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A PHOTOGRAPHIC STUDY OF A BROMINE JET IN A COAXIAL AIRSTREAM WITH HONEYCOMBS AT THE INJECTION PLANE

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Cleveland, Ohio

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16. Abstract
A photographic study was made of a bromine jet issuing into a coaxially flowing airstream. Honeycomb sections were placed into either or both the airstream and the bromine jet. The objective was to determine if the amount of bromine in the near jet region can be increased by the presence of a honeycomb at the jet injection plane. It was found there was no increase of bromine in the near jet region by the presence of honeycomb sections in either or both the bromine tube or airstream at the jet injection plane. However, the presence of honeycomb sections influences the transition from laminar to nonlaminar appearing jets.

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A PHOTOGRAPHIC STUDY OF A BROMINE JET IN A COAXIAL AIRSTREAM WITH HONEYCOMBS AT THE INJECTION PLANE

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SUMMARY

A photographic study was made of a bromine jet issuing into a coaxially flowing airstream. The objective of the study was to determine if the amount of bromine in the near jet region can be increased by the presence of a honeycomb section at the bromine injection plane. Photographs were taken with (1) a honeycomb section in the bromine injection tube only, (2) a honeycomb section in both the bromine and airstream, and (3) a honeycomb section in the airstream only. These photographs were then compared to photographs taken with no honeycomb sections present in either the bromine or airstream.

Bromine jet velocities varied from 0.3 to 2.65 meters per second, and airstream velocities varied from 0.5 to 20.6 meters per second. At velocity ratios of eight or more there appears to be no increase of bromine in the near jet region when honeycomb sections are present in either or both the airstream and bromine at the injection plane.

The presence of honeycomb sections influences the transition at which the jet appears to change from laminar to nonlaminar. A honeycomb present in only the bromine tube retarded the transition from laminar to nonlaminar appearing flows. Honeycomb sections in both the bromine tube and airstream caused the transition from laminar to nonlaminar appearing flows to occur sooner than without honeycomb sections. A honeycomb section in the airstream only caused the transition from laminar to nonlaminar appearing jets to occur sooner than when honeycombs were present in both the bromine jet and airstream.

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 densities and stream to jet velocities 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 streams 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, Weinstein, and Lanzo (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 hydrogen-uranium 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. This was investigated by Masser and Taylor (ref. 8), and results indicated there was no substantial increase of bromine in the near jet region.

The objective of the present investigation is to determine if the amount of bromine in the near jet region can be increased by the presence of honeycomb flow straighteners into the flowing gases just at the injection plane. Discussion will center around the observed change in shape of the bromine jet boundary with and without the honeycomb sections. 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.

SYMBOLS

D inside diameter of jet injection tube

Fr Froude number, V^2/gD

g gravitational constant

Re_j jet Reynolds number, $\rho_j V_j D/\mu_j$

V velocity

μ absolute viscosity of gas

ρ density of gas

Subscripts:

j bromine jet

o outer airstream

EXPERIMENTAL APPARATUS

The experimental apparatus used in this study is the same as that used in reference 7 except for the insertion of small pore honeycomb sections at the jet injection plane. A schematic diagram of the system is shown in figure 1. The 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

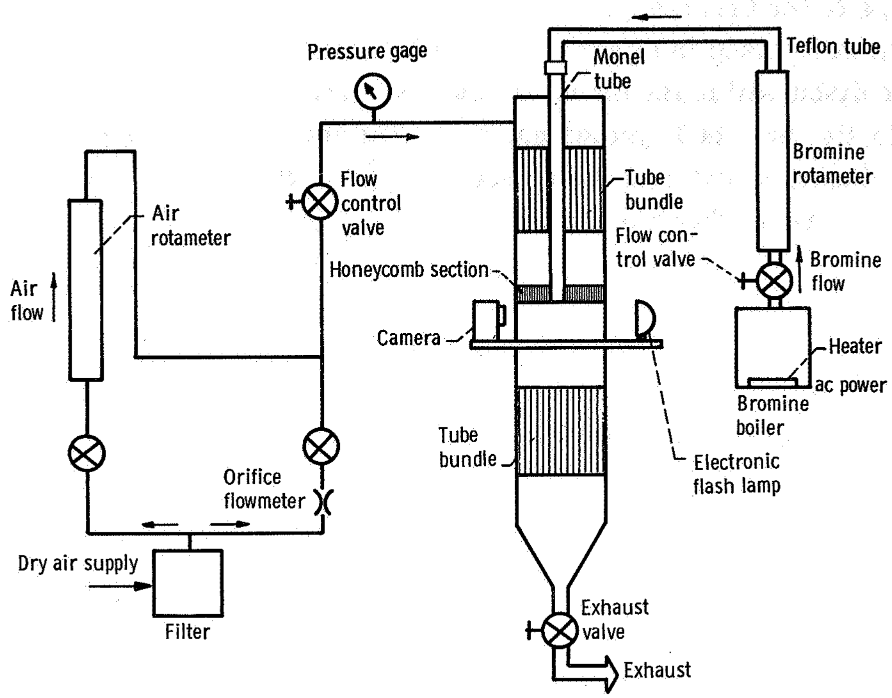


Figure 1. - Schematic drawing of air-bromine system.

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 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 (40.5 and 51.5 psia) 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 and honeycomb section can be important and is therefore shown in more detail in figure 2. The Mylar honeycomb used in this study is shown in figure 3. The honeycomb is 5 centimeters thick and the pores are hexagonal in shape and number four to the centimeter. There is a removable section of honeycomb for both the airstream and bromine. The effect on jet mixing of each honeycomb can be photographed and studied independently. After the bromine leaves the monel tube, it mixes with the airstream, 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. 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

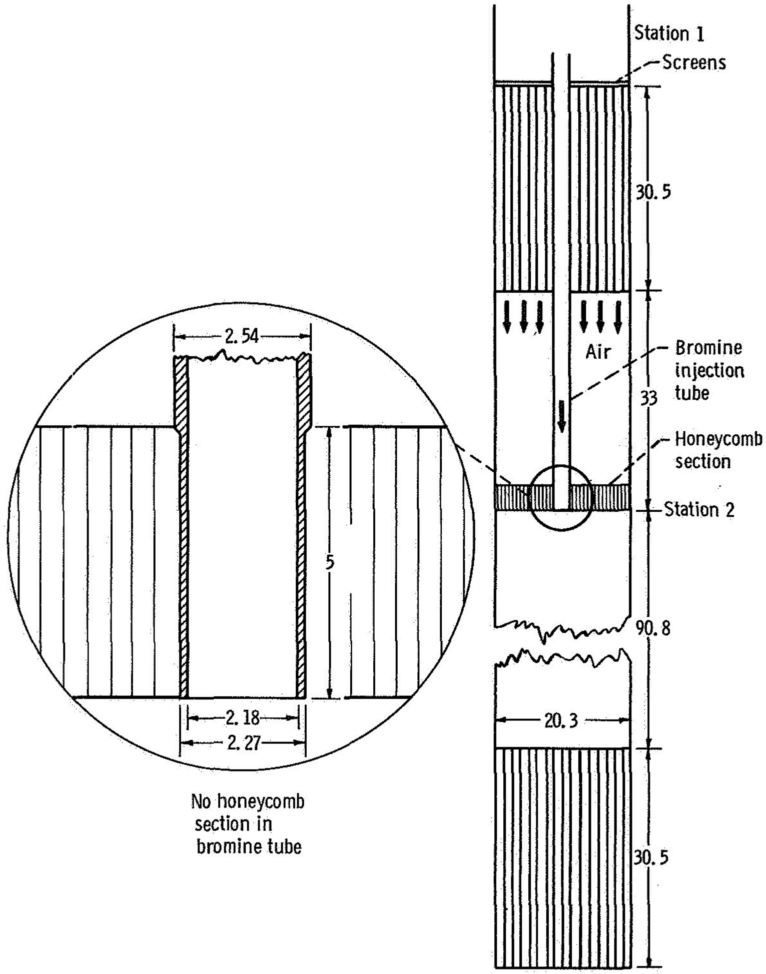


Figure 2. - Schematic drawing of test chamber. (All dimensions are in centimeters.)

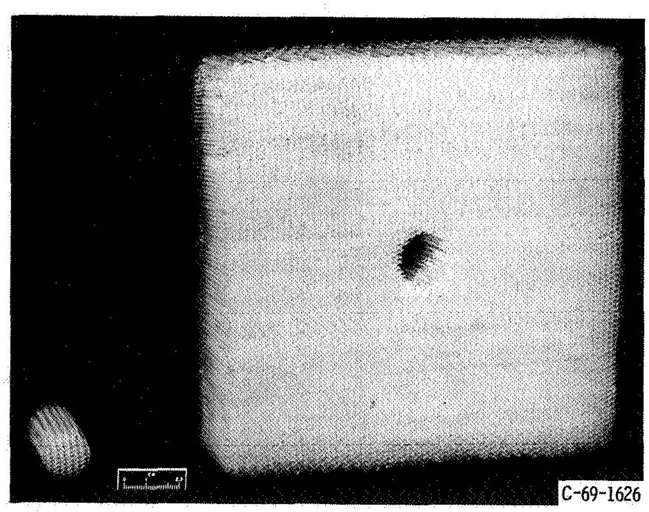


Figure 3. - Mylar honeycomb sections.

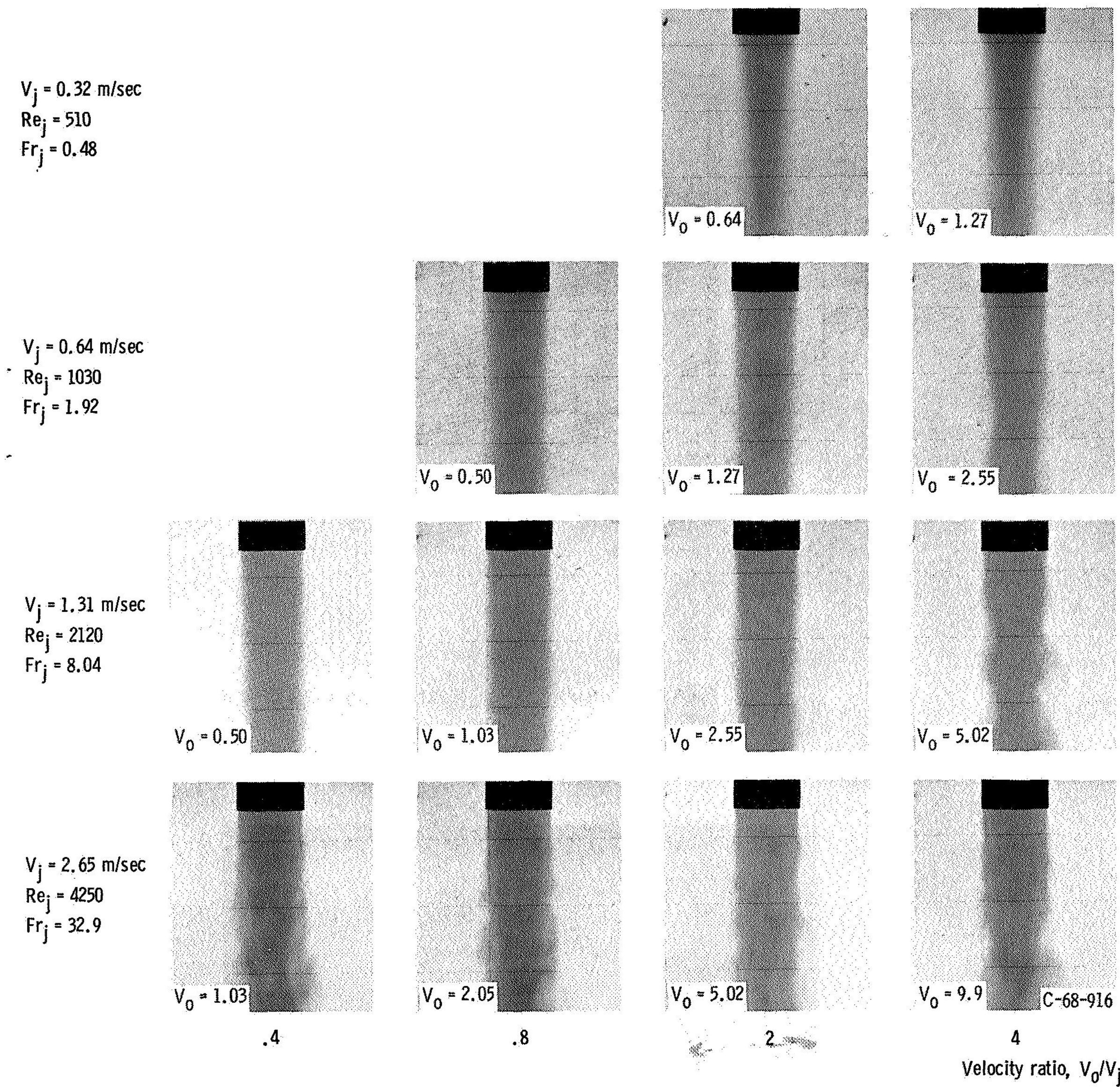
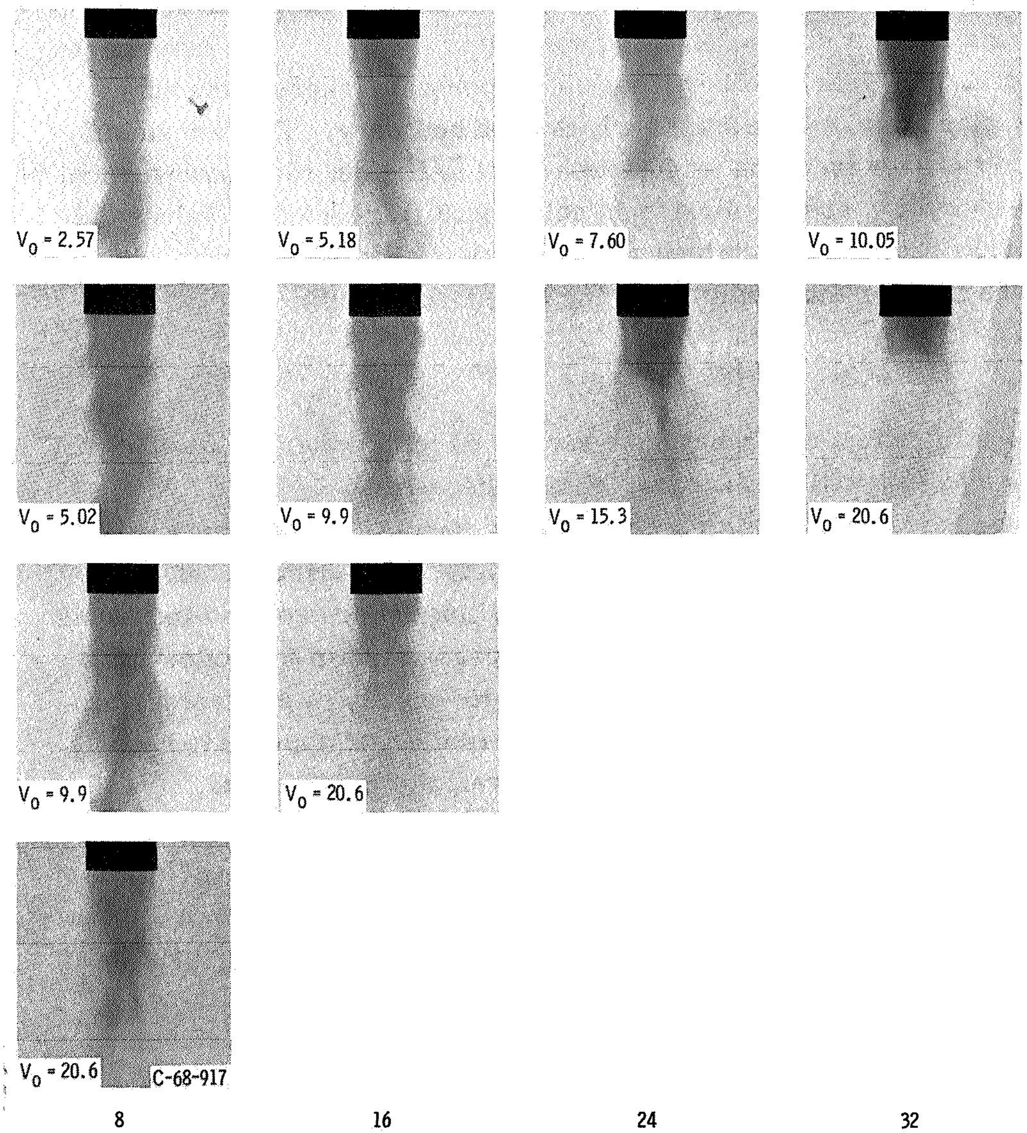


Figure 4. - Bromine jet issuing into coaxially flowing airstream.



Both jet and stream velocity are varied. (Data from ref. 7.)

ASA rating of 320. The camera was approximately 90 centimeters from the bromine stream and 150 centimeters from the light source.

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 honeycomb sections. 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 five jet radii downstream. 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.

Free Jet

Before photographing the effect of a honeycomb section on jet mixing, the basic case of no honeycombs, or a free jet, will be photographed and discussed.

Figure 4 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 4, the bromine jet appears to become less laminar as either the outer stream velocity or the jet velocity is increased.

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 4. The velocity of the bromine jet is also increased by the faster moving outer airstream.

From these pictures and others studied by Taylor and Masser (ref. 7), a general conclusion was reached for the conditions investigated. 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.

This result along with the data of reference 7 is shown in figure 5. All of the data of reference 7 is not shown in figure 4.

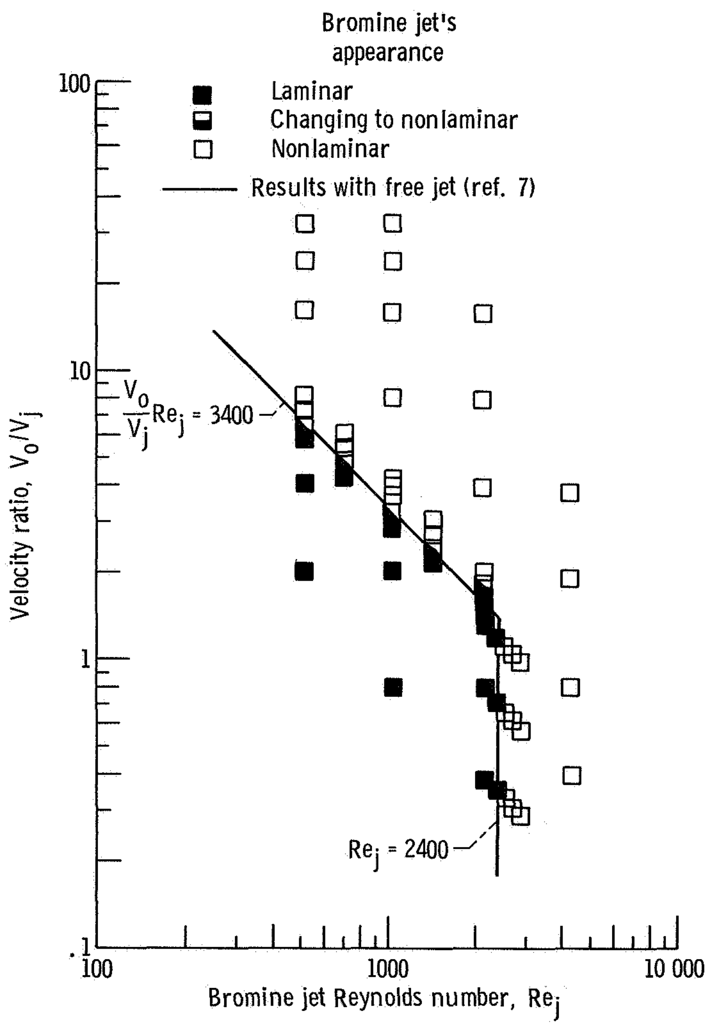


Figure 5. - Variation of velocity ratio with jet Reynolds number. (Data from ref. 7.)

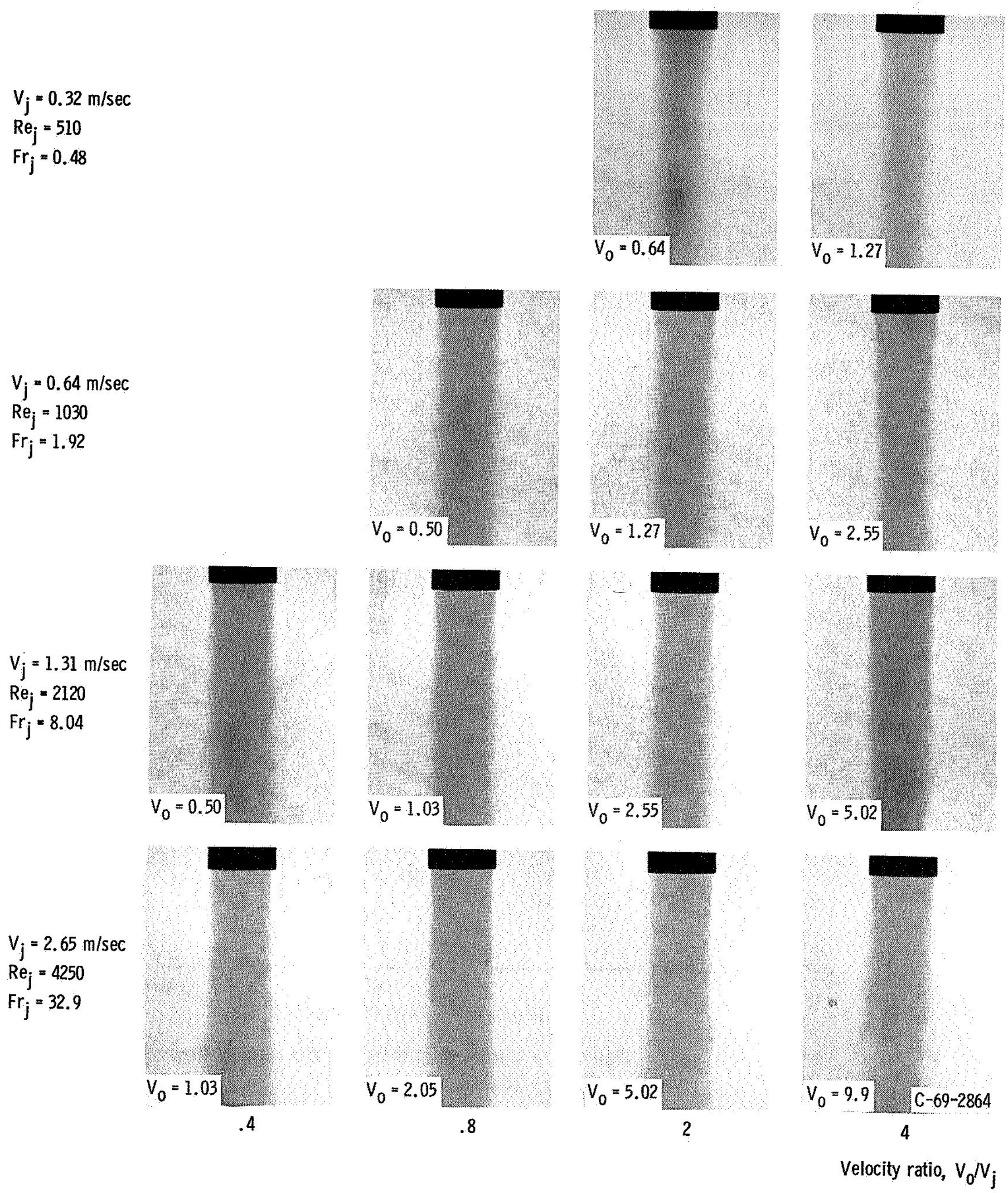
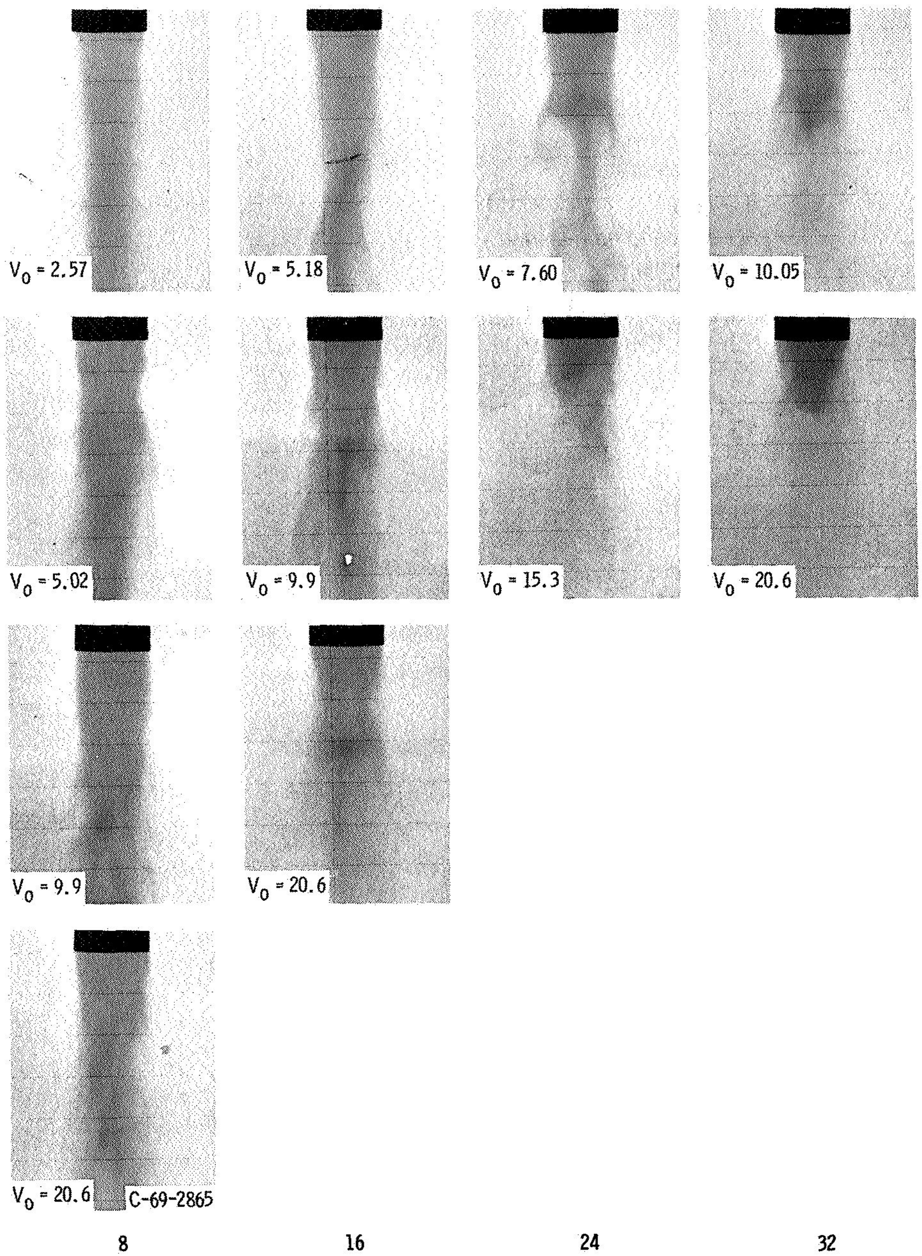


Figure 6. Bromine jet issuing into coaxially flowing airstream.



Honeycomb section is present in bromine tube only.

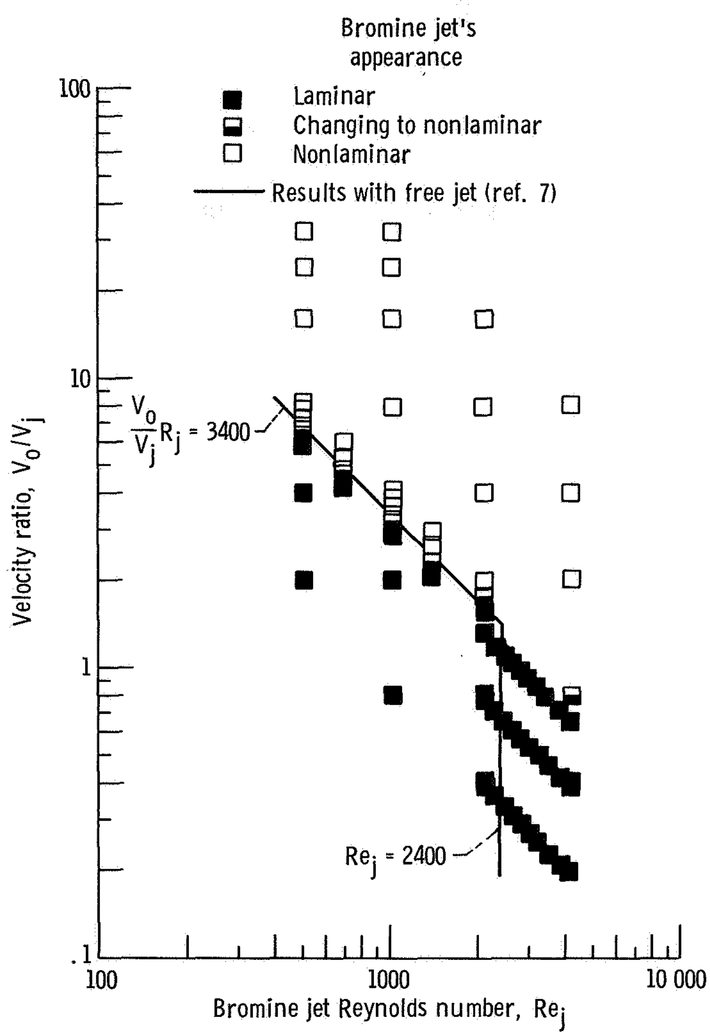


Figure 7. - Variation of velocity ratio with jet Reynolds number. Honeycomb present in bromine tube only.

Effect of Honeycomb in Jet

With the photographic data from reference 7 for a free jet as a basic case, one can compare the results when a honeycomb section is inserted in the jet just at the jet injection plane. Figure 6 is identical to figure 4 except for the cylindrical section of honeycomb which has been inserted in the bromine tube.

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. As in figure 4, the bromine jet appears to become less laminar as either the outer stream velocity or the jet velocity is increased. However, at a jet velocity of 2.65 meters per second, the interaction between the bromine and air is much less in figure 6 than in figure 4. In fact, at velocity ratios of 0.4 and 0.8 the bromine jet has a laminar appearance. This laminar appearance may be due to the local Reynolds number in the honeycomb section passages being much less than the bulk Reynolds number calculated using the inside diameter of the injection tube.

More photographs were taken with the honeycomb in the injection tube near the boundary separating laminar and nonlaminar appearing flow. These photographs and those of figure 6 are shown in graphical form in figure 7. The open symbols represent photographs for which the bromine jet appears nonlaminar, and the solid symbols are for laminar appearing jets. The laminar appearing region has been extended by using a honeycomb in the bromine injection tube.

Effect of Honeycomb in Both the Jet and Airstream

The results on jet mixing when a honeycomb is inserted into the injection tube have just been discussed. The next step is to insert a honeycomb section into the airstream, while keeping the honeycomb in the injection tube. In figure 8 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 8, the bromine jet appears to become less laminar as either the outer stream velocity or the jet velocity is increased. However, in this case the interaction between the bromine jet and airstream is much more evident. In every case of figure 4 where the jet appeared nonlaminar, this appearance is much more apparent in figure 6.

In figure 8 at a jet velocity of 2.65 meters per second the jet has a laminar appearance at velocity ratios of 0.4 and 0.8. This was true for figure 6, but not for figure 4 where there was no honeycomb in the injection tube. Again, the laminar appearance of

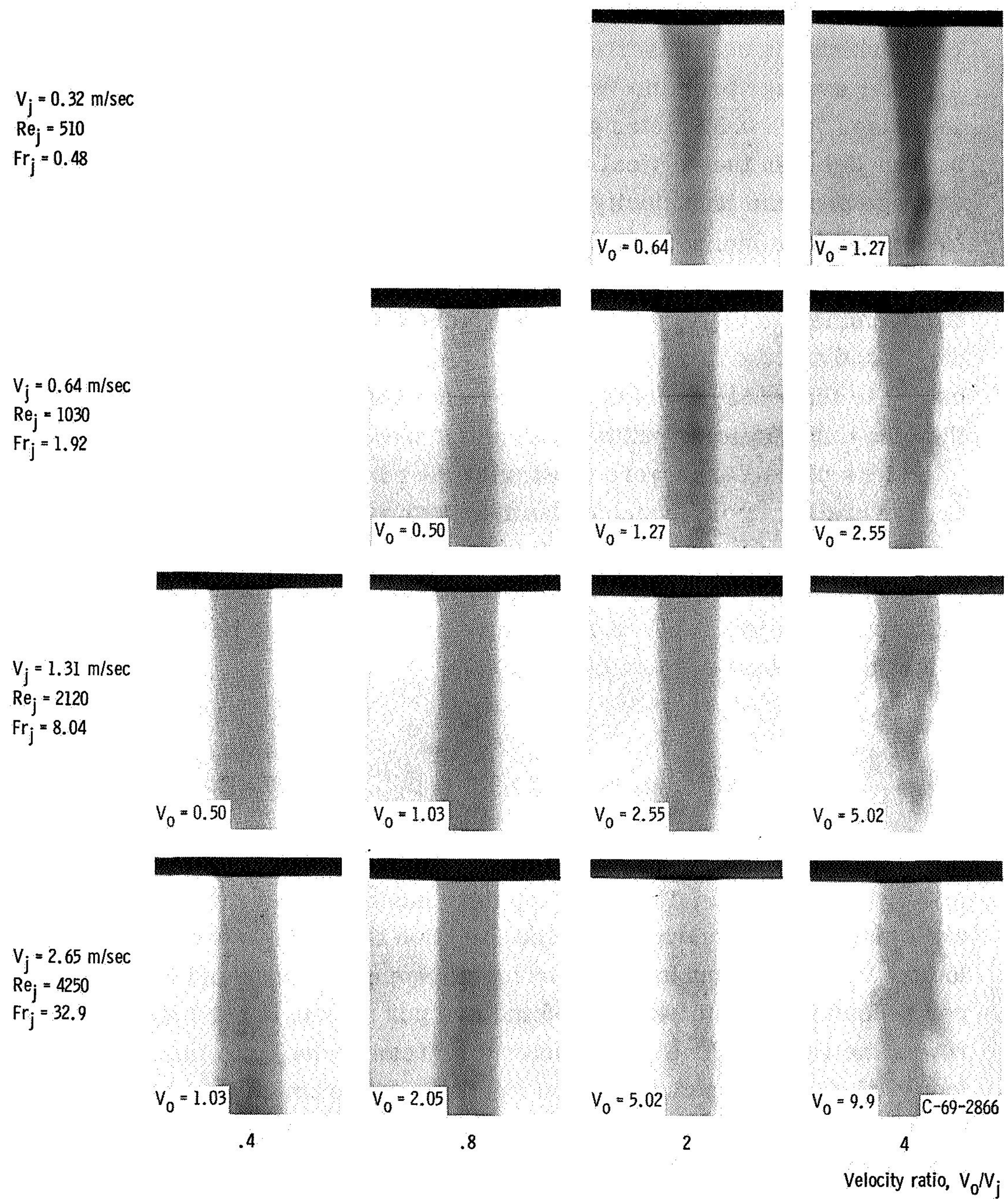
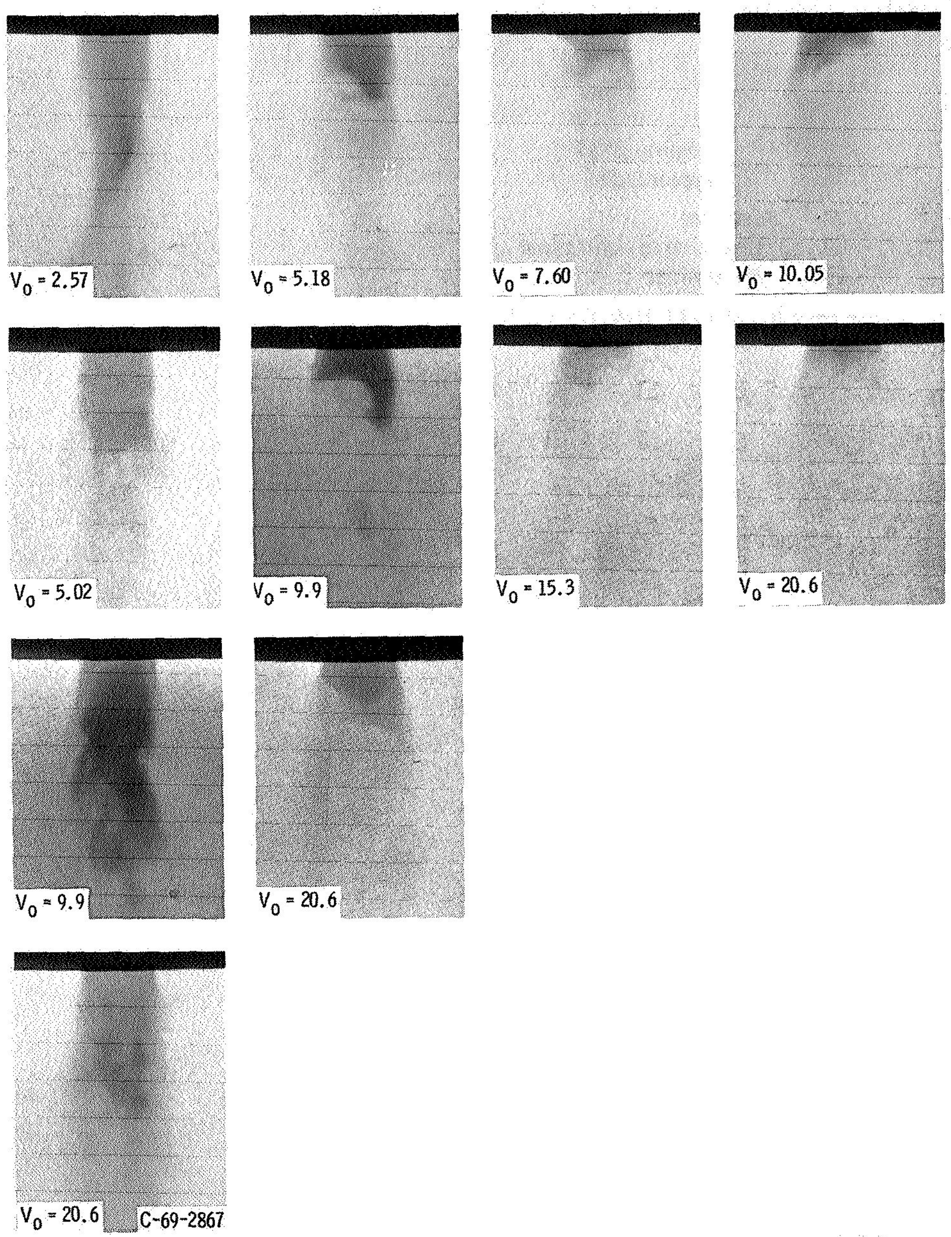


Figure 8. - Bromine jet issuing into coaxially flowing airstream.



Honeycomb sections are present in both bromine tube and airstream.

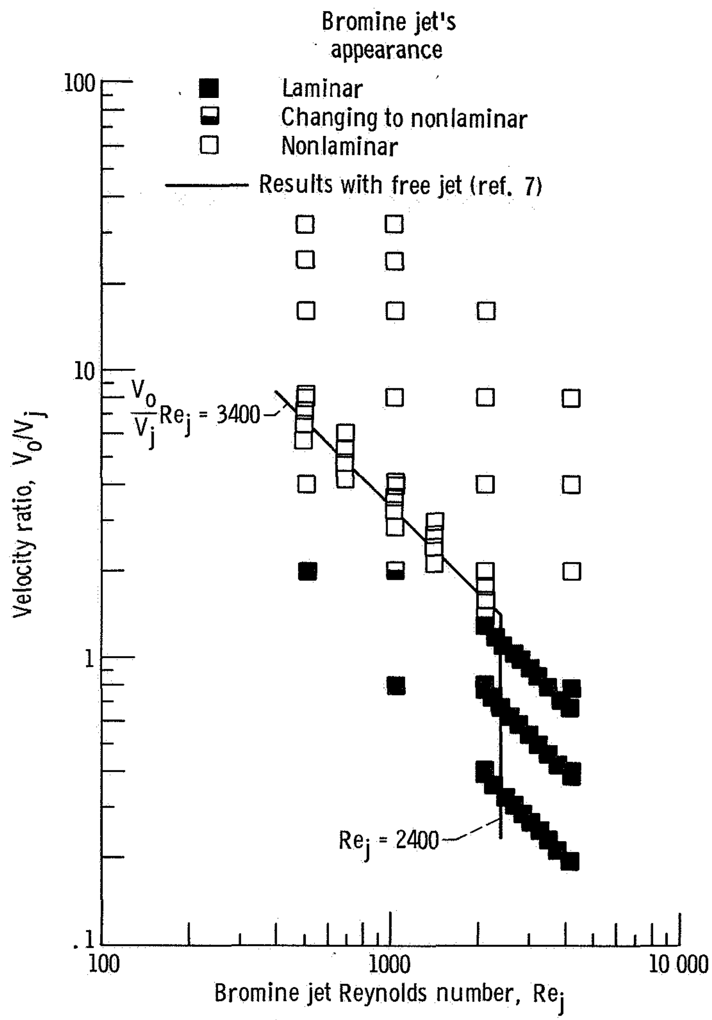


Figure 9. - Variation of velocity ratio with jet Reynolds number. Honeycomb present in both bromine tube and airstream.

these two photographs may be due to the local Reynolds number based on the diameter of the honeycomb section passages being much less than the bulk Reynolds number calculated using the inside diameter of the injection tube.

More photographs were again taken with the honeycomb sections in the injection tube and airstream near the boundary separating the laminar and nonlaminar appearing flow. These photographs and those of figure 8 are shown in graphical form in figure 9. The solid symbols represent laminar appearing jets, while the open symbols represent nonlaminar appearing jets. The laminar appearing region has been reduced from figure 5 in the area of large velocity ratios, while it has been extended in the area of low velocity ratios as was the case in figure 7.

Effect of Honeycomb in Airstream Only

The last set of photographs will show the effect on jet mixing when a honeycomb section is inserted in the outer airstream only. Figure 10 is identical to figure 4 except for the honeycomb section present in the airstream. 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 10, the bromine jet appears to become less laminar as either the outer stream velocity or the jet velocity is increased.

As in figure 8, the interaction between the airstream and bromine jet is much more evident than in figure 4. In fact, using a honeycomb in the airstream only causes more mixing than was present in any of the other cases studied. This may be caused by the more uniform velocity profile produced by the honeycomb. When the honeycomb is not present, the layer of air around the bromine injection tube slows in speed and the resultant velocity gradient between the airstream and bromine jet is less, thereby causing less mixing.

Again, more photographs were taken with the honeycomb section in the airstream only near the boundary separating the laminar and nonlaminar appearing flow. These photographs and those of figure 10 are presented in graphical form in figure 11. Again, the solid symbols are for laminar appearing jets while the open symbols are for nonlaminar appearing jets. The laminar region is smaller in this case than for any of the other cases studied in this report. The adverse effect of a honeycomb section in the outer airstream, plus the effect of not having a honeycomb insert in the bromine injection tube, are both present.

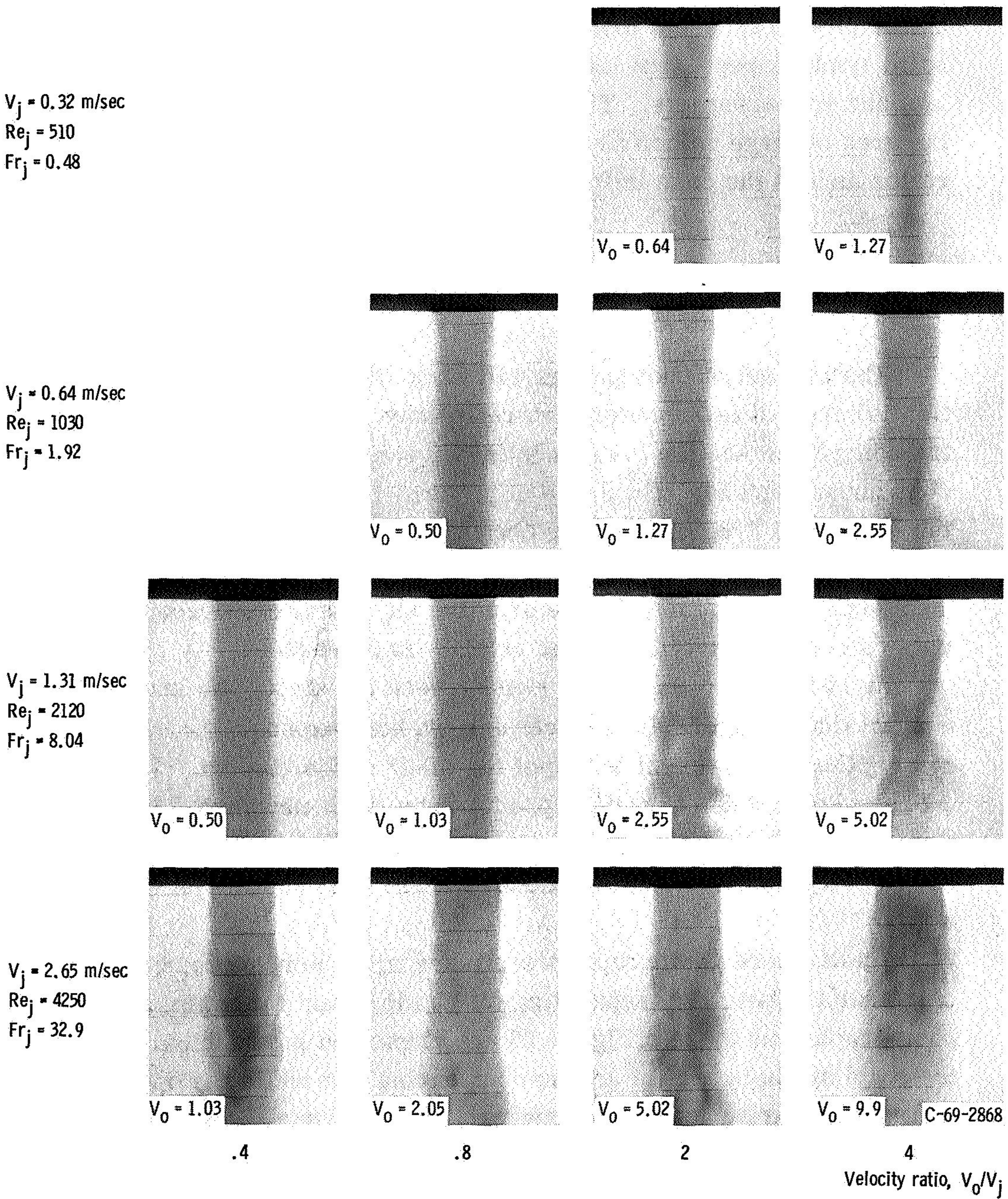
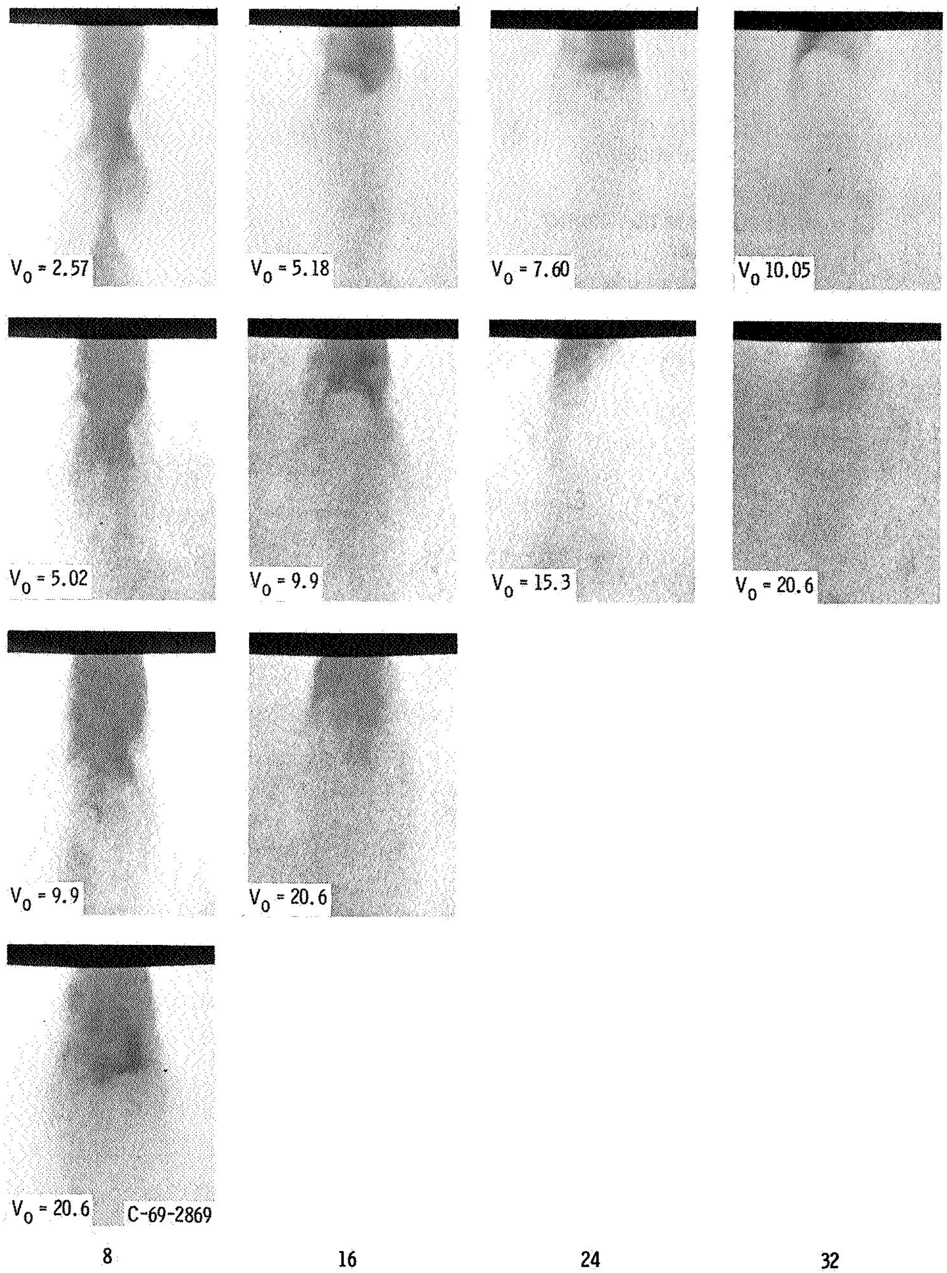


Figure 10. - Bromine jet issuing into coaxially flowing airstream.



Honeycomb section is present in airstream only.

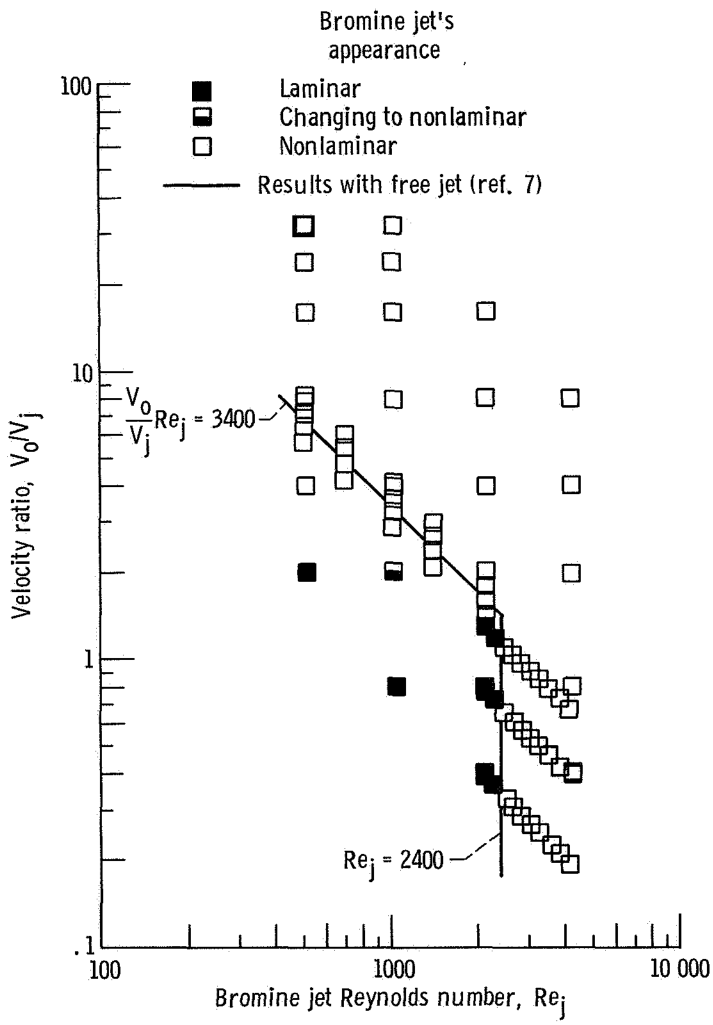


Figure 11. - Variation of velocity ratio with jet Reynolds number. Honeycomb present in airstream only.

SUMMARY OF RESULTS

A photographic study was made of a bromine jet issuing into a coaxially flowing airstream. The objective of this study was to determine if the amount of bromine in the near jet region can be increased by the presence of a honeycomb section in the injection plane. Photographs were taken of the bromine jet with

1. A honeycomb section present in bromine injection tube only
2. A honeycomb section present in both bromine tube and airstream
3. A honeycomb section present in airstream only

These photographs were then compared to photographs taken with no honeycomb present in either the bromine tube or airstream. Bromine jet velocities varied from 0.3 to 2.65 meters per second and airstream velocities varied from 0.5 to 20.6 meters per second. The results of this study can be summarized as follows:

1. At velocity ratios of eight or more, there appears to be no increase of bromine in the near jet region when honeycomb sections are present in either or both the airstream and bromine tube at the injection plane.

2. The presence of honeycomb sections influences the transition at which the jet appears to change from laminar to nonlaminar in the following ways:

   a. A honeycomb present in only the bromine tube retarded the transition from laminar to nonlaminar appearing flows.

   b. Honeycomb sections in both the bromine tube and airstream caused the transition from laminar to nonlaminar appearing flows to occur sooner than without honeycomb sections.

   c. A honeycomb section in the airstream only caused the transition from laminar to nonlaminar appearing jets to occur sooner than when honeycombs were present in both the bromine jet and airstream.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 8, 1969,
122-28.

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TABLE I. - RANGE OF TEST CONDITIONS

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

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

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