

AFOSR 68-1572

AD671977

INVESTIGATION OF  
JET TRANSITION  
PHENOMENA

OR 9442

June 1968

C. P. McKenzie

D. B. Wall

Martin Marietta Corporation  
Orlando Division

Air Force Office of Scientific Research  
██████████

DDC  
REF  
JUL 19 1968  
A

Reproduced by the  
CLEARINGHOUSE  
for Federal Scientific & Technical  
Information Springfield Va. 22151

1. This document has been approved for public  
release and sale; its distribution is unlimited. 27

**INVESTIGATION OF  
JET TRANSITION  
PHENOMENA**

**C. P. McKenzie  
D. B. Wall**

## **FOREWORD**

This report is submitted by the Martin Marietta Corporation, Orlando Division, in full compliance with Contract AF 49(638)-1725, Mod2. It records work performed from 1 June 1967 to 31 May 1968 under the cognizance of Major Donald L. Calvert. It is issued as Martin Marietta report number OR 9442, dated June 1968.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

## ABSTRACT

This experimental investigation examines jet phenomena, gaseous and liquid, in small submerged and bounded jets. Its general objectives are to acquire experimental data and to develop mathematical expressions for predicting the behavior of fluidic elements and designs. Data are presented for circular nozzles of 0.25 to 4.6 mm and square nozzles of 0.5 to 1.0 mm, observed by Schlieren and birefringent flow techniques at low Reynolds numbers compatible with miniature fluidic designs. Good correlation between compressible and incompressible flow is obtained.

Three principal nondimensional terms are used to evaluate and correlate experimental results. They are Reynolds number, transition number (a relationship of nozzle diameter and length of laminar flow), and momentum number (represented the interaction of two jets).

Three sets of tests are described. One measures the transition from laminar flow to turbulence in single submerged jets. The second introduces a secondary jet flow to determine its effect upon transition and deflection of the primary jet. The third involves variations of nozzle geometry commonly used in fluidic elements: sidewall divergence, sidewall setback and reinjection curvature. These geometries provide feedback paths and reflecting surfaces, allowing the jet to produce premature transition.

Based upon an apparent need for transition to effect wall attachment in fluidic devices, the use of reinjection geometries can contribute to minimum power levels and maximum element packaging densities.

## CONTENTS

I. Introduction . . . . .	1
II. Defining Flow Parameters . . . . .	3
III. Experimental Data . . . . .	7
IV. Geometrical Influences . . . . .	11
V. Conclusions and Recommendations . . . . .	17
References . . . . .	19

## ILLUSTRATIONS

1	Schematic of Transition Point . . . . .	4
2	Transition versus Reynolds Number for Single Submerged Gaseous and Liquid Jets . . . . .	6
3	Arrangement of Test Nozzles . . . . .	6
4	Interaction of Two Submerged Jets, Gaseous and Liquid . . . . .	8
5	Schematic of Deflection Angle . . . . .	9
6	Transition Advancement Due to Secondary Injection . . . . .	9
7	Comparison of Deflection Angles for Submerged Jets . . . . .	10
8	Test Planes Used for Geometry Changes . . . . .	12
9	Transition as a Function of Divergence without Setback . . . . .	13
10	Transition as a Function of Divergence with Setback . . . . .	14
11	Transition for Circular Exhaust Section . . . . .	15
12	Incompressible and Compressible Flow in a Bistable Amplifier . . . . .	16

## I. INTRODUCTION

When fluidics was first introduced to the aerospace community, it created considerable interest because of such advantages as low cost, reliability, nuclear survivability, and vibration insensitivity. Several deficiencies, however, were also observed. The elements had slow response characteristics and excessive power consumption, and performance predictions were difficult. Since then, industry and the universities have attempted to reduce these problems.

The general approach to solving fluidics problems is to understand the intrinsic behavior of submerged and bounded jet phenomena identified with operational fluidic components, most of which utilize one or more fluid jets. This understanding, coupled with results from numerous experiments should lead to improved packaging densities, higher efficiencies, and improved output performances. At the same time, it should also define some of the predominant fluid and geometrical parameters that govern the operation of fluidic components more generally.

Jet transition has not been described adequately in the literature. Analysis of mass addition or the interaction of jet streams is very limited (References 1 and 2). Analytical expressions that represent the behavior of laminar and turbulent jets influenced by mass addition or rejection are needed to effectively design fluidic elements.

This report presents the results of an experimental investigation to observe and characterize jet phenomena for both gaseous and liquid media in small, submerged and bounded jets. Such phenomena are of interest because the working fluids within most fluidic components function under a bounded and submerged condition. The primary objective of the investigation is to derive mathematical expressions that will effectively predict the characteristics and behavior of fluidic elements and designs. In method, it is oriented toward examining this transition of fluid jets from laminar flow to turbulence when influenced by secondary injection and geometrical changes.

A primary jet usually activates a fluidic device. The state, laminar or turbulent, of this primary jet may then determine the predominant characteristics of the device. Laminar flow is usually preferred when operating efficiencies are important. Turbulence is undesirable because power and noise levels are increased while pressure recovery is decreased. However, experiments on fluid amplifiers have shown that, for effective operation, the primary jet should begin in the laminar state and later become turbulent. Thus, it is apparent that knowledge of the transition from laminar to turbulent regimes could be used to predict performance characteristics of fluidic components.

## II. DEFINING FLOW PARAMETERS

To present the test data in a concise manner, the equations will be nondimensionalized. The transition point is presented in terms of nozzle lengths.

Determining the position at which laminar jet will respond to disturbances and transform into a turbulent flow regime is difficult analytically. During transition, major changes also occur in the velocity profile. The velocity profile may be derived from the equation of motion (Reference 3).

$$\rho D\vec{V} = -\nabla P + \mu \nabla^2 \vec{V} + \rho \vec{g} \quad (1)$$

where  $\rho$  is the medium density,  $\vec{V}$  is the velocity,  $p$  is the pressure,  $\vec{g}$  is the gravity vector, and  $\mu$  the viscosity or "eddy viscosity." The latter is used for turbulent flow.

It is convenient to nondimensionalize Equation (1) with respect to the mass bulk velocity,  $U_o$ , and the nozzle diameter or width,  $a$ .

The bulk average velocity is defined as

$$U_o = \frac{1}{A} \int_{\text{Area}} \vec{V} \cdot d\vec{A} \quad (2)$$

where  $A$  is the cross-sectional area of the nozzle and  $V$  is the local velocity. For a circular nozzle, Equation (2) may be written as

$$U_o = \frac{4}{\pi} \frac{Q_o}{a^2} \quad (3)$$

where  $Q_o$  is the volume flow rate. The linear dimensions become  $r' = r/a$ , and  $z' = z/a$ . Applying these relations to Equation (1) and examining only the axial direction after performing an order of magnitude analysis, the equation of motion for the  $z$  direction is obtained:

$$V'_r \frac{\partial V'_z}{\partial r'} + \frac{V'_\theta}{r'} \frac{\partial V'_z}{\partial \theta} + V'_z \frac{\partial V'_z}{\partial z'} = \frac{1}{N_R} \frac{\partial^2 V'_z}{\partial z'^2} \quad (4)$$

where

$$N_R = \frac{\rho U_o a}{\mu} = \text{Reynolds number}$$

The Reynolds number appears to be a dominant parameter for investigating jet phenomena. It will be one of the principal parameters in evaluating and correlating experimental results.

During the investigation, the transition point was varied over a large range. The data appeared more uniform and offered increased utility when nondimensionalized. Hence, it was convenient to define the ratio of the location of the transition point,  $Z_T$ , to the nozzle diameter (or width),  $a$ , as the transition number,  $T$ .

$$T = \frac{Z_T}{a} \quad (5)$$

A schematic showing the location of the transition point is given in Figure 1. The laminar and turbulent regions are indicated, and the location of the transition point is defined by the intersection of the turbulent envelope. Thus, the Reynolds number and transition number are sufficient to describe the transition point in submerged jets.

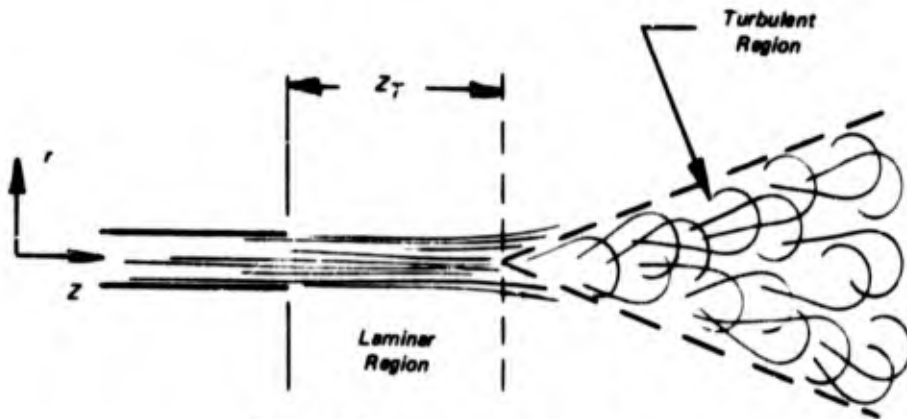


Figure 1. Schematic of Transition Point

Secondary injection is essentially a second jet with a given momentum  $M_1$  interacting with a primary jet of momentum  $M_2$ . During the analysis of the interaction of two jets, a momentum ratio number  $M$  was used as a useful parameter.

$$M = \frac{M_2}{M_1} = \frac{\omega_2 U_2}{\omega_1 U_1} \quad (6)$$

where  $\omega$  is the mass flow rate. It is expressed as  $\omega = \rho AU$ , where  $\rho$  is the density. Applying  $Q_i = A_i U_i$  to Equation (6), the momentum ratio number is obtained.

$$M = \left( \frac{Q_2}{Q_1} \right)^2 \left( \frac{a_1}{a_2} \right)^2 \quad (7)$$

These nondimensional numbers will be used to correlate and present the experimental data.

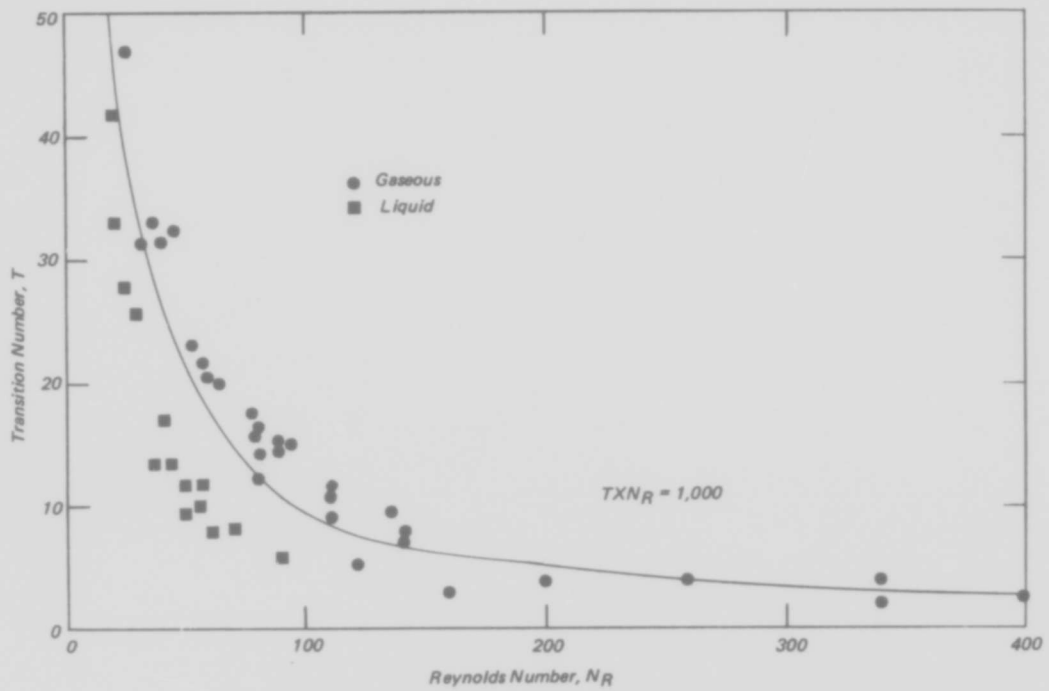
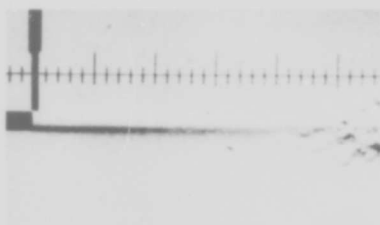
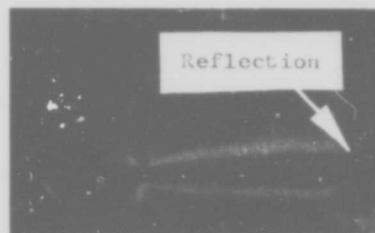


Figure 2. Transition versus Reynolds Number for Single Submerged Jets



Compressible



Incompressible

Figure 3. Arrangement of Test Nozzles

### III. EXPERIMENTAL DATA

A design trend is to reduce amplifier sizes to obtain lower power consumption and higher operating rates. This trend, however, has compounded the need for experimental data in jet transition because, to ensure optimized power consumption, the fluid jet must egress from a fluidic element's nozzle in the laminar regime.

The initial set of tests in this investigation involved single submerged jets, both gaseous and fluid. Observations were directed toward determining the transition to turbulence. Those characteristics became most discernible when the transition number was plotted against Reynolds number. In such observations, no data were recorded for transition points occurring more than 90 nozzle widths downstream from the nozzle exit. This bandwidth provided a locus of transition points extensive enough to show the approximate critical Reynolds number. During the investigation, all experiments were performed in an environmentally controlled atmosphere, monitored by sensors to detect any random fluctuations of temperature or pressure. The same restriction was imposed on observations of bounded jets and, of course, those with secondary injection.

Data points from the initial set of tests are presented in Figure 2. A median curve, represented by the expression  $T \times N_R = 1000$  is also shown. It is important to note that this figure contains data from both fluid media, thus exhibiting a correlation within the Reynolds number range. The liquid points lie below the gaseous points, but this separation is attributable to the small size of the liquid test chamber, which apparently introduced reflections that caused premature turbulence. Future experiments conducted in a larger test cell should show an increase in the transition number to further substantiate the correlation between liquid and gaseous media. Another significance of the data curve in Figure 2 is that it shows the regions of laminar and turbulent flow for submerged undisturbed jets at Reynolds numbers that apply to miniature fluidic devices.

In a second series of tests, data for secondary injection were obtained with the apparatus shown in Figure 3. No geometry variations were included in this series or in the initial series of tests. A scale was incorporated into the test fixtures to facilitate measuring the transition number and to preclude any scaling problems caused by photographic reductions.

The test procedure used for the two-jet interaction experiments was: (1) establish a given flow in the primary jet, (2) adjust the output level of the secondary flow, and (3) photograph the position of the transition point. Figure 4 was developed from data acquired in this manner. The locus of data points could be approximated by the expression  $T \times M = 0.20$ . Once again, the transition occurs earlier in the liquid tests, and the effects of chamber sidewalls are considered to contribute to this disparity.

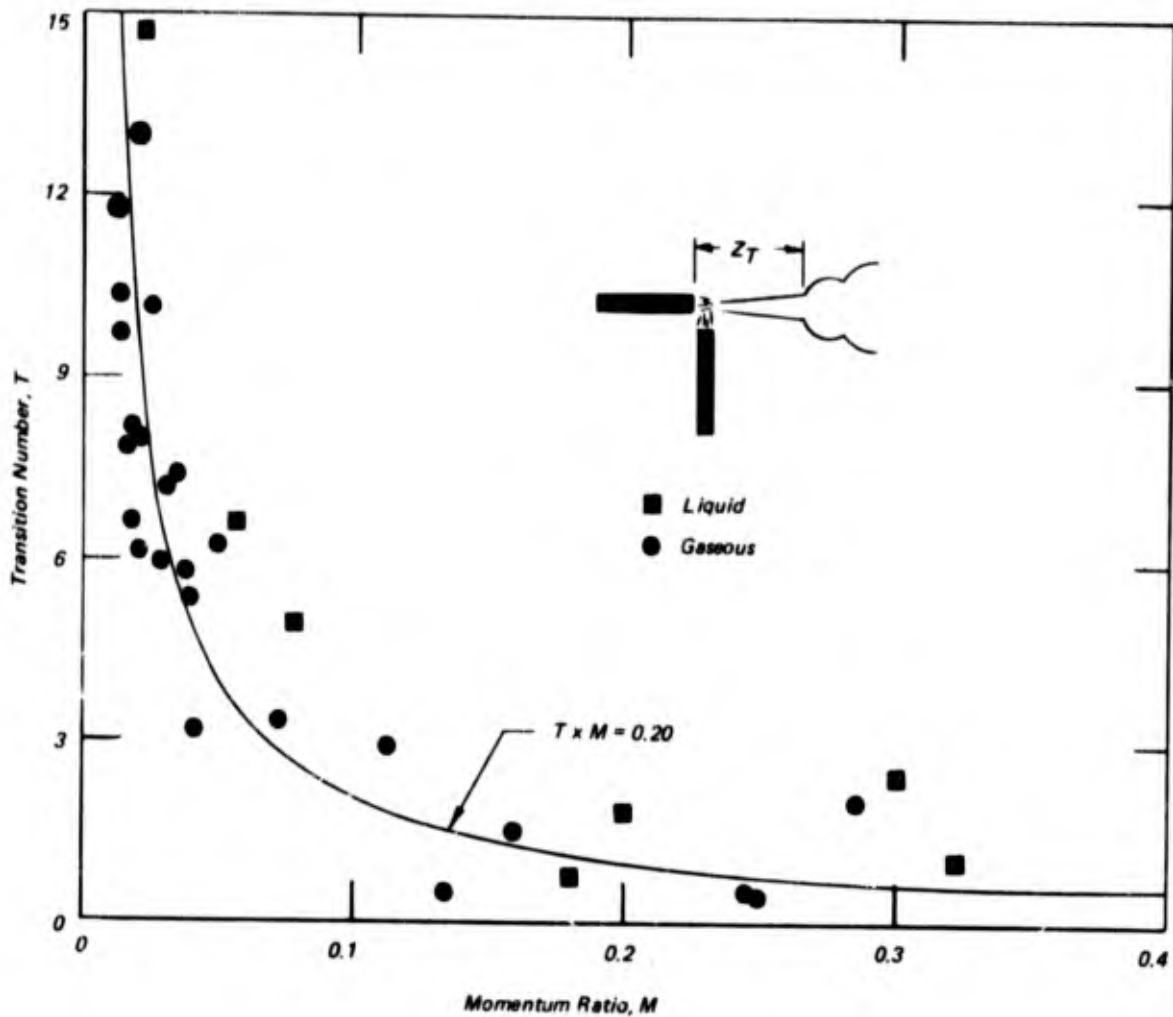


Figure 4. Interaction of Two Submerged Jets

A momentum ratio test using two jets was performed by examining the amount of deflection of the primary jet when influenced by a secondary jet. Figure 5 shows schematically this deflection angle,  $\theta$  and the general test configuration. Two typical flow situations are shown in Figure 6. In both cases the flow of the secondary jet is seen to intercept the principal jet. The transition point appears ill-defined unless one accepts the previous definition, that is, where the envelopes intercept. Photographs of this type were used to collect and record the data. Data reduction was performed and the information is displayed in Figure 7. The deviation of the experimental curve from the ideal curve at low momentum numbers can be attributed to the characteristics of a laminar jet. When a small disturbance intercepted a large primary jet, this disturbance caused the transition point to advance toward the nozzle with no measurable deflection. As the disturbance increased, the transition point advanced and jet deflection occurred; however, the deflection was less than the predicted amount. Apparently, as the secondary jet penetrates the laminar stream, its momentum is absorbed and does not appear to contribute to the angular deflection. Instead, it disturbs the jet's cohesiveness and induces premature turbulence. The experimental data agreed closely with the analytical curve after the momentum ratio exceeded 0.4.

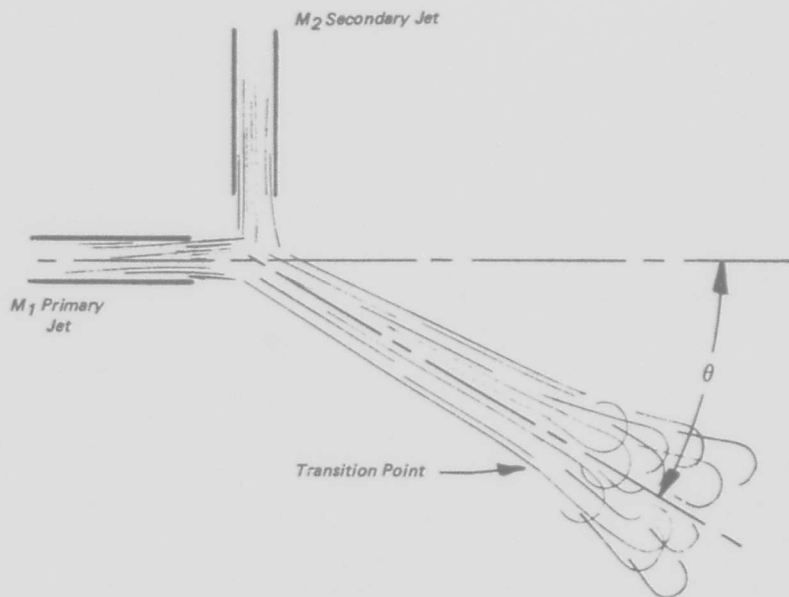
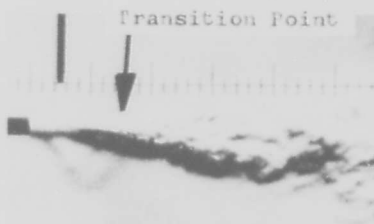
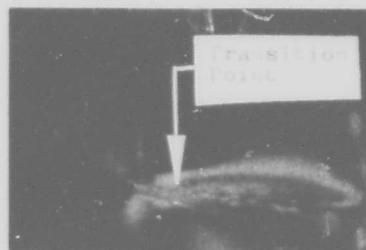


Figure 5. Schematic of Deflection Angle



Compressible



Incompressible

Figure 6. Transition Advancement Due to Secondary Injection

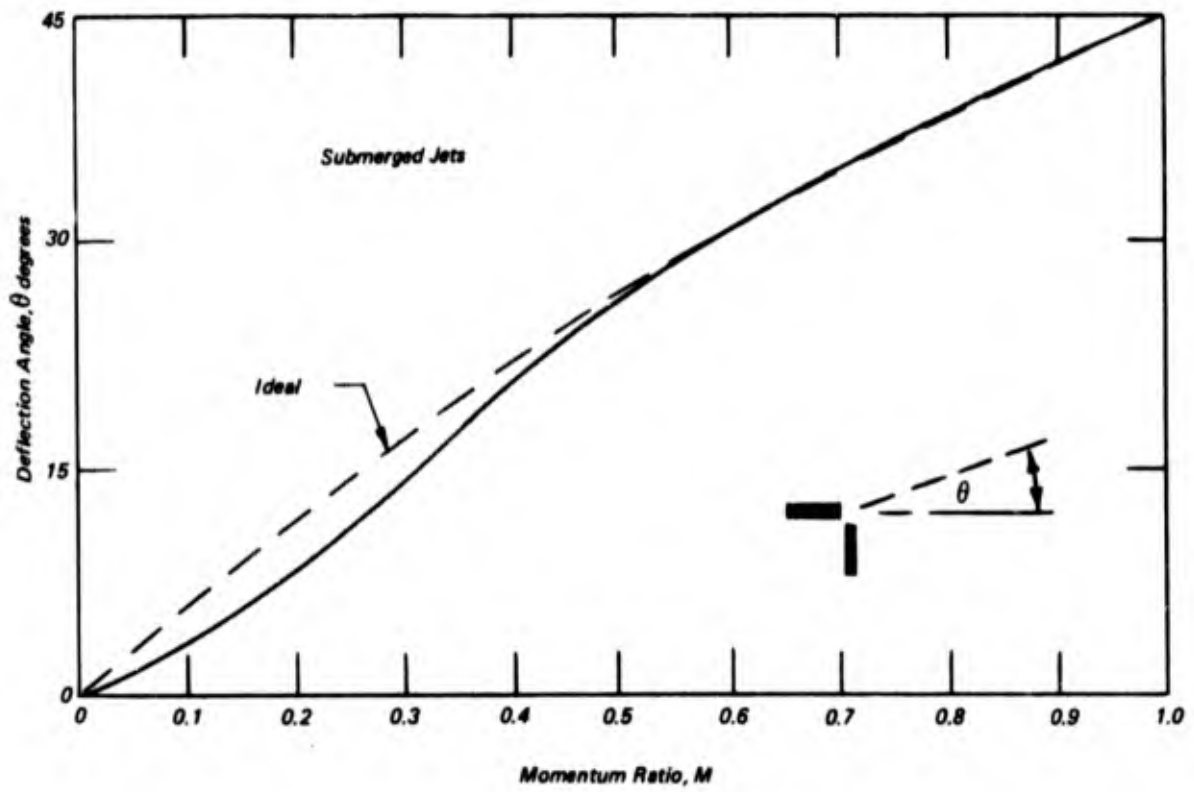


Figure 7. Comparison of Deflection Angles

#### IV. GEOMETRICAL INFLUENCES

Although the flow from the primary jet of a fluid amplifier is similar in many respects to idealized jet flow, geometrical differences will influence the nature of the flow. These differences may promote premature transition to turbulence for digital operation, or they may provide damping to reduce internally created transient noise in proportional amplifiers. Fluid amplifier sidewalls contain the jet in the expansion region downstream of the nozzle exit and provide reflecting surfaces that influence the nature of the disturbances acting on the jet. The upper and lower walls also affect the distance at which the vortices meet, leading to the formation of a fully developed turbulent jet.

These phenomena inhibit analytical determinations of the point of transition to turbulent flow (Reference 4). Thus, analytical methods for designing fluid amplifiers must supplement existing theoretical approaches with empirical equations obtained from experimental data.

In the experimental investigation, the point of transition advanced upstream and finally reached a constant value until the power was increased enough to effect turbulence flow within the nozzle. These observations tend to indicate the existence of a critical turbulent energy level which must be reached before the Coanda effect can occur.

If wall attachment occurs only after some minimum turbulence level has been reached, then any geometric factors that prematurely promote turbulence would become controlling parameters in the design of minimum power miniature fluidic devices. (In the observed experiments, the minimum turbulence level was related to the asymptote reached by the locus of the points of transition to turbulence.) Therefore, geometries commonly used in fluidic elements were evaluated to determine their effects on transition.

The geometric parameters included in the experiments were sidewall divergence, sidewall setback, and re-injection curvature. The explanation of the influence of the output geometry on the transition point is that these regions protrude into or interfere with the primary flow field. These geometries provide feedback paths and reflecting surfaces for portions of the flowing fluid. This condition allows the jet to act as its own disturbing or driving force and, thus, to trigger itself into premature transition.

Although the aspect ratio was maintained at unity, the effects of any change can be reasonably anticipated. For example, increasing the aspect ratio, which decreases the influence of edge effects from the upper and lower bounding surfaces, increases the amount of fluid subjected to sidewall shear and reflection. A greater volume of fluid surrounding the jet is

retarded, and the regions of large velocity gradients are increased. This condition will make the jet mixing regions more susceptible to amplification by residual turbulent fluctuations.

Figure 8 shows three typical planes used in the investigation. The center plane is the simple divergent; the left plane has the same divergent angles but includes sidewall setback; and the right plane contains the circular or re-injection type geometry. The test specimens for the experiments were constructed of thin copper laminates and stacked together to form a square nozzle.

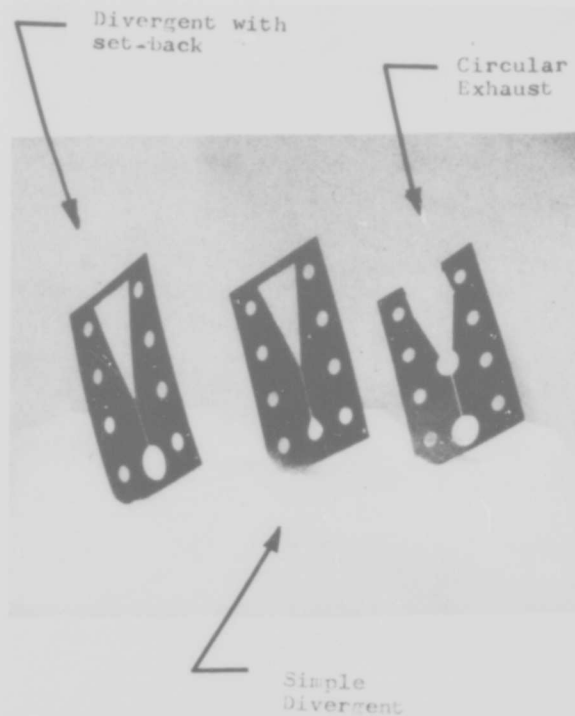


Figure 8. Test Planes Used for Geometry Changes

Sidewall divergence (Figure 9) with respect to the centerline of the jet nozzle had negligible effect on tendencies of the jet to become turbulent prematurely (Reference 4). The jet was found not to attach to either wall when the included angle of the sidewalls was greater than 50 degrees. This upper limit was expected because the greater the wall angle the greater the pressure difference required to force the jet's momentum change as it is deflected over to the attachment point.

Another series of tests was performed with a geometry changed to include sidewall setback of one nozzle width on each side of the jet exhaust port. The same divergence angles were used.

This configuration approximated the presence of control ports near the exit of the power nozzle in fluid amplifiers. Setback at the nozzle caused the fluid jet to see a sudden expansion and experience a rapid decrease in static pressure. This drastic alteration to the downstream pressure gradient was expected to cause the mixing regions to grow faster and to move the transition point nearer the nozzle exit for the same nozzle Reynolds number.

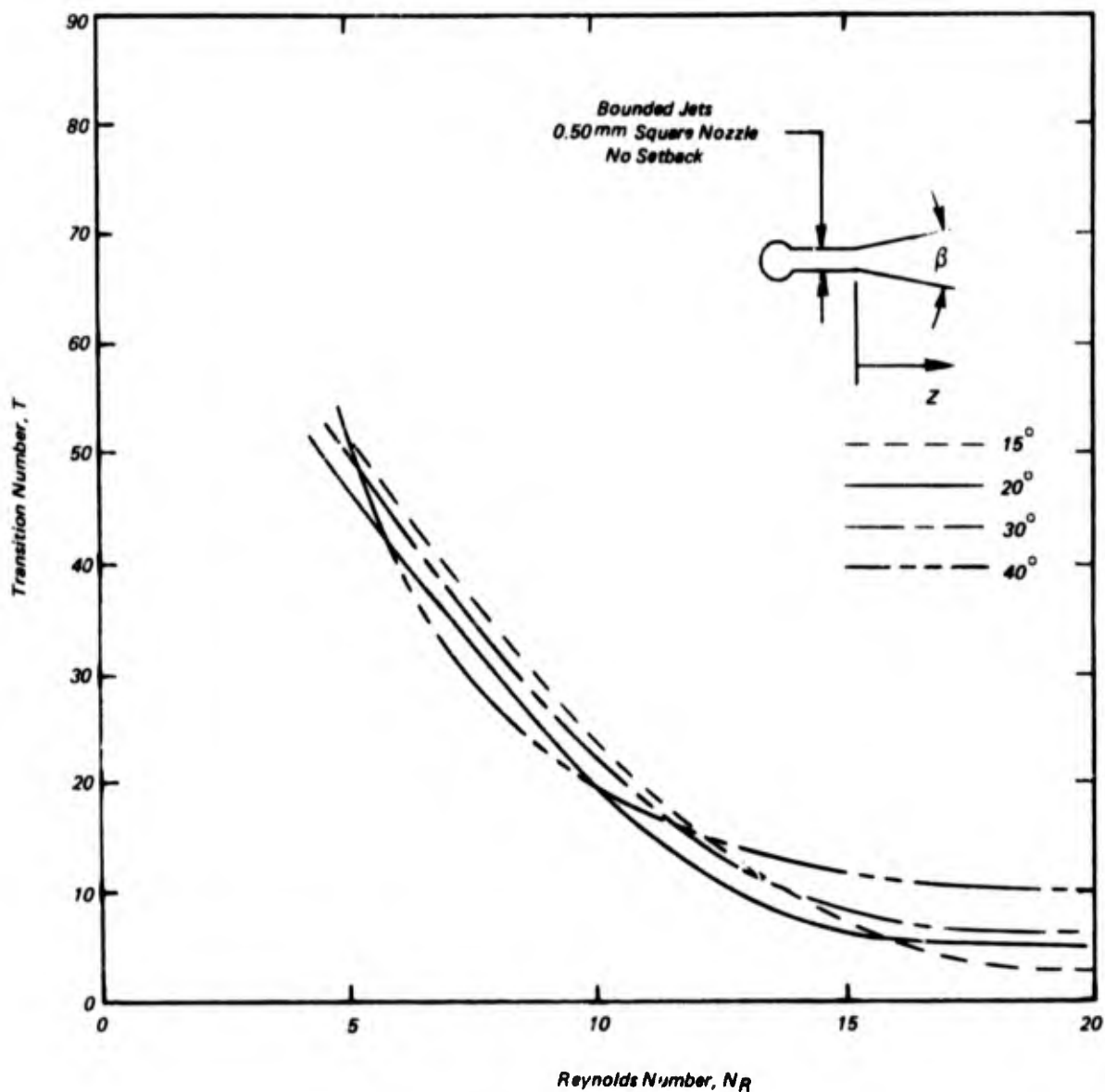


Figure 9. Transition as a Function of Divergence

Results of tests on the setback geometry are presented in Figure 10. Comparison of Figures 9 and 10 indicates that the effect of setback on transition is negligible. The jet, nevertheless, was found to attach at a slightly lower Reynolds number in this geometry than in the purely divergent channels.

The cylindrical design (Figure 11) was tested in an effort to promote premature transition. The jet exhaust chamber was designed to feed part of the fluid back into the jet before much of

its kinetic energy had diminished. This circular exhaust region adjacent to the nozzle exit had the effect of first subjecting the jet to a sudden expansion and then feeding back into the exhaust nozzle region part of the fluid from the boundary regions of the flow. These two disturbances caused a premature triggering of the transition point. Portions of the geometry provided volume for flow circulation of the separation bubble in addition to providing feedback. With a progressively enlarged diameter of the circular section and increased nozzle cross-sectional area, the transition point attained a symptotic value for significantly smaller Reynolds numbers in this geometry than in the simple divergent and setback divergent channels. Attachment occurred at lower Reynolds numbers, indicating that feedback due to circulation had a significant effect on the characteristics of the jet. Figure 11 shows the advancement of the transition point.

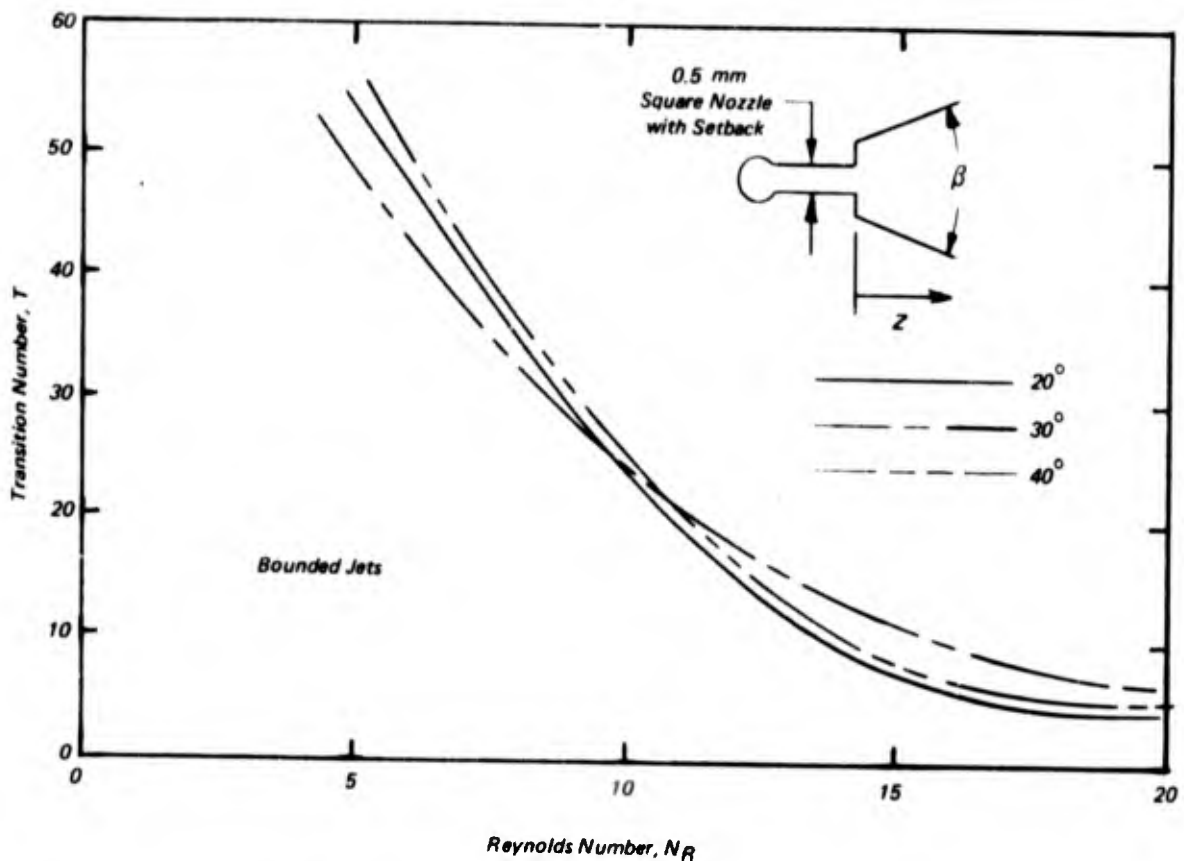


Figure 10. Transition as a Function of Divergence with Set-back

Based on these observations, the 0.5mm square nozzle's transition point could be decreased by 50 percent, thereby allowing a similar reduction in element geometry and weight. This circular geometry thus appears significant to the effective operation of miniature fluidic amplifiers.

Figure 12 presents photographs of two geometrically identical bistable power amplifiers. The amplifier on the right is operating in a birefringent liquid, and the other is operating in a helium-enhanced nitrogen mixture. The chamber diameters for both cases are 10 millimeters.

These photographs demonstrate flow similarity, although no attempts were made to assure identical flow parameters. In both cases, the flow can be seen issuing out the left output of the element. The photograph of the Schlieren shadow (a) shows secondary jet flow entering from the right. The flow pattern of the primary jet issuing down the left leg is clearly visible. The circulation and the separation bubble are also visible in both cases, especially 12 b. Present tests are underway to define more conclusively the flow patterns in gaseous and liquid elements of this type.

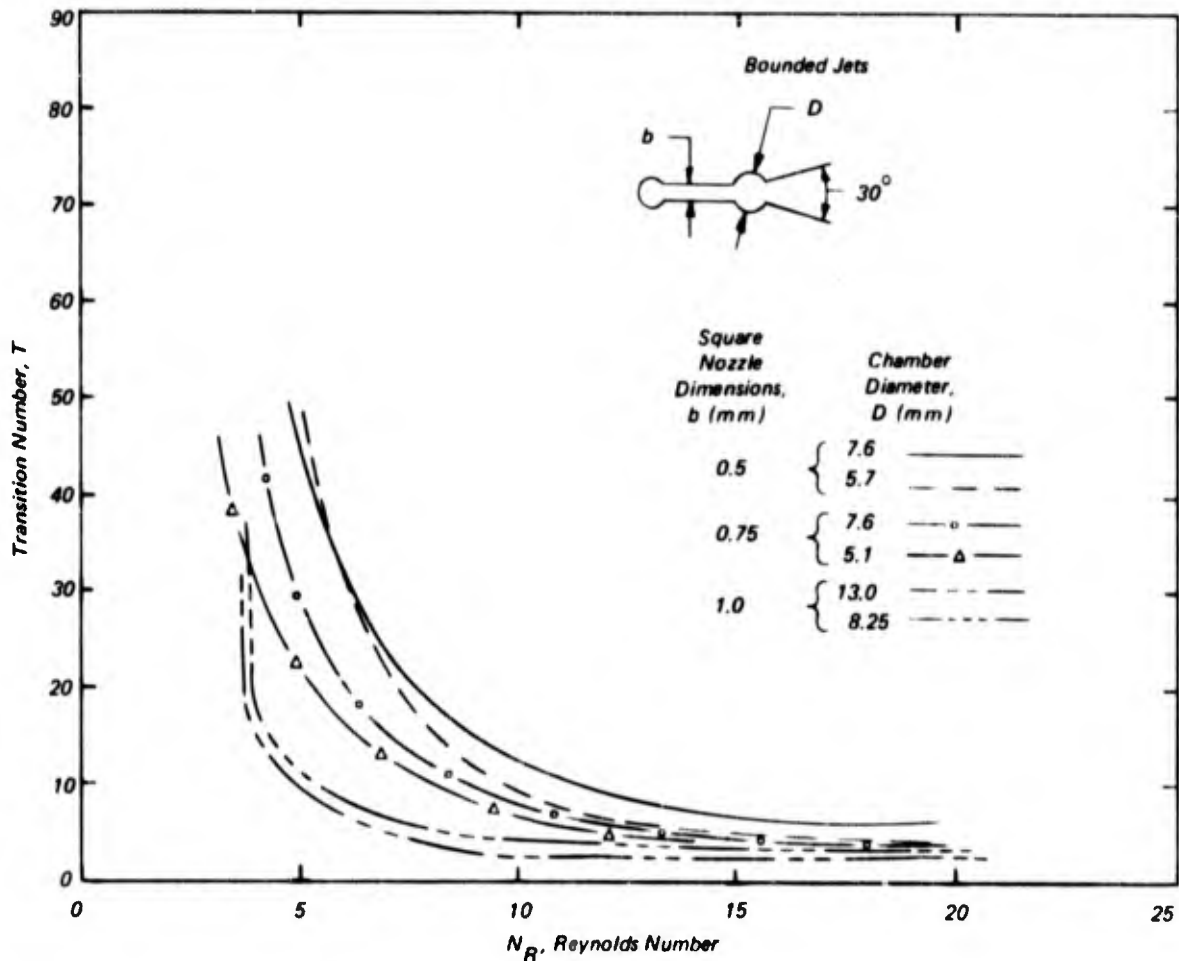


Figure 11. Transition for Circular Exhaust Section



(a) Compressible



(b) Incompressible

Figure 12. Incompressible and Compressible Flow in a Bistable Amplifier

## V. CONCLUSIONS AND RECOMMENDATIONS

The investigation of both compressible and incompressible flow shows that transition from laminar to turbulent regimes occurs in both fluids at Reynolds numbers that are compatible with miniature fluidic designs.

The transition point exhibits similar behavior for two interacting jets or for single jets. Initial injection of a secondary flow only disturbs the flow, thus causing premature transfer into the turbulent regime, and produces no deflection of the primary jet until the transition point approaches the nozzle exit. As the mass flow of the secondary jet increases, ideal momentum relationships accurately predict the deflection angle.

The geometry of the receiver section into which a jet exhausts influences the slope and nature of the curve describing transition behavior. Those geometries which aid in returning part of the principal jet to be entrained or recirculated cause transition to occur in shorter axial distances than plain divergent geometries. In all cases, recirculation or secondary injection causes premature transition to turbulence.

Since it appears that transition must occur for effective wall attachment, these experiments show that reinjection should be incorporated into fluidic element designs if minimum power levels and maximum element packaging densities are desired.

The transition distance has been reduced, in some cases, to less than one quarter of the original amount. This large reduction in distance allows a similar reduction in overall dimensions of the amplifier.

## REFERENCES

1. Kirsher, J., *Fluid Amplifiers*, McGraw Hill, New York, N.Y., 1966
2. Olsen, R. E., "Analytical Techniques for Predicting the Characteristics of Jet Flows in Fluidic Devices," *Fluidic Quarterly*, Vol 1, No. 1, Fluid Amplifier Associates, Ann Arbor, Michigan
3. Bird, R. D., et al., *Transport Phenomena*, John Wiley and Sons, Inc., 1960
4. Martin Marietta Corporation, OR 8882, "Transition to Turbulence," Orlando, Florida, June 1967

UNCLASSIFIED

Security Classification

## DOCUMENT CONTROL DATA - R &amp; D

Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified.

1. ORIGINATING ACTIVITY (Corporate author) Martin Marietta Corporation Engineering Mechanics Research Laboratory Orlando, Florida 32805		2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	
		2b. GROUP	
3. REPORT TITLE INVESTIGATION OF JET TRANSITION PHENOMENA			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Scientific Final			
5. AUTHOR(S) (First name, middle initial, last name) C P McKenzie D B Wall			
6. REPORT DATE June 1968		7a. TOTAL NO. OF PAGES 17	7b. NO. OF REFS 4
8a. CONTRACT OR GRANT NO. AF 49(638)-1725		9a. ORIGINATOR'S REPORT NUMBER(S) OR 9442	
b. PROJECT NO. 9781-01		9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) <b>AFOSR 68-1572</b>	
c. 6144501F			
d. 681307			
10. DISTRIBUTION STATEMENT 1. This document has been approved for public release and sale; its distribution is unlimited.			
11. SUPPLEMENTARY NOTES TECH, OTHER		12. SPONSORING MILITARY ACTIVITY AF Office of Scientific Research (SREM) 1400 Wilson Boulevard Arlington, Virginia 22209	
13. ABSTRACT This experimental investigation examines jet phenomena, gaseous and liquid, in small submerged and bounded jets. Its general objectives are to acquire experimental data and to develop mathematical expressions for predicting the behavior of fluidic elements and designs. Data are presented for circular nozzles of 0.25 to 4.6 mm and square nozzles of 0.5 to 1.0 mm, observed by Schlieren and Birefringent flow techniques at low Reynolds numbers compatible with miniature fluidic designs. Good correlation between compressible and incompressible flow is obtained. Three principal nondimensional terms are used to evaluate and correlate experimental results. They are Reynolds number, transition number (a relationship of nozzle diameter and length of laminar flow), and momentum number (represented the interaction of two jets). Three sets of tests are described. One measures the transition from laminar flow to turbulence in single submerged jets. The second introduces a secondary jet flow to determine its effect upon transition and deflection of the primary jet. The third involves variations of nozzle geometry commonly used in fluidic elements: sidewall divergence, sidewall setback and reinjection curvature. These geometries provide feedback paths and reflecting surfaces, allowing the jet to produce premature transition.			

DD FORM 1 NOV 68 1473

UNCLASSIFIED

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Jet Flow						
Transition Flow						
Laminar Flow						
Turbulence						