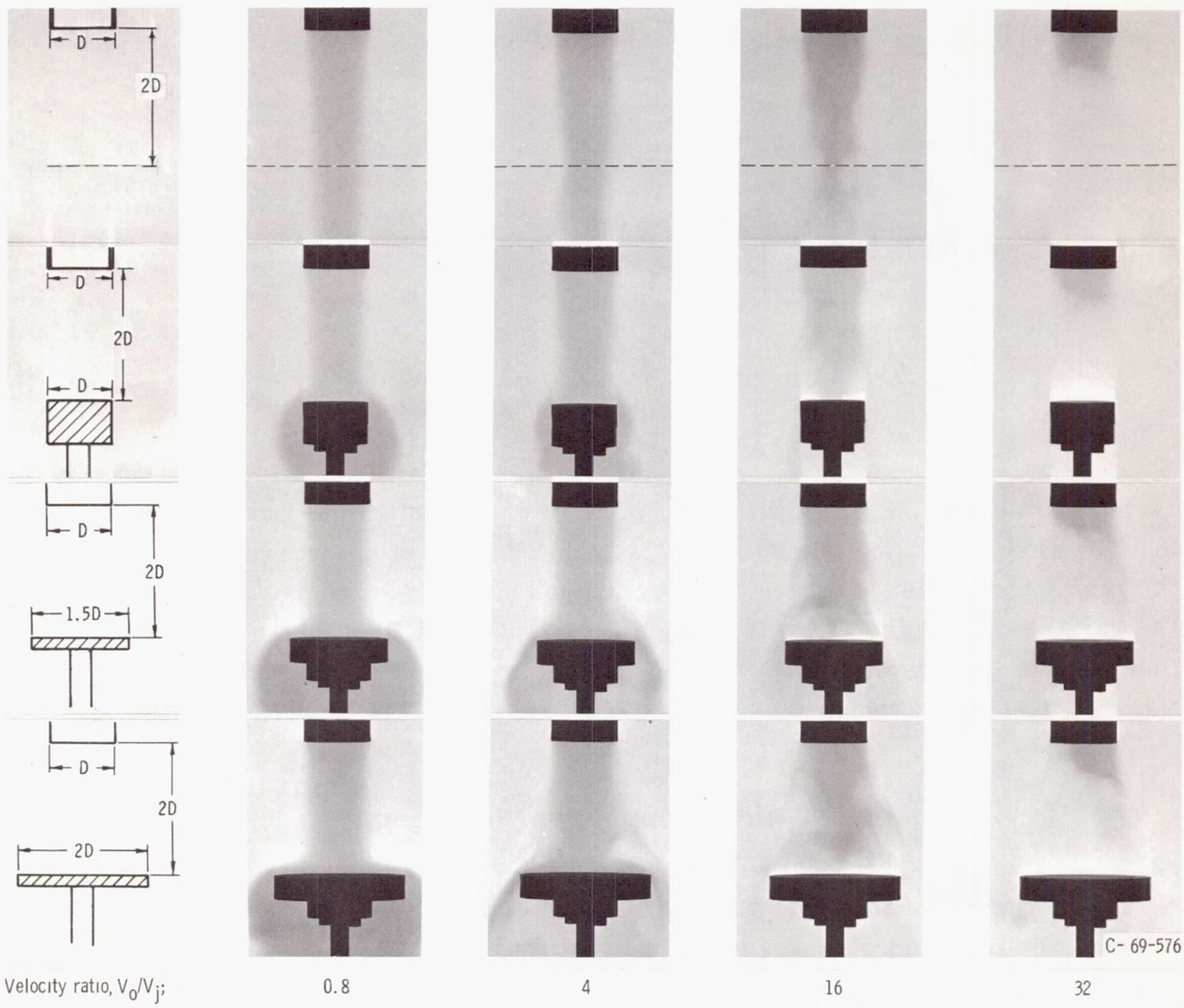
Figure 3. - Stagnation surfaces.

In most of the flow visualization photographs presented in this report the stagnation surface was located 2 jet diameters downstream from the bromine injection point. However, the effect of distance from the injection point was observed using the 1 jet diameter flat plate. This flat plate was placed 1.0, 1.5, and 2.0 jet diameters downstream from the bromine injection point. In one special case the convex surface was observed at 2.5 jet diameters downstream.

DISCUSSION OF PHOTOGRAPHIC RESULTS

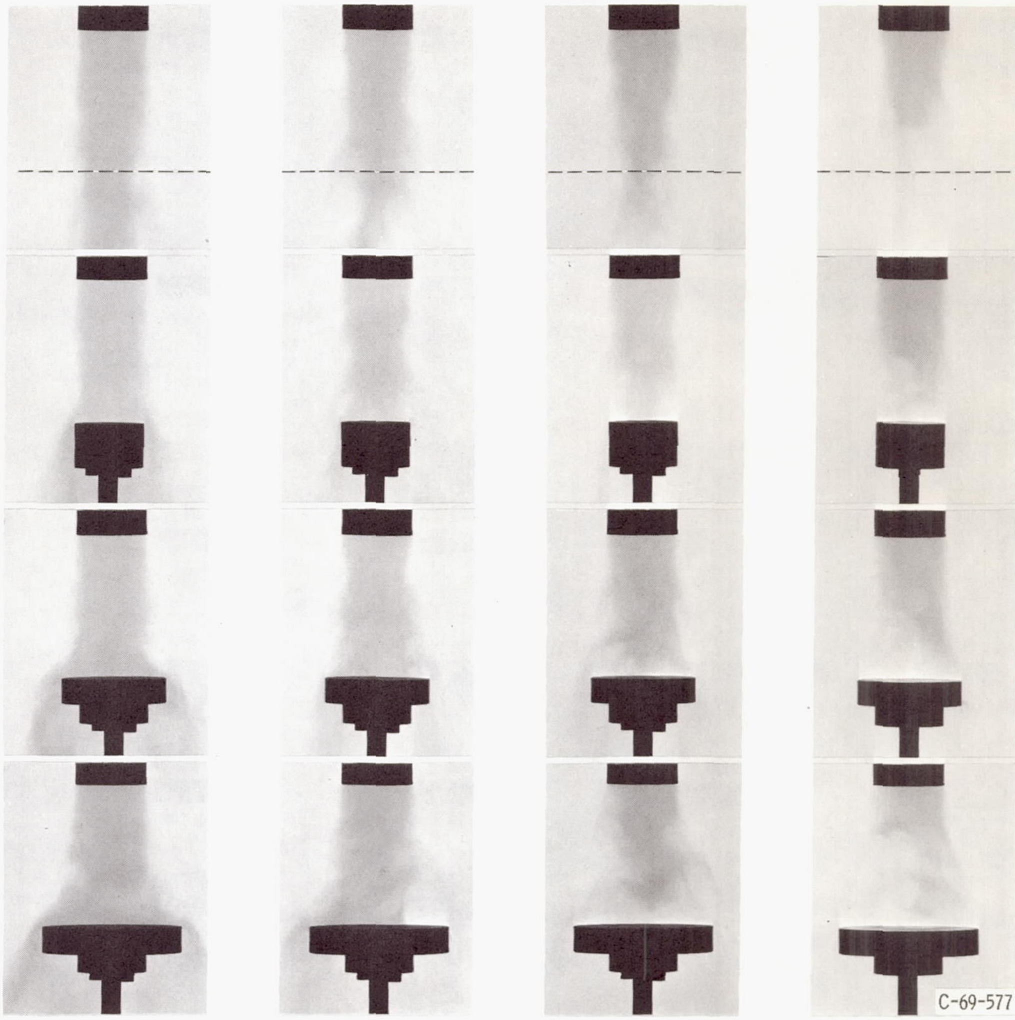
The discussion of the photographs will be limited to an observed change in the appearance of the bromine jet with and without the stagnation surface. In the discussion of the photographs the terms laminar and nonlaminar appearance are used. The laminar jet has the appearance of a sharp, clearly defined, persistent boundary whereas the nonlaminar jet appears as undulating or as a not clearly defined boundary. The flow field region will be limited to the area from the jet injection point to the stagnation surface. 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 the conditions at the jet injection point.

The effect of (1) stagnation surface diameter, (2) stagnation surface distance from bromine injection point, and (3) stagnation surface shape, can be observed on two composite photographs. Figures 4(a), 5(a), and 6(a) show the effect of changing the air-



(a) Jet velocity, 0.64 meter per second; jet Reynolds number, 1030.

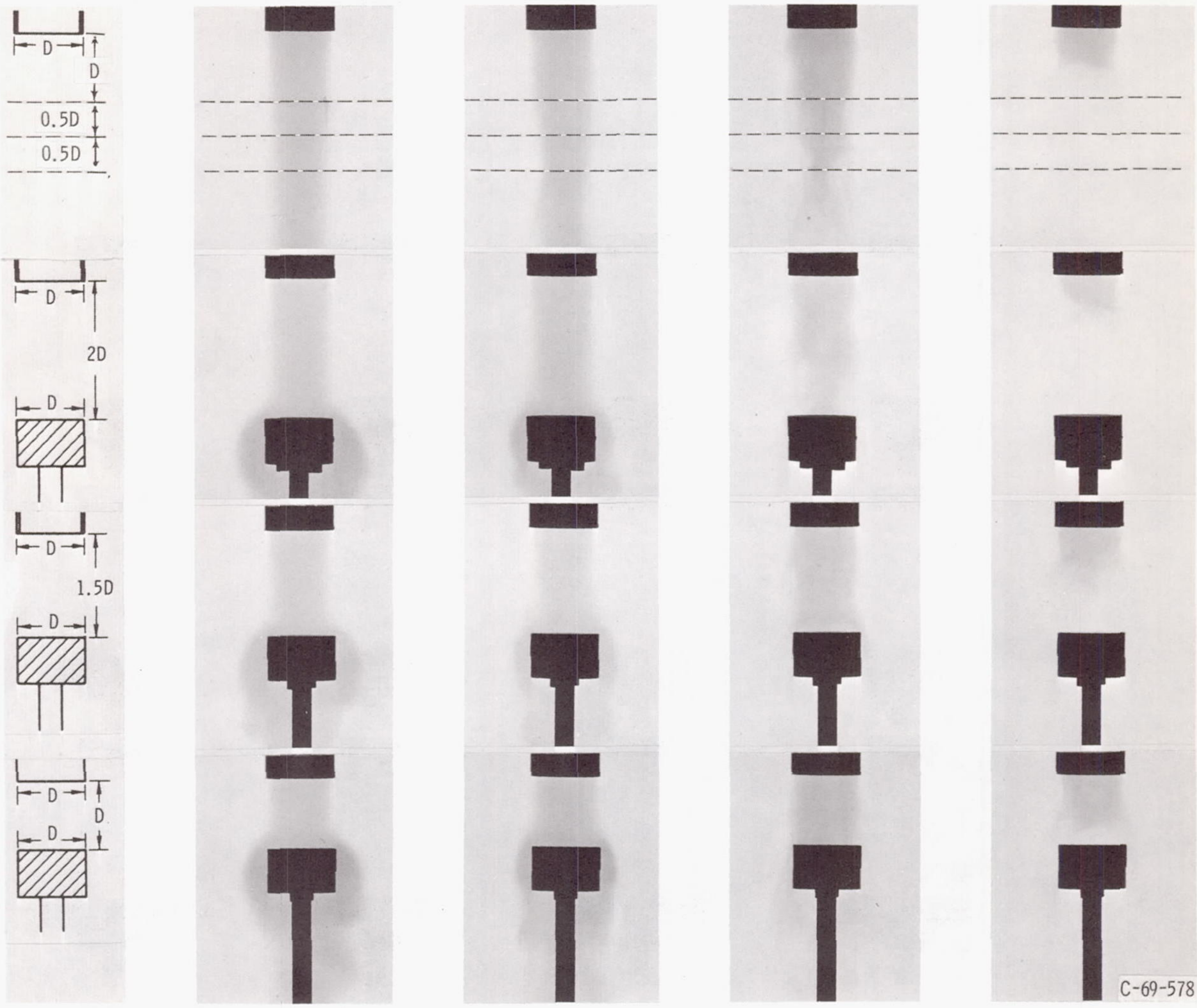
Figure 4. - Effect of downstream stagnation



Velocity ratio, V_0/V_j;	4	8	16	32
Jet Reynolds number;	4250	2120	1030	510

(b) Air velocity, 9.9 meters per second.

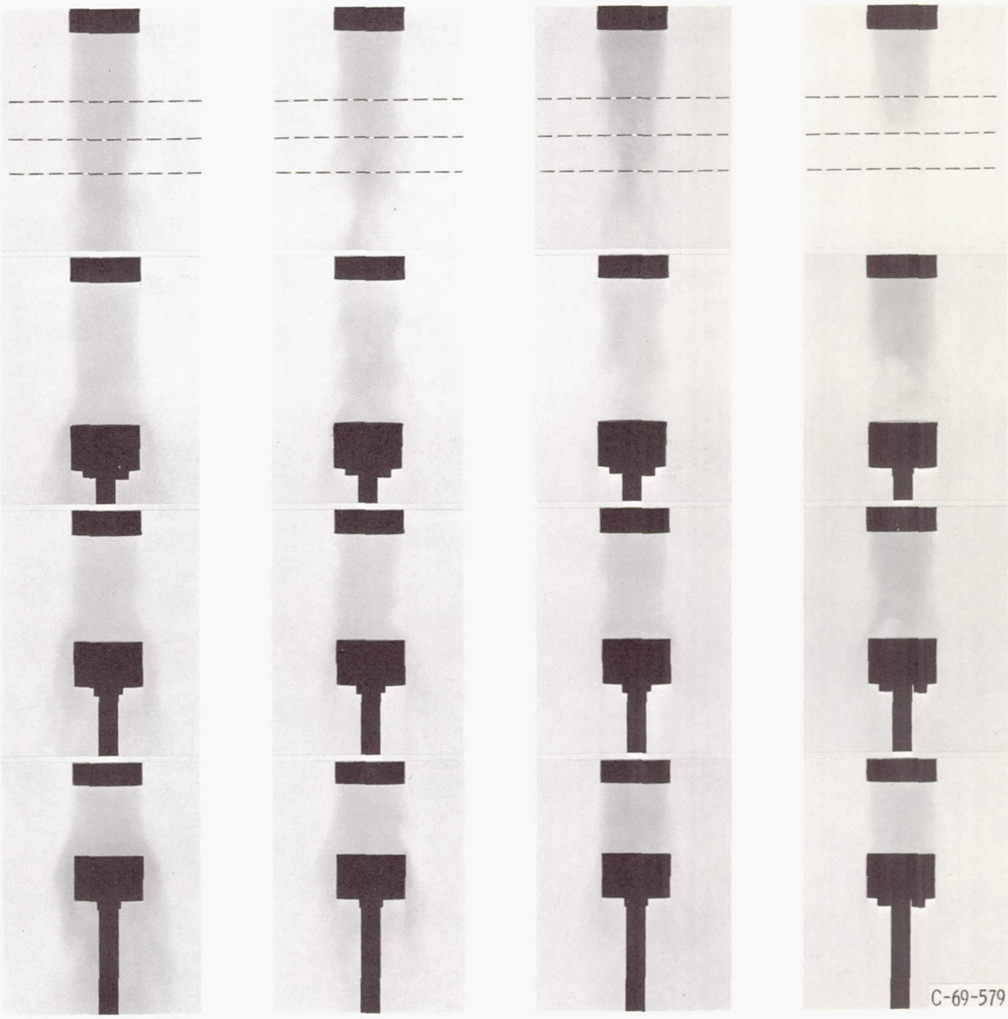
surface diameter on shape of jet boundary.



Velocity ratio, V_0/V_j; 0.8 4 16 32

(a) Jet velocity, 0.64 meter per second; jet Reynolds number, 1030.

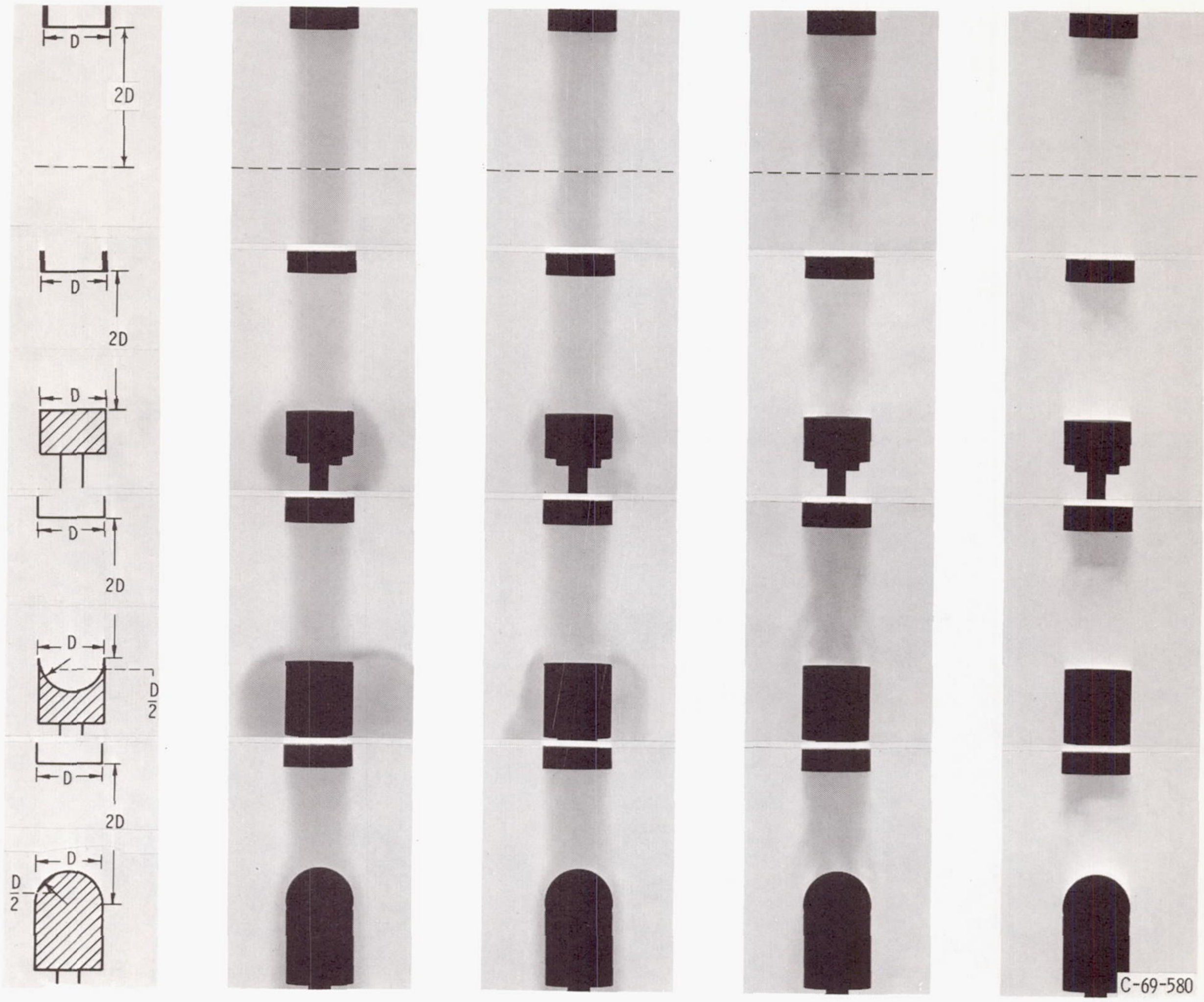
Figure 5. - Effect of distance from jet injection point



Velocity ratio, V_0/V_j;	4	8	16	32
Jet Reynolds number;	4250	2120	1020	510

(b) Air velocity, 9.9 meters per second.

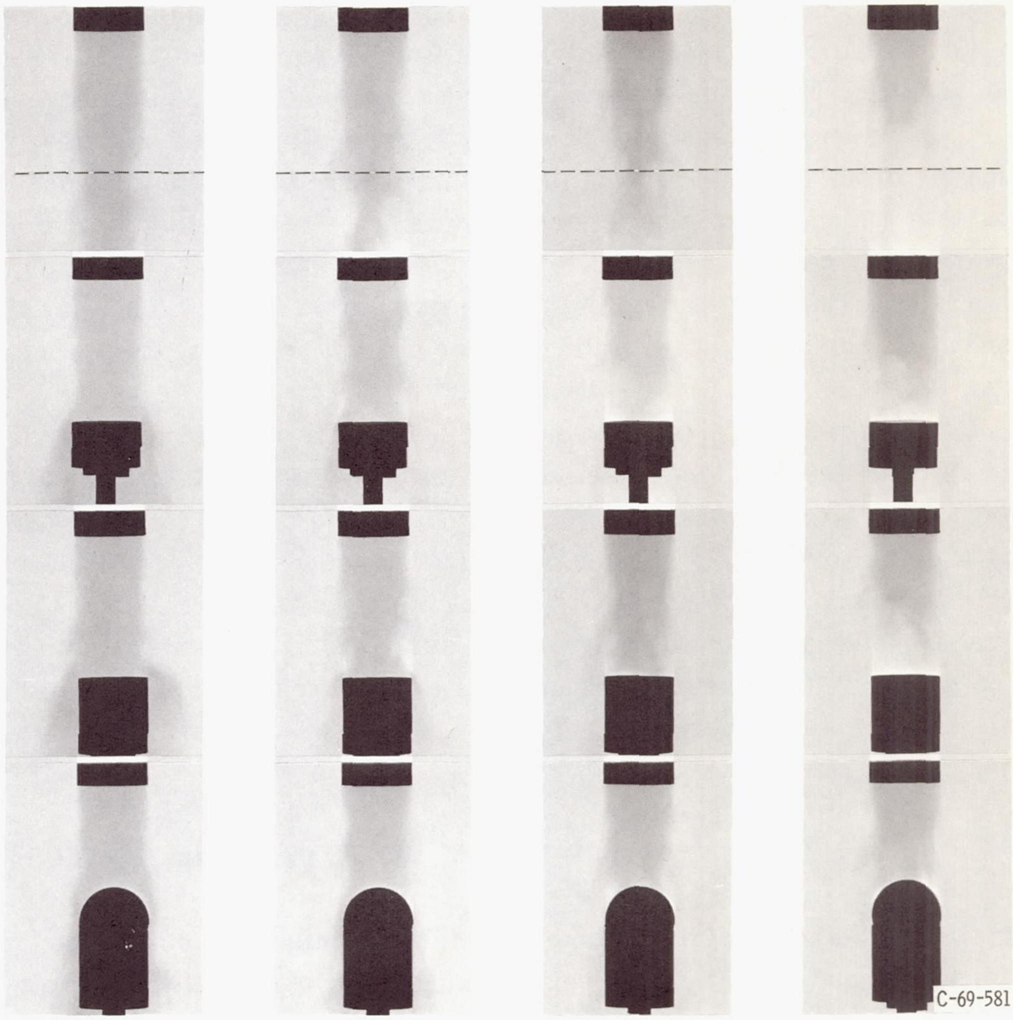
to stagnation surface on shape of jet boundary.



Velocity ratio, V_o/V_j; 0.8 4 16 32

(a) Jet velocity, 0.64 meter per second; jet Reynolds number, 1030.

Figure 6. - Effect of stagnation surface



Velocity ratio, V_0/V_j;	4	8	16	32
Jet Reynolds number;	4250	2120	1020	510

(b) Air velocity, 9.9 meters per second.

geometry on shape of jet boundary.

stream velocity while keeping the jet velocity constant. Figures 4(b), 5(b), and 6(b) show the effect of varying the jet velocity for a given airstream velocity.

Effect of Stagnation Surface Diameter

Figure 4(a) and (b) show the effect of stagnation surface diameter on near jet interaction. In figure 4(a) the jet velocity os 0.64 meter per second, and the jet Reynolds number is 1030. The velocity ratio is increased from 0.8 to 32 by increasing the air velocity. At a velocity ratio of 0.8, as the flat plate diameter increases, the interaction between the bromine and air is unaffected upstream of the stagnation surface. At the stagnation surface the bromine is forced around it. As the velocity ratio increases to 4, it appears that the bromine jet is breaking up faster and the jet boundary is becoming more erratic. This is more evident at a velocity ratio of 16. At a velocity ratio of 32, the air has completely broken up the bromine stream before it reaches the stagnation surface.

In figure 4(b) the airstream velocity is 9.9 meters per second, and the velocity ratio is varied from 4 to 32 by decreasing the jet velocity. At a velocity ratio of 4, the bromine has a more erratic appearance than in figure 4(a). This is in agreement with Taylor and Masser (ref. 7) where a critical jet Reynolds number of 2400 was found separating laminar and nonlaminar flow. The same increase in erratic behavior of the jet as the velocity ratio is observed in figure 4(b) as in 4(a) is increased. As the stagnation surface diameter increases and the velocity ratio increases, the bromine jet boundary appears to become more erratic.

Effect of Stagnation Surface Distance from Jet Injection

In figures 5(a) and (b) the distance from the jet injection point to the stagnation surface is varied, and its effect is observed using the 1 jet diameter flat plate. In figure 5(a) the jet velocity is 0.64 meter per second which gives a jet Reynolds number of 1030. The velocity ratio is varied from 0.8 to 32 by increasing the airstream velocity. It appears the 1 jet diameter stagnation surface has no influence on the upstream jet boundary at velocity ratios of 0.8 to 4. At a velocity ratio of 16, the jet appears to become less erratic as the flat plate is moved to 1 jet diameter of the injection tube. At a velocity ratio of 32, the amount of bromine appears slightly larger when the flat plate is moved to 1 jet diameter of the bromine tube.

In figure 5(b) the airstream velocity is held constant at 9.9 meters per second while the bromine velocity is lowered to obtain velocity ratios from 4 to 32. As the stagnation surface is moved close to the bromine injection point, the bromine is forced around the stagnation surface. In several cases, with this movement of bromine around the stagnation surface, the jet boundary appears to become slightly less erratic.

Effect of Stagnation Surface Shape

For figures 6(a) and (b) the stagnation surface shape is varied, and the observed effect on upstream jet boundary appearance is photographed. The three shapes, flat, concave, and convex, were placed at the same distance from the bromine injection point. In figure 6(a) the bromine velocity is 0.64 meter per second, and the airstream velocity is increased to obtain velocity ratio from 0.8 to 32. Upstream of the stagnation surface, the jet boundary appears to be unaffected by the stagnation surfaces. However, due to its somewhat streamline shape, the convex surface disturbs the bromine jet the least as it flows around the stagnation surface.

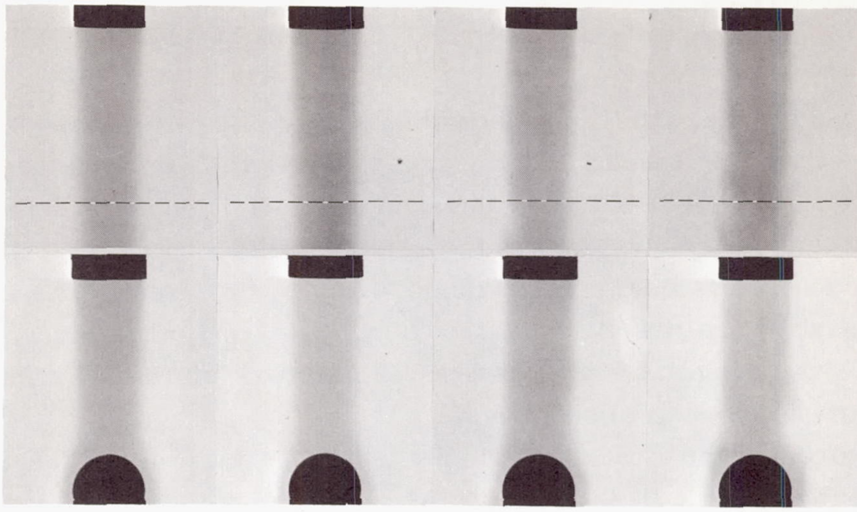
In figure 6(b) the airstream velocity is held constant at 9.9 meters per second, and velocity ratios from 4 to 32 are obtained by lowering the bromine velocity. At velocity ratios of 4 and 8, the convex surface appears to make the jet boundary less erratic. At velocity ratios of 16 and 32, all of the stagnation surfaces appears to slightly increase the amount of bromine in the near jet region.

Taylor and Masser (ref. 7) observed that the appearance of a free jet changed rapidly at critical values of several parameters. They discussed their photographs of jets in terms of laminar and nonlaminar appearance. The laminar jet had an appearance of a sharp, clearly defined, persistent boundary whereas the nonlaminar jet appeared as an undulating or not clearly defined boundary between the bromine jet and airstream. Their results were summarized as follows. The bromine jet will have a laminar appearance if both the following conditions are met:

(1) The jet Reynolds number is less than 2400.

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

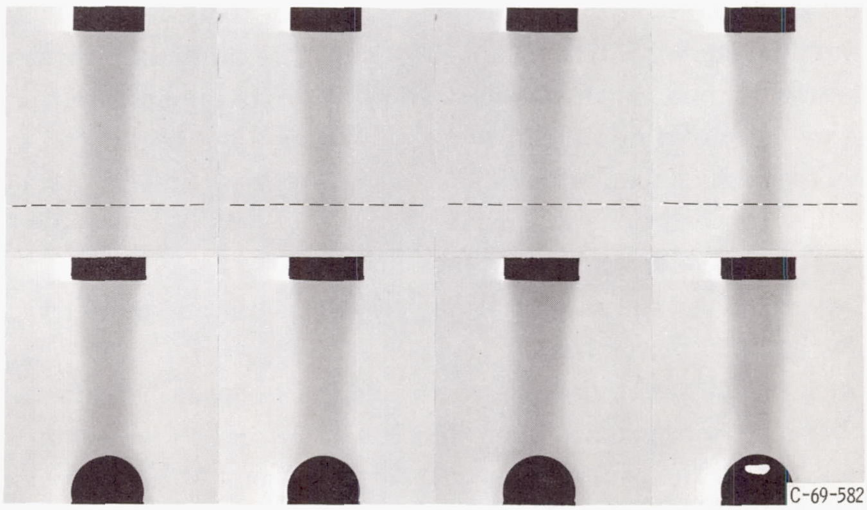
It is of interest to see if these conditions still apply when stagnation surfaces are placed in the near jet region. From figures 4, 5, and 6 the convex stagnation surface appeared to disturb the bromine jet boundary the least at low velocity ratios and increase the amount of bromine in the near jet region the most at high velocity ratios. Since Taylor and Masser studied only the near jet region of 2.5 jet diameters the convex surface was placed so the stagnation point was 2.5 jet diameters from the bromine injection point. Figure 7(a) and (b) show the results. In figure 7(a) the airstream velocity is held constant at 1 meter per second, and jet velocity and, hence, Reynolds number are increased from 2120 through the critical value to 2660. And it appears the stagnation surface does change the critical jet Reynolds number for the laminar-nonlaminar division from approximately 2400 to 2500. This change is small and may be due to experimental



Jet velocity, V_j, m/sec: 1.31 | 1.44 | 1.55 | 1.65

Jet Reynolds number: 2120 | 2320 | 2500 | 2660

(a) Airstream velocity, V_0 = 1 meter per second.



Airstream velocity, V_0, m/sec; 1.8 | 2.05 | 2.30 | 2.60

Product of jet Reynolds number and velocity ratio, $Re_j(V_0/V_j)$; 2870 | 3200 | 3770 | 4140

(b) Jet velocity, 0.32 meter per second; jet Reynolds number, 510.

Figure 7. - Comparison of critical parameters with and without a stagnation surface.

error. In figure 7(b) the jet velocity is held constant at 0.32 meter per second and the product of jet Reynolds number and velocity ratio is increased by increasing the airstream velocity. The stagnation surface does appear to reduce the undulating jet boundary. The product of jet Reynolds number and velocity ratio of about 4000 is reached before the nonlaminar undulating boundary is established. The photographic data of figure 7 are shown in graphical form in figure 8. The dashed line is the division line for laminar-nonlaminar appearing jet found by Taylor and Masser (ref. 7). The data with the convex stagnation surface are shown, and the new division between laminar and nonlaminar jets is shown as a solid line. This difference is small and may be due in part to experimental error.

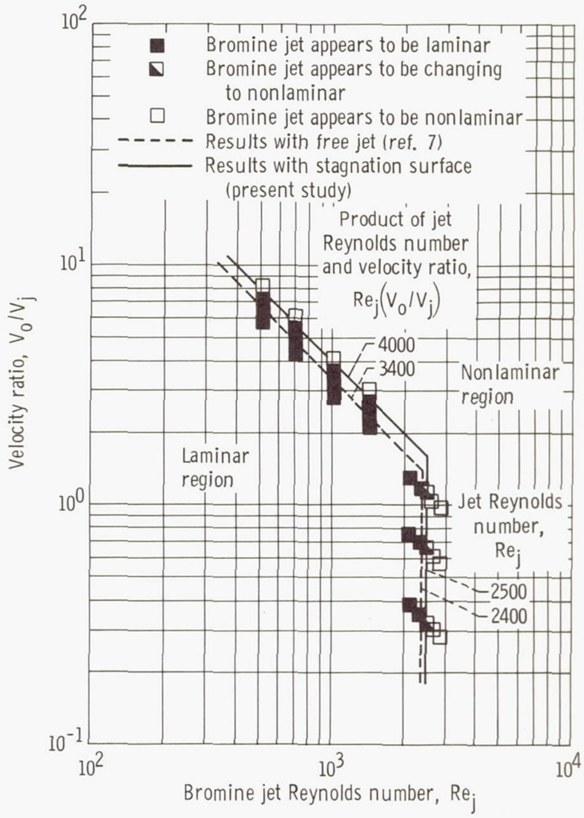


Figure 8. - Variation of velocity ratio with jet Reynolds number.

SUMMARY OF RESULTS

A photograph study was made of a bromine jet issuing into a coaxially flowing airstream and impinging on a stagnation surface. The objective of the study is to determine if the amount of bromine in the near jet region can be increased by the insertion of stagnation surface in the jet. Photographs were taken of the bromine jet with and without the presence of a stagnation surface. Bromine jet velocities varied from 0.3 to 2.67 meters per second, and airstream velocities varied from 0.5 to 20.6 meters per second. The diameter of the stagnation surface varied from 1, 1.5, and 2 times the diameter of the bromine injection tube. The distance of the stagnation surface to the bromine injection tube varied from 1 to 2.5 jet diameters. And three shapes of stagnation surface, flat, concave, and convex, were photographed. The results of this study can be summarized as follows:

1. It was found there was no substantial increase of bromine in the near jet region by using a stagnation surface.

2. The presence of a stagnation surface did not greatly influence the parameters at which the jet appears to change from laminar to nonlaminar. The transition from laminar to nonlaminar appearance occurred whenever the jet Reynolds number was greater than 2500 or the product of velocity ratio and jet Reynolds number was greater than 4000.

3. The near jet appearance of the bromine jet is changed by the presence of a flat stagnation surface placed 2 jet diameters downstream from the jet injection point. As the stagnation surface diameter increases at velocity ratios of 4 or more, the bromine jet boundary becomes more erratic.

4. For a flat stagnation surface equal in diameter to the bromine injection tube, the bromine jet boundary appears to be affected as the stagnation surface is moved from 2 jet diameters downstream to 1 jet diameter downstream. The bromine jet boundary appeared to become less erratic as the stagnation surface approached the jet injection point. At a velocity ratio of 32, the stagnation surface appeared to cause a slightly larger amount of bromine to be present.

5. For various shaped stagnation surfaces equal in diameter to the bromine injection tube and held at a constant 2 jet diameters downstream, the upstream jet boundary does appear to be affected. Of the three types of surfaces, flat, concave, and convex, the convex surface appears to give a less erratic nature to the bromine jet boundary. At a velocity ratio of 32, there appears to be a slight increase in the amount of bromine in the near jet region.

The above summary of results indicates there would be no advantage to using a stagnation surface in the gas-core nuclear rocket concept.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 7, 1969,
122-28-02-33-22.

REFERENCES

1. Jacobs, Paul F.: Turbulent Mixing in a Partially Ionized Gas. Aeron. Eng. Rep. 625, Princeton University, Oct. 1962.
2. Ferri, Antonio; Libby, Paul A.; and Zakkay, Victor: Theoretical and Experimental Investigation of Supersonic Combustion. High Temperatures in Aeronautics. Carlo Ferrari, ed., Pergamon Press, 1964, pp. 55-118.
3. Ragsdale, Robert G.; and Weinstein, Herbert: On the Hydrodynamics of a Coaxial Flow Gaseous Reactor. Conference on Nuclear Propulsion, Monterey, Calif., Aug. 16, 1962. AEC Rep. TID-7653, pt. 1, July 1963, pp. 82-88.
4. Weinstein, Herbert; and Todd, Carroll A.: A Numerical Solution of the Problem of Mixing of Laminar Coaxial Streams of Greatly Different Densities - Isothermal Case. NASA TN D-1534, 1963.
5. Ragsdale, Robert G.; Weinstein, Herbert; and Lanzo, Chester D.: Correlation of a Turbulent Air-Bromine Coaxial-Flow Experiment. NASA TN D-2121, 1964.
6. Ragsdale, Robert G.; and Edwards, Oliver J.: Data Comparisons and Photographic Observations of Coaxial Mixing of Dissimilar Gases at Nearly Equal Stream Velocities. NASA TN D-3131, 1965.
7. Taylor, Maynard F.; and Masser, Charles C.: Photographic Study of a Bromine Jet in a Coaxial Airstream. NASA TN D-4660, 1968.

NASA-Langley, 1969 —— 12 E-4668