Technical Report No. 32-207

On the Dynamic Characteristics of Free-Liquid Jets and a Partial Correlation with Orifice Geometry

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ABSTRACT

A technique for evaluating the dynamic characteristics of free-liquid jets on a comparative basis is presented. This method consists of determining the pressure distribution produced by the perpendicular impingement of a jet upon a flat plate and using these data for comparing and categorizing jets with unknown properties in terms of similar data produced by jets having known characteristics–i.e., with jets produced by fully developed turbulent flow, fully developed laminar flow, and a jet having a near-uniform velocity profile.

The visual characteristics, as well as both the mean and the fluctuating pressure distributions, are presented for these three reference configurations and for a number of jets produced by orifices having varying length–diameter ratios, combined with varying degrees of surface roughness in the initial five diameters of straight bore.

I. INTRODUCTION

A. *Historical Interest*

The use of the free jet in practical devices is as old as man himself; therefore, it is not surprising that the free jet has been the subject of intensive experimental investigation and mathematical analysis for more than a hundred years. Of particular interest within this field is the liquid jet in a gaseous medium, which has seen application in such varied fields as fire fighting and hydraulic mining (see, for example, Refs. 1, 2, 3), as a primary element in turbines, and more recently in diesel injection and as an essential component of injectors for liquid rocket motors.

B. *Definition of Free Jet*

The term, free jet, refers in the general sense to fluid in motion that is bounded by a surface of constant pressure (Ref. 4). This surface may also be associated with a discontinuity such as exists with a liquid jet in air where a step change in fluid density occurs; but it is still true that if extraneous forces are neglected, the pressure must be constant along such a surface. Also, in the general sense, there are no restrictions upon the geometry of the jet. However, for the purposes of this Report, the term, free jet, will always imply a cylindrical jet of liquid—which in most cases is water—bounded by air at atmospheric pressure. The term, cylindrical, has significance only insofar as the mean cross section of an axially symmetric jet can be considered circular and because the exit cross section of the orifices that were used in these experiments was in all cases circular.

C. The Problem

Free-liquid jets that in general conform to the conditions just noted have been utilized as primary elements in the injectors of liquid rocket motors for many years. Their application varies from the so-called showerhead injector through a whole series of impinging-stream configurations that include the one-on-one (both "like" and "unlike"), the two-on-one, and so forth. It is also used as the primary element in "target" injectors, in which the jet impinges upon a splash plate that can also have one of many varied configurations. Thus, it is seen that the elemental jets may alternately be required either to disintegrate in the shortest possible time (i.e., showerhead) or to retain a maximum degree of stability for an appreciable distance of penetration into a combustion chamber (i.e., impinging jets). In addition, the jet (or more specifically, the orifice producing it) may be used as a part of the fluid-metering system and, at the same time, be required to produce a particular mass and mixture-ratio distribution in the spray resulting from impingement. It is, therefore, obvious that adequate control of injection processes can stem only from a thorough knowledge of the properties of the jets and their relation to the geometry of the orifices that produce them. The data presented herein are the consequence of an effort to provide this information.

In general, the properties of a jet that are of prime importance in a rocket-motor injector are its stability (or instability), the scale and intensity of turbulence, and the velocity profile at some specified distance along the free jet.

Jet stability implies stability in mean flow and direction as well as boundary and is particularly important in injectors composed of impinging streams. The scale and intensity of turbulence are significant, because they may contribute to mixing along the interface produced by two impinging jets as well as to the disintegration of individual jets. The velocity profile is particularly significant for impinging streams, as it determines the momentum distribution along the interface between the two liquids (which is a consequence of impingement) and, together with the relative jet momenta, determines the shape of the interface, which, in turn, determines the resulting mass and mixture-ratio distribution.

It is obvious that nonsteady flow, which is characterized by time-varying flow rates from the jets of a liquid propellant rocket injector, for example, can influence combustion phenomena, particularly if in a bipropellant injection scheme the flows from the two systems are out of phase. But what is not so obvious is that variations in jet properties which are not uniquely related to flow rate can also affect the impingement process and, hence, combustion. Variations in momentum distribution within the jets of any impinging pair, for instance, even when the flow rate is constant, can have a marked effect upon mixture-ratio distributions in the resulting spray and, hence, on local combustion processes. Therefore, resolution of the problems associated with predicting and controlling the dynamic properties of injection schemes (e.g., discrete properties of free-liquid jets) is prerequisite to an understanding of the combustion process.

D. Technical Literature Review

Most of the available information concerning the properties of jets is the result of investigations that have been directed either toward the development of diesel injectors (Refs. 5 through 12) or to an understanding of the mechanism of jet breakup accompanying that type of injection (Refs. 13 through 25). Therefore, a great deal of emphasis has been placed upon the length of the continuous portion of the free jet as an important jet characteristic. In several of the more recent papers, the turbulence of the jet has also been given some consideration (Refs. 18, 19, and 22), but it is only in a relatively few instances that the velocity distribution has even been mentioned (Ref. 18 and Appendix of 7). In most cases, it is assumed that the velocity profile of the jet at the orifice exit is uniform (even though this is rarely, if ever, true), so that the hydrodynamic analyses that are based upon this assumption (particularly the analysis of Rayleigh, Ref. 26) are not applicable to the experimental conditions. In addition, it should be noted that the hydrodynamic conditions that prevail in an injector for diesel-engine application become extremely complicated when the transient characteristic of the flow is incorporated into the problem.

In an investigation of a somewhat different nature, Howe and Posey (Ref. 1) were concerned with the dispersion characteristics of jets produced by fire-fighting equipment. As part of these experiments, they evaluated the velocity profiles of jets near the exit of the nozzles. Although their reported measurements were restricted to the edge of the jet, where pitot pressures are somewhat questionable, they were able to demonstrate a reduction of velocity at the surface of a jet issuing from a long nozzle. They also observed that "... jets having reduced velocity at the edge caused by separation have a frosty appearance, while those with the uniform distribution characteristic ... were smooth and nearly transparent. It is thus apparent that nozzle form influences the surface texture of the jet and accounts for much of the spray which falls off as the water leaves the nozzle."

Although observations reported here are consistent with this description, it is now clear that Howe and Posey's explanation of the phenomenon is only partially correct. It is true that the form of the nozzle does contribute to the appearance of the jet; but in the end, it must be recognized that the jet is extremely sensitive to the upstream conditions. It is fairly certain that the velocity reduction that Howe and Posey observed can be attributed to the presence of a low-velocity boundary layer of substantial thickness at the orifice exit, and that the "frosty" appearance is simply the consequence of turbulent disturbances within the boundary layer. Conversely, the "smooth" jets are associated with nonturbulent conditions in the jet boundary.

C. C. Miesse has studied the characteristics of jets such as might be encountered in rocket-motor injectors (Ref. 25) but did not consider the velocity profile as a parameter.

The possibility that the velocity profile of the jet could be one of its most significant characteristics was demonstrated, at least in a preliminary way, by the earlier phase of a continuing investigation that was reported by this author in Ref. 27. It was shown therein that the mass and mixture-ratio distribution of sprays produced by pairs of impinging jets were at least partially dependent upon the local properties of the individual jets (e.g., the shape of the velocity profile immediately upstream of the impingement point). It was concluded that "...the dynamic characteristics of the free jets have a marked influence on jet stability, on spatial distribution, and, to some extent, on liquid phase mixing. Jet dynamics are controlled by upstream conditions, orifice Reynolds number, and orifice design; the data available indicated that optimum jet pairs require symmetrical, similar (only in lieu of uniform), and stable free-stream velocity profiles." This conclusion was inferred from the variation in mass distribution that occurred when one jet was rotated a fixed increment about its centerline between two successive measurements. Although an attempt was made to correlate spray properties with the gross dynamic properties of the jets, it was only partially successful and the data were later presented in a revised form, together with some additional experimental information, in Ref. 28. This latter correlation served to demonstrate the significance of the gross stream parameters but still retained excessive scatter that was attributed to an inadequate evaluation and control of stream characteristics. However, in order to verify that latter conclusion, it was necessary to obtain more discrete information covering the dynamic properties of the jets.

It is to be noted that the significance of data such as those reported in Refs. 27 and 28 are based upon several basic assumptions relating injection characteristics with combustion phenomena. These assumptions include the following: (1) Rocket-motor combustion phenomena are closely related to mass and mixture-ratio distribution. (2) The mass and mixture-ratio distributions obtained in quiescent systems are applicable to the pre-reaction zone of a combustion chamber (in order to generalize the preliminary findings of Ref. 27). (3) The free-jet velocity profile, together with the distribution of turbulence intensity, is instrumental in determining the said mass and mixture-ratio distribution.

II. OBJECT

The objectives of this investigation were (1) to devise a technique for evaluating the dynamic characteristics of free-liquid jets, with particular emphasis upon the velocity distribution and distribution of turbulence intensity; (2) to evaluate the dynamic properties of the jets produced by the three limiting flow configurations, i.e., fully developed laminar flow, laminar flow with a uniform velocity profile, and fully developed turbulent flow; and (3) to determine the effectiveness of turbulence-inducing devices as a means of controlling the dynamic properties of jets.

III. SUMMARY OF RESULTS

A probing technique for evaluating the pressure distribution produced by a free-liquid jet impinging upon a flat plate has been developed. Although this method does not provide a quantitative measure of the velocity distribution within a free jet, it does provide a qualitative classification of unknown profiles by comparison with the pressure distributions produced by jets having known velocity profiles (i.e., with jets produced by fully developed turbulent flow, fully developed laminar flow, and a jet having a uniform velocity profile). This technique does provide a true measure of the velocity along the centerline of the jet, as long as the velocity distribution is axially symmetric and exhibits a single maximum along the centerline.

The pressure distributions produced by fully developed laminar jets, fully developed turbulent jets, and near-uniform jets impinging on a flat plate are presented.

The distribution of a measure of the intensity of the pressure fluctuations occurring on the plate are included in all measurements of turbulent flow. Although no quantitative turbulence measurements were evolved, it is inferred that there is a unique relationship between these measurements and the distribution of turbulence intensity within the free jet.

A series of experimental orifices having similar basic geometries but incorporating a turbulence-inducing section of varying degrees of roughness and provisions for varying the total length/diameter ratio have been constructed. The pressure distributions produced by jets from these orifices have been evaluated and the data presented, so that a given proximity to a fully developed turbulent profile may be obtained by choosing a combination of orifice length and roughness.

It is shown that a relatively short orifice (i.e., 10 diameters long) that combines a good entry with a turbulence-inducing section having a roughness factor of 0.0417 in the initial 5 diameters of straight bore will produce a jet having essentially the same characteristics as the jet produced by fully developed turbulent flow.

It is shown that the change in the centerline stagnation pressure associated with the transition from "slug flow" to fully developed turbulent flow is not a monotonic function of distance from the pipe entrance. It was found that this parameter actually passes through at least one measurable maximum, followed by a minimum, before achieving its ultimate stable value. It appeared that this phenomenon was limited to flow Reynolds numbers exceeding the so-called critical value (Ref. 29) and that the magnitude of the oscillation can be accentuated by incorporating roughness in the initial portion of the transition length.*

The data show that the velocity profile of a free jet tends toward uniformity, as would be expected, and, moreover, that the time required is comparable to the time required to produce a stable profile in the entry section of the pipe. It is also indicated that the energy that becomes available as the velocity profile of the jet tends toward uniformity can be an important factor in the jet breakup process.

The pressure distributions produced by a number of different configurations of a free-liquid jet impinging on a flat plate are presented.

*The term, transition length, as used here, is analogous to the "length of transition" adopted by Prandtl to describe the length of pipe required to produce a stable velocity profile (Ref. 29).

IV. EVALUATING THE VELOCITY PROFILE

The obvious approach to an evaluation of the velocity profile of a free jet is to probe the jet with a device similar to a pitot tube which measures a local stagnation pressure that is, in turn, related to the local velocity. This technique was, in fact, attempted but was abandoned in favor of a so-called "flat-plate probe" for the following reasons: (1) When even the smallest practical probe was inserted into the jet, it produced separation at or near the probe entrance. Although the quantitative effect of this phenomenon was not determined, it was felt significant that it appeared to vary with the position of the probe in the jet and therefore would probably be influenced by the gradient in the velocity profile. (2) For most of the jets, the exterior surface was distorted, and therefore, when measurements were obtained in this region – where the maximum velocity variation occurs – it was possible to get impact readings that are in error by a factor of two due to reversal of flow at the point being sampled by the probe entry. Also, under these conditions, it is impossible to distinguish between velocity fluctuations and intermittent flow. (3) A probe small enough to be suitable for this type of sampling requires a relatively long entry port; hence, its frequency response was very poor and therefore was not suitable for evaluating the intensity of turbulence.

On the other hand, if the jet is allowed to impinge perpendicularly upon a flat plate, the resultant momentum change produces a pressure field upon the plate that bears a unique relationship to the velocity profile of the approaching jet. Thus, an evaluation of this pressure field can also lead to the determination of the velocity distribution within the approaching jet. This technique has several advantages in that the flow configuration is constant for steady flow, surface disturbances of the jet have a negligible influence, and it is relatively easy to construct a probe having a satisfactory frequency response. Although it can be shown that it is theoretically possible to compute the actual velocity profile from the pressure distribution on the plate, it did not appear that the present degree of experimental accuracy would justify the effort, since it would be necessary to evaluate second-order differentials from the experimental data. Thus, this technique has the practical disadvantage that the data obtained are primarily comparative.

In many cases, the qualitative nature of the information is entirely satisfactory, since it is possible to evaluate pressure distributions of jets with known velocity profiles (known at least at the orifice exit) and thereby arrive at a method of categorizing unknown pressure distributions. Insofar as the requirements of jets to be used in rocket motors is concerned, it is not yet possible to be explicit in specifying a required velocity profile. To date, it has only been demonstrated that the velocity profile should be symmetrical, stable, and reproducible from jet to jet. For these purposes, it can be assumed that the pressure distribution produced by impinging the jet upon a flat plate is just as suitable as is an evaluation of the actual velocity profile. If it is further assumed that the velocity profile of the free jet is essentially the one that would be obtained by fully developed pipe flow (i.e., measurements taken at the exit of a sufficiently long straight pipe), then it is possible to produce experimentally the fully developed laminar profile and the fully developed turbulent profile and thereby obtain pressure distributions produced by velocity profiles that are known. Since these two profiles actually represent the only stable configurations for flow in a pipe, they serve to define categorical limits that may be further associated with the orifice Reynolds number. For jets that are produced within the transition length (from one flow regime to another or from one velocity profile to another so that the profile is not stable at the time the jet is formed), there is the additional possibility of producing a third limiting configuration which is characterized by a near-uniform velocity profile. The pressure distribution produced by this configuration can be approximated experimentally by the perpendicular impingement upon a flat plate of a jet produced with a sharp-edged orifice mounted in the end of a relatively quiescent reservoir. An independent check on this latter pressure distribution is available as the electrical analog solution to this problem which was obtained by LeClerc (see Ref. 30). Thus, if the geometry of the orifice is restricted to one that is axially symmetric with a single external boundary (i.e., no plugs or baffles, etc.), then the pressure distributions produced by these three limiting profiles will serve as an adequate basis for comparing and categorizing unknown jets.

It should also be noted that for these particular orifice geometries, the jet will always have its maximum velocity along the centerline, so that the flat-plate probe does provide a true measure of the maximum velocity in a symmetrical profile.

V. EXPERIMENTAL APPARATUS AND TECHNIQUES

The free-liquid jets were formed by pumping the appropriate fluid with a conventional gas-pressurized system through a calming section before it was discharged through a suitable orifice. The jet thus formed was arranged to impinge perpendicularly upon the flat-plate probe so as to produce the pressure field to be evaluated. The spray resulting from impingement of the jet was enclosed within a spray booth, with the controls and position indicators for the probe located just outside of the booth. A general view of this system is shown in Fig. 1.

The jets were composed of either tap water or a mixture of tap water and glycerine. Water properties were taken from Dorsey (Ref. 31), and properties and concentrations of the glycerine–water mixtures were determined from the tables given in Lange's "Handbook of Chemistry" (Ref. 32) and a density measurement.

The calming section that preceded the orifice for most of the experiments contained two 200-mesh screens, one at the entry and one at the exit of a 50-diameter length of

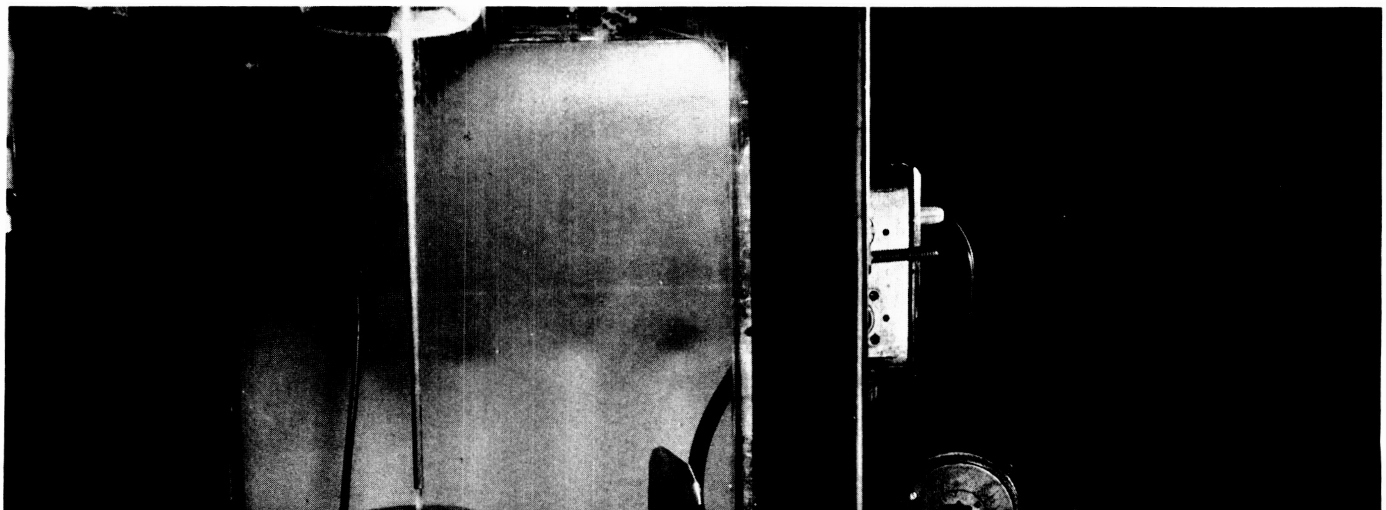


Fig. 1. The flat-plate probe with traversing mechanism

straight tubing in which the mean velocity never exceeded 5% of the mean velocity of the jet. An additional 2 diameters of straight pipe between the last screen and the beginning of the contraction section actually formed a part of the orifice.

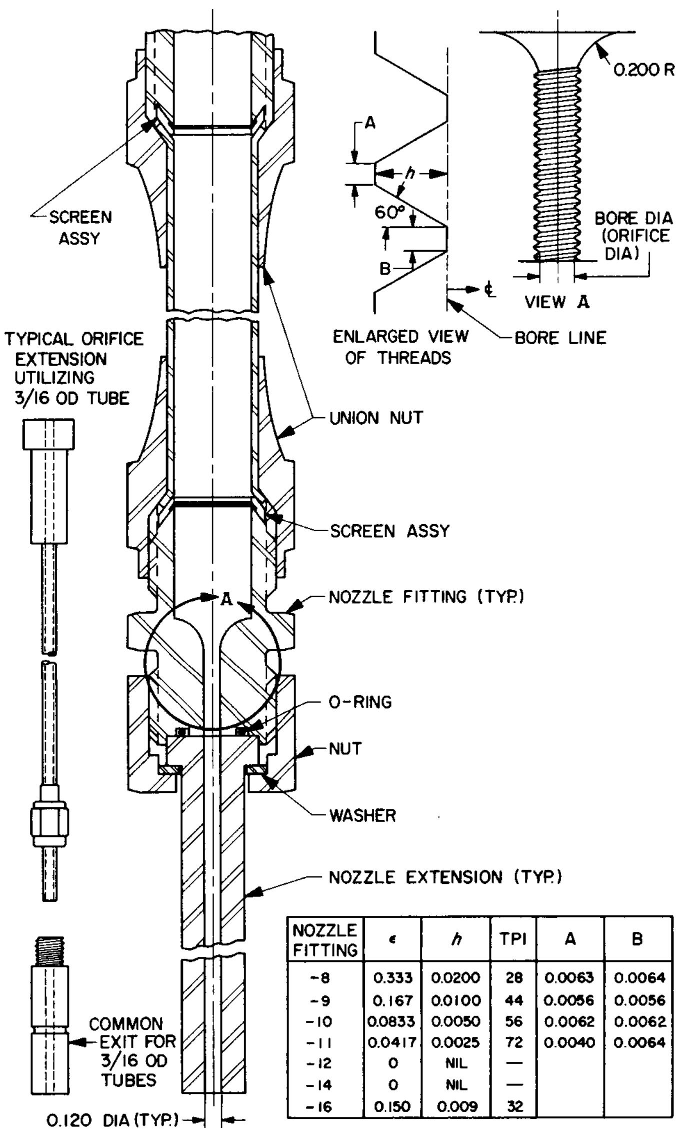
The physical and functional characteristics of the probe and the experimental techniques associated with the determination of a typical pressure distribution have been presented in some detail in Ref. 33 and will not be repeated here. It is noted, however, that the mean pressure data reported here were obtained by direct measurement with a Bourdon-type pressure gage rather than with a Photocon pressure transducer in order to increase the accuracy of these measurements by eliminating the zero shift inherent in the Photocon system.*

The RMS value of the fluctuating pressure that is superimposed on the mean value was determined with the Photocon system, as described in Ref. 33, since a small zero shift does not affect the sensitivity of this measurement. Quantitatively, these latter measurements represent the RMS value of the pressure fluctuation for all frequencies up to 2.0 kc and provide a comparative measure of the intensity of turbulence existing in the approaching jet.

High-speed flash photographs of the various jets were obtained with the JPL flash unit that produces an effective flash time of approximately 2.0 μsec. This unit flashes four G. E. FT-127 microsecond flash tubes simultaneously. The jet photos were obtained with three of the tubes positioned behind a ground glass to the rear of the jet and one just above the camera lens so as to provide some front lighting.

Unless otherwise specified, the pressure distribution measurements were obtained with the plate positioned at a distance of 4 orifice diameters from the orifice exit. This arrangement was chosen in order to be as close to the exit as possible without distorting the standing wave produced by the impingement process with the orifice itself and was based upon the data of LeClerc, which indicated that the effect of the wave decreases to a very small value within 2 diameters.

The several different orifices and/or orifice assemblies that were utilized during the investigation differed primarily in length and surface roughness. At one extreme was the sharp-edge orifice, approximately 1/20 diameter long, which was used to produce the so-called uniform velocity-profile jet. At the other limit was the 200-diameter-long orifice that was used to produce the so-called fully developed turbulent flow (FDTF) jet and the nearly fully developed laminar flow (FDLF) jet. Intermediate-length orifices up to 40 diameters in length and including assemblies incorporating various degrees of roughness in the initial 5 diameters of straight bore were formed by combining a number of different elements (Fig. 2). A typical cross-section of one of these assemblies, together with its upstream section, is shown in Fig. 2, which shows how various combinations of entry sections and nozzle extensions were obtained.



NOZZLE FITTING	ϵ	h	TPI	A	B
-8	0.333	0.0200	28	0.0063	0.0064
-9	0.167	0.0100	44	0.0056	0.0056
-10	0.0833	0.0050	56	0.0062	0.0062
-11	0.0417	0.0025	72	0.0040	0.0064
-12	0	NIL	—		
-14	0	NIL	—		
-16	0.150	0.009	32		

Fig. 2. Details of experimental orifices with turbulence-inducing sections

*Manufactured by Photocon Research Products, Pasadena, Calif.

This set of components included five different entry sections having varying degrees of roughness in the straight bore and three smooth-bored extensions that could be appended to each entry section. Thus, it was possible to assemble twenty different configurations, varying from a smooth-bored orifice, 45 diameters long, to the roughest entry section having only 5 diameters of straight bore. It is noted that (1) all of these orifices were the same diameter (i.e., 0.1200 $\pm$0.0005 in.); (2) the actual length of the turbulence-inducing section was a constant 5 diameters, so that its relative length varied as the nozzle extensions were added; and (3) the entry contour was also constant, having the form of a 0.200-in. radius. Figure 3b shows the four roughened entry sections, together with the special taps and contour reamers that were required to produce them. Figure 3a shows an exploded view of a typical assembly (exclusive of the calming-section tubing and fittings), the several extensions used to increase orifice length, and a cross-section of a typical entry configuration.

This series of bored orifices was supplemented with an additional group of orifices (including the 200-L/D orifice used to produce the reference jets) that were constructed from commercial grade seamless tubing in order to provide length–diameter ratios up to 200 in increments of approximately 10 diameters (see Fig. 2). An entry section without special turbulence-inducing devices was constructed with the same tooling described above, and these orifices were alternately attached to this device with a standard flared-tube assembly. Thus, there was one slight discontinuity in the wall near the entrance to the straight section that was ignored because of the relatively great length of these orifices. After some considerable experience with these orifices, it was determined that what had been assumed to be minor variations in the configuration of the orifice exit had a predominant effect on the jet properties. Although time did not permit a complete evaluation of these effects, it was noted, for example, that the centerline-stagnation-pressure ratio* of a fully developed turbulent jet at 4 diameters from the orifice exit could be decreased

*The ratio of the centerline stagnation pressure produced by a free jet to the centerline stagnation pressure that would have been produced by a jet having the same flow rate but a *uniform* velocity profile.

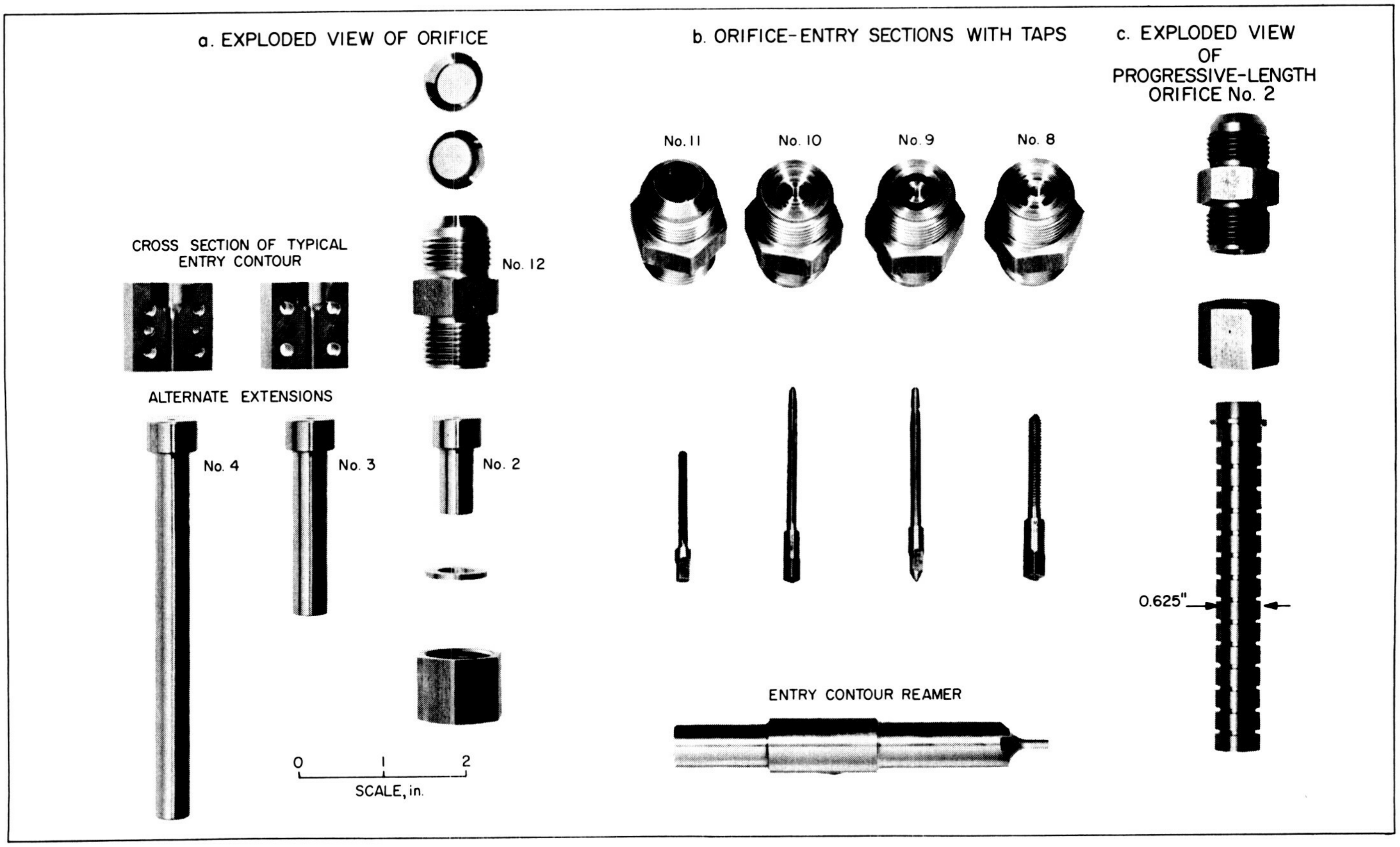


Fig. 3. Details of orifice components

from 1.48 to approximately 1.31 by tapering the exit over a length of 1 orifice diameter to give an exit diameter 1% larger than the mean. Therefore, these orifices were modified to accommodate an exit extension approximately 10 diameters long, which was bored and honed to the same diameter as the "average" of the several tubes. Thus, each orifice assembly had the same exit geometry, even though a slight discontinuity might exist 10 diameters upstream (see Fig. 2).

For similar reasons, a so-called "progressive-length orifice" (Fig. 3c) was used to evaluate the centerline-stagnation-pressure ratio versus orifice L/D from length–diameter ratios of 6.8 to 45, in increments of approximately 2.5 diameters. In each case, after the data for a given length were obtained, the "upstream" 2.5 diameters of the orifice extension was machined off and the entry geometry carefully reworked before obtaining the next set of data. Thus, the exit geometry remained constant, while any inadvertent discontinuity occurred upstream.

The assembly that was used to produce a jet having a near-uniform velocity profile was somewhat different in that the diameter of the calming section, which also incorporated turbulence-damping baffles and screens, was appreciably larger, so that the mean approach velocity was never greater than 1.0% of the mean velocity of the jet. The jet was formed by a sharp-edged orifice, flush-mounted in the end of this approach section. The orifice was 0.128 in. in diameter to be consistent with the other orifices. However, the vena contracta which was formed with this system resulted in a jet diameter of approximately 0.100 in. This value was determined from measurements of a photographic image and corresponds to a contraction ratio of 0.62, which checks the theory (Ref. 4).

The pertinent physical dimensions of the orifices as used in these experiments are summarized in Table 1 and the methods utilized in determining these properties in the Appendix.

Table 1. Summary of orifice dimensions

Orifice entry No. 10671A			
Dash No.	Exit diameter[a] in.	Length of straight bore diam	ϵ
-8	0.12169	5.00	0.333
-9	0.11993	5.00	0.167
-10	0.11956	5.00	0.0833
-11	0.11950	5.00	0.0417
-12	0.12047	5.00	0
-14	0.12028	1.00	0
-16	0.11948	1.00	0.150

[a]Determined on comparator.

1/10-diam-long common exit for 10671A entries

Diameter (determined on comparator) = 0.12000 in.

Maximum length = 0.025 in.

Bored extensions for 10671A entries[b]

Dash No.	Extension length: Nominal diam	Extension length: True, in.	Extension length: True, diam	Exit diameter[c] in.	Average diameter[d] in.
-2	10	1.200	9.93	0.12085	0.12016
-3	20	2.409	20.06	0.12006	0.11939
-4	40	4.798	39.97	0.12004	0.12000
-4	40	4.667[e]	38.86	0.12009	0.12000

[b]Add 5 diam to length for straight bore when appended to -8 through -12 entry.
[c]Determined on comparator.
[d]Determined by weight method.
[e]Length reduced to eliminate damaged exit.

Table 1. (Cont'd)

A series of 3/16-OD tubes

Nominal diam	Extension length: True, in.	Extension length: True, diam	Exit[f] diameter in.	Average[g] diameter in.	Total length: With -9 exit, in.	Total length: With -9 exit, L/D	Total length: Entry plus exit L/D
-25[h]	2.40	20	—	0.12067	3.50	29.00	34.0
-45[h]	4.85	40	—	0.12067	5.95	49.3	54.3
-55	6.03	49.9	0.12254	0.12086	7.13	59.0	64.0
-65	7.11	58.9	0.12132	0.12077	8.21	68.0	73.0
-75[j]	8.41	66.52	0.12774	0.12649	9.52	75.3	80.3
-85	9.45	78.13	0.12230	0.12096	10.55	87.2	92.2
-100	11.26	93.47	0.12190	0.12047	12.36	102.6	107.6
-120	13.72	113.6	0.12219	0.12075	14.82	122.7	127.7
-140	16.13	133.6	0.12194	0.12069	17.23	142.8	147.8
-160[i]	18.31	151.7	0.12222	0.12067	19.41	160.8	165.8
-200	23.28	192.5	0.12094	0.12095	24.38	201.6	206.0

[f] Average of at least 9 diam determined on comparator.
[g] Determined from weight method.
[h] Made from -160 tube.
[i] Destroyed after getting data (used for -25 and -45).
[j] Not used for data because of out-of-tolerance diameter.

—9 extension (to provide common exit geometry for 3/16-diam tubes)[k]

Exit diameter in.	Average diameter in.	Length of 0.1021 bore, in.
0.12015		
0.11991		
0.12024		
0.12010		
0.12014		
	0.12011	1.1021 (9.17 L/D)

[k] Determined on comparator.

Progressive-length orifice No. 2

Nominal diam	Extension length: True, in.	Extension length: True, diam	Length with 10671A-12 diam	Orifice exit diameter in.
40	4.807	39.74	44.74	0.12096[l]
37.5	4.500	37.25	42.25	0.12096[l]
35	4.196	34.73	39.73	0.12096[l]
32.5	3.889	32.19	37.19	0.12096[l]
30	3.584	29.67	34.67	0.12096[l]
27.5	3.278	27.13	32.13	0.12096[l]
25	2.972	24.60	29.60	0.12096[l]
22.5	2.667	22.08	27.08	0.12096[l]
20	2.360	19.54	24.54	0.12096[l]
17.5	2.054	17.00	22.00	0.12096[l]
15	1.748	14.45	19.45	0.12096[l]
12	1.440	11.92	16.92	0.12096[l]
9.5	1.137	9.41	14.41	0.12096[l]
7	0.830	6.87	11.87	0.12096[l]
4.5	0.525	4.35	9.35	0.12118[m]
2	0.219	1.81	6.81	0.12118[m]

[l] Average of five determinations.
[m] Measured after cleaning, deburring, and relapping.

VI. PROPERTIES OF REFERENCE JETS

A. Jet Properties at Orifice Exit

As has already been noted, the limiting configurations of pipe flow are characterized by (1) the fully developed laminar profile, (2) the fully developed turbulent profile, and (3) the uniform velocity profile. Since there is a unique relationship between velocity profile and pressure distribution, it follows that the pressure distributions produced by these several flow conditions are also limiting cases.

Fully developed turbulent pipe flow was produced with an "orifice" that was approximately 200 diameters long, in which water was flowing at a velocity sufficient to produce a Reynolds number of at least 45,000.

Although the transition length (i.e., the length of orifice required to produce a stable velocity profile) for turbulent flow is normally taken to be considerably shorter than 200 diameters (see, for example, Ref. 29, p. 49, which quotes transition lengths of 50 to 100, 25 to 40, and 10 diameters, attributable, respectively, to Kirsten, Nikuradse, and a theory of Latzko), preliminary measurements indicated that variations in centerline velocities could still be detected for orifice lengths greater than 100 diameters. Therefore, a substantially longer orifice was utilized in order to assure a complete transition. Assuming, then, that fully developed turbulent flow was actually achieved at the orifice exit, it was expected that the velocity profile at that station could be characterized by Rouse's version of the Karman–Prandtl equation, which states that

$$\frac{u}{\bar{u}} = \sqrt{f}\,(2.15 \log_{10} \frac{r}{r_0} + 1.43) + 1$$

so that the centerline velocity is given by

$$\frac{u_{max}}{\bar{u}} = 1.43\sqrt{f} + 1$$

where

u = local axial velocity

$\bar{u}$ = mean axial velocity

f = friction coefficient

r_0 = radius of orifice at exit

r = radial distance from centerline to point of evaluating u.

Then, if one assumes a typical friction coefficient of 0.028 for smooth pipe with Reynolds numbers from 50,000 to 100,000, the ratio $u_{max}/\bar{u}$ may be computed to give a nominal value of 1.23, so that the equivalent centerline-stagnation-pressure ratio is 1.51. Thus, it is reasonable to expect that pressure ratios measured in the jet would be bounded by this value at the orifice exit and decrease with free-jet length as the velocity profile tends toward uniformity.

The fully developed laminar flow was produced with the same orifice flowing a mixture of water and glycerine (approximately 79% by weight glycerine) as the test fluid. This mixture has a viscosity of 37.2 centipoise and a density of 1.2060 g/cm^3 at 28.5°C, giving a Reynolds number (at that temperature) that is approximately 0.031 times that of the turbulent jet for a given fluid velocity. Thus, the laminar jet would have a subcritical Reynolds number of about 1350 for the same mean velocity associated with the turbulent jet at a Reynolds number of 45,000; yet, both aerodynamic drag forces and impact pressures would be directly comparable.

The transition length x for the fully developed laminar jet is directly proportional to Reynolds number and is given, for example, by Prandtl from data by Nikuradse as

$$\frac{x}{D} = 0.125\, N_R$$

Thus, it is seen that fully developed laminar flow should be expected in the 200-L/D tube only for Reynolds numbers below about 1600. Therefore, most of the experiments with fully developed laminar flow were conducted at or below that value, and it was assumed that the velocity profile at the tube exit would conform to the parobolic shape given by Prandtl, where

$$\frac{u}{\bar{u}} = 2\left[1 - \left(\frac{r}{r_0}\right)^2\right]$$

As has already been noted, the jet having a near-uniform velocity profile was produced with water issuing from a sharp-edged orifice formed in one end of a relatively quiescent reservoir and, of course, created a vena contracta. Although it can be argued that sidewall effects as well as the contraction itself will modify the potential flow model, this was the only configuration that appeared to satisfy the experimental requirement. It was assumed, therefore, for the purpose of these experiments, that the velocity profile was near-uniform immediately downstream from the contraction. It should be remembered that, by definition, this flow configuration is also laminar even though Reynolds numbers (based either on jet diameter or on orifice diameter) may be 50,000 or higher.

B. Visual Properties of Reference Jets

The superficial appearance of the jets produced by these several flow regimes is shown in Fig. 4, which includes photographs of each type of jet at two different Reynolds numbers, as noted. As would be expected, the fully developed turbulent jets exhibit surface disturbances that are undoubtedly a function of scale and intensity of turbulence at the orifice exits and, of course, contribute to jet breakup. In general, the characteristics of these turbulent jets are comparable to those studied by Lee and Spencer (Ref. 10), Castleman (Ref. 15), DeJuhasz, *et al.* (Ref. 7), and others. On the other hand, the higher-velocity laminar jet exhibits certain characteristics that are significantly different from those previously reported (for instance, by Lee, Ref. 10). It is noted that this jet breaks up in an extremely violent fashion much sooner than does the fully developed turbulent jet, even though the flow is laminar and the aerodynamic forces are presumably lower, since

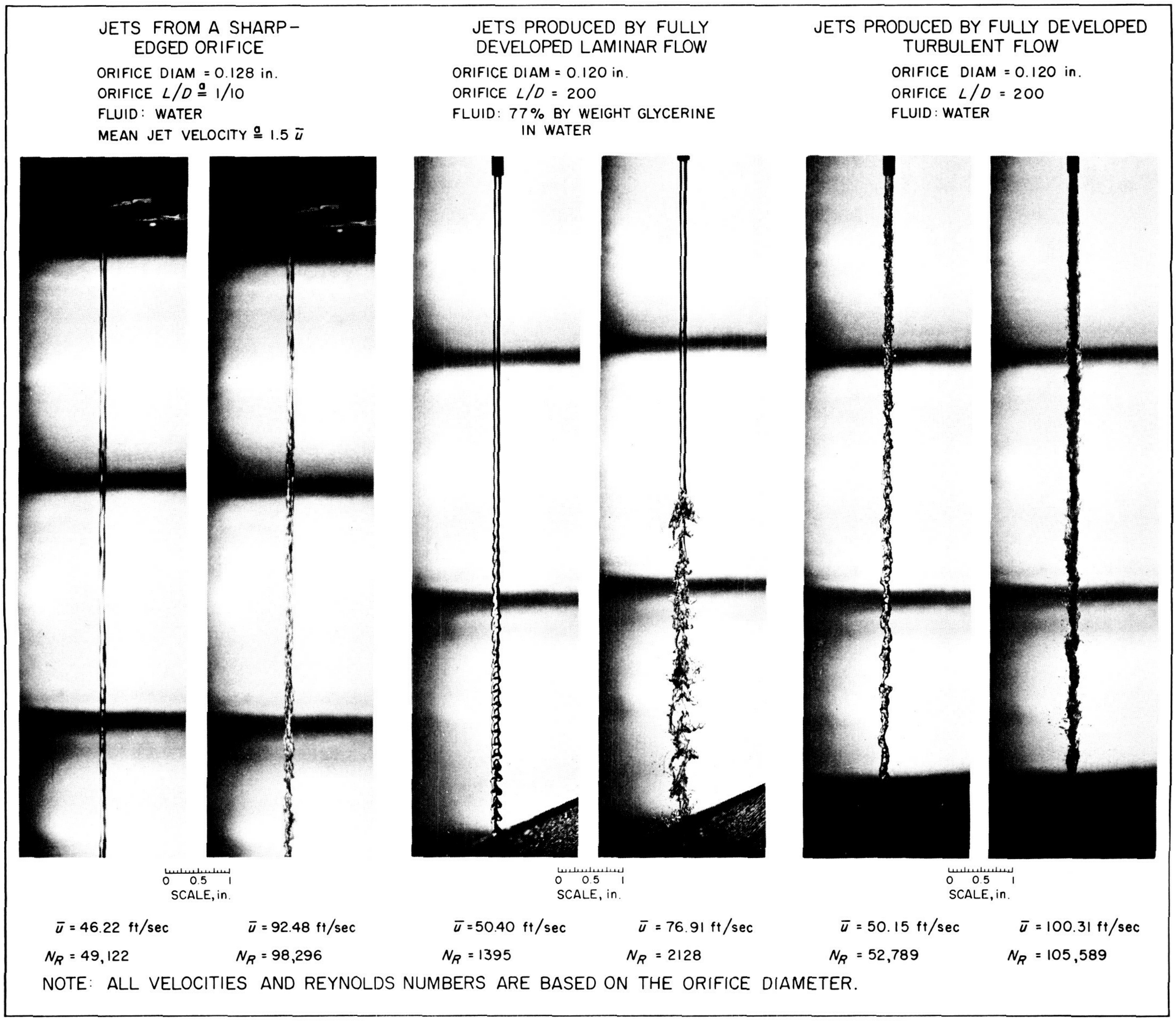


Fig. 4. Flash photographs of reference jets

the surface preceding the disintegration point is relatively smooth. A comparison of the lower-velocity laminar jet with the lower-velocity turbulent jet also shows that the relative *amplitude* of the sinuous disturbance is larger in the laminar jet, this fact, too, being inconsistent with previous information.

A precise explanation of this phenomenon will not be attempted here, but it is believed to be striking evidence of one of the basic mechanisms by which jets disintegrate. It is hypothesized that this phenomenon is due to what might be termed an energy excess contained in the free jet as a consequence of the nonuniformity of the velocity profile. It is clear that the velocity profile at the exit of an orifice of any appreciable length is nonuniform and that the shear stresses that exist within the fluid at that station (for steady flow) are stabilized by the drag at the wall. However, after the fluid leaves the confines of the orifice, the wall drag is instantaneously reduced to near-zero, even though the velocity profile remains essentially unchanged. The internal stresses tend to redistribute the flow, thus restoring equilibrium within the jet. This, of course, is the situation that is achieved once a near-uniform velocity profile has been established.

As the velocity profile approaches uniformity in the free jet, the energy equivalent of one full dynamic head (based upon the mean velocity of the FDLF jet) must be distributed among the various dissipative mechanisms. This energy tends to be concentrated along the core of the jet and becomes available for producing an increase in the mean axial velocity of the jet and/or conversion to potential energy. This pressure then appears in the form of a radial pressure gradient and, hence, produces a radial-velocity component. Once these radial velocities overcome the inertial and surface-tension forces, the jet disintegrates and "throws out" ligaments that may, in turn, be broken up by aerodynamic drag. The magnitude of the internal forces produced in this manner can be quite high, even if the rate at which the velocity profile is transformed is ignored. This was inadvertently shown by Harmon (Ref. 34), who assumed conservation of axial momentum and energy, continuity, and *no breakup* in a free-liquid jet in order to demonstrate that attainment of a uniform profile resulted in an energy excess of approximately 10% (based on mean exit velocity). He concluded that most of this energy was lost through viscosity, since the energy required for surface formation is relatively small. However, he did not consider the possibility that *axial* momentum and kinetic energy can both be conserved, even if it is assumed that there are no viscous losses, simply by giving the liquid an axially symmetric radial-velocity component which must obviously result in forces that tend to disintegrate the jet.

This hypothesis is also supported by the photographs of the jets having a relatively uniform velocity profile, since the mean velocity is again essentially the same as for the laminar and turbulent jets; yet, the relative stability of the jet is quite apparent. Even the FDTF jets convey a similar impression if some allowance is made for the small-scale disturbances of turbulence.

It should be noted that the "instabilities" that are illustrated here were, for the most part, contained within the dynamic characteristics of the jet at the orifice exit, so that it is imperative that consideration be given to the transient characteristics of a jet whenever an application involves jet length as a parameter.

C. Properties of Jets Produced by Fully Developed Turbulent Flow

The pressure distributions produced by a jet formed by fully developed turbulent flow are shown in Fig. 5 for two different Reynolds numbers. It can be seen that the centerline stagnation pressure is somewhat lower for the jet having the higher Reynolds number. This effect is to be expected, since the transition length of the orifice is relatively shorter for the higher Reynolds numbers (see Section VI-A) and, in accordance with the empirical expression for the velocity profile, the centerline-stagnation-pressure ratio decreases as the Reynolds number increases

ORIFICE NO. 10671-12, -200, AND -9
IMPINGEMENT ANGLE = 90 deg
LENGTH OF FREE JET = 4 diam
FLUID: WATER (TEMPERATURE = 60° F)

	DIAM, in.	L/D	N_R
o	0.12095	206.6	41,794
x	0.12095	206.6	75,073

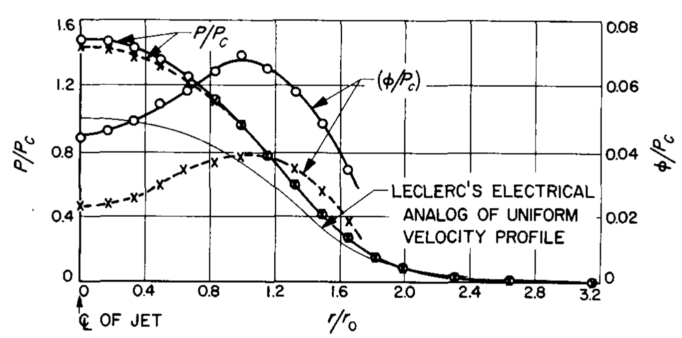


Fig. 5. The pressure distribution produced on a flat plate by the impingement of a free-liquid jet formed from fully developed turbulent pipe flow

(because of the decrease in the friction coefficient). On the other hand, no attempt was made to determine the influence of Reynolds number on the "transition length"* for the free jet, and this could also influence the measurements. As a consequence of this real though small effect of Reynolds number, most of the data on turbulent jets were restricted to a range of N_R from about 30,000 to 40,000.

Also shown in Fig. 5 is a plot of the RMS value of the pressure fluctuation as measured along the surface of the probe. It will be noted that when this average is presented as a ratio to the equivalent stagnation pressure for the jet, the level of the disturbance decreases as N_R increases, even though the converse is true for a comparison based on absolute magnitude. Although these measurements do not in themselves provide enough information to determine the distribution of turbulence intensity within the original jet, it is fairly clear that the maxima located near $r/r_0 = 1.0$ are a consequence of the very high intensity that normally exists near the boundary of a tube (see, for example, Ref. 35). The fact that there must be some attenuation in turbulence level within the free jet once the wall is removed, and that one would expect the turbulence characteristics to be modified in the vicinity of the surface of the probe, complicates the analysis of these data. However, as will be seen, the data can be utilized to characterize, albeit in a rather gross way, the turbulence characteristic of a free jet.

The characteristics of the transition length of the free jet produced by fully developed turbulent flow are illustrated in Figs. 6 and 7, which present, respectively, the variation in the centerline-stagnation-pressure ratio with jet length and the pressure distributions produced by a given jet at various distances from the orifice exit. The decay of the turbulent velocity profile is clearly demonstrated by the changing centerline stagnation pressure, as shown in Fig. 6, and is substantiated by the distributions shown in Fig. 7. It was rather surprising to note that the transition in the free jet takes place as rapidly as it does and, in fact, occurs within a length that is directly comparable to that observed for the transition in the inlet section of a pipe. Although Nikuradse's data for a pipe (Table 2, as adopted from Ref. 29), which are superimposed upon the data shown in Fig. 6, depict an initial gradient that is somewhat steeper than in the jet, it is seen that the gradients are similar in magnitude but of opposite sign over most of the transition length and that in both cases the transition is 80–90% complete within the first 25 diameters. This similarity is obviously due to the relative importance of the fluid properties, regardless of boundary configuration, in determining the transient.

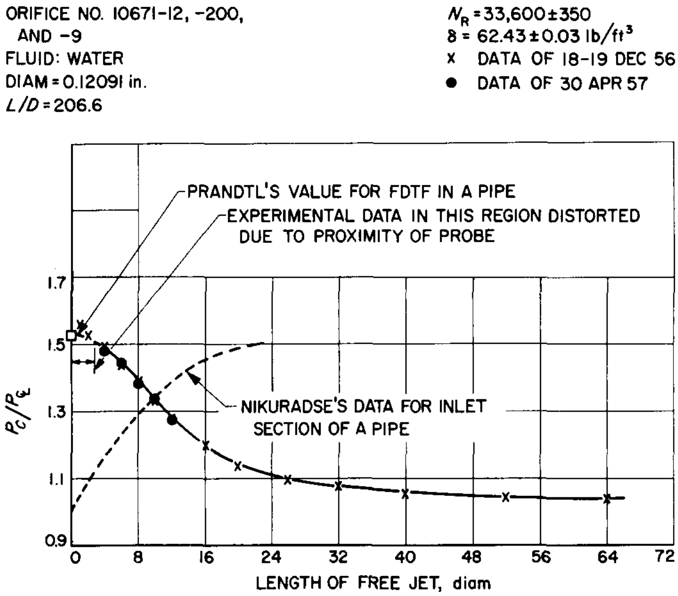


Fig. 6. The variation of centerline stagnation pressure with jet length for a jet produced by fully developed turbulent flow

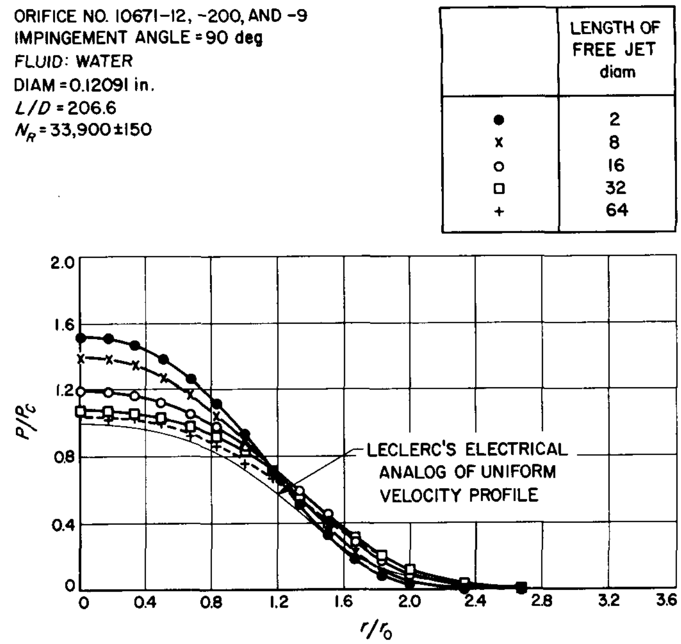


Fig. 7. The variation of the flat-plate pressure distribution with free-jet length for a jet formed by fully developed turbulent flow

The data of Figs. 6 and 7 serve to illustrate the importance of free-jet length whenever the centerline stagna-

*That length of free jet over which the velocity profile is changing.

tion pressure, for instance, is an important parameter. Thus, it is clear that for the case of a pair of impinging liquid jets, the momentum interchange along the hypothetical interface between two fluids, and hence, the mass and mixture-ratio distributions in the resulting spray, must vary with free-jet length even for jets having known jet properties at the orifice exit. The singular exception is, of course, the jet having an initially uniform velocity profile.

Table 2. Nikuradse's data on relative centerline velocity in the transition length of a pipe having a well-rounded entry

L/D	$u_{℄}/\bar{u}$	$P_{℄}/P_c$	$(P_{℄}/P_c)_{4D}$
0	1.00	1.00	1.00
1.0	1.02	1.040	1.038
2.0	1.04	1.082	1.070
3.2	1.06	1.124	1.092
4.2	1.08	1.166	1.122
5.6	1.10	1.210	1.151
7.1	1.12	1.254	1.182
8.5	1.14	1.300	1.217
10.3	1.16	1.346	1.240
12.1	1.18	1.392	1.278
13.5	1.19	1.416	1.300
14.8	1.20	1.440	1.335
17.5	1.21	1.464	1.365
20.0	1.22	1.488	1.395

[a]It is assumed that the centerline stagnation pressure of a free jet decreases from any given value in the same manner as was established for a jet produced by FDTF at the orifice exit regardless of the previous history of said centerline stagnation pressure (see Fig. 6). Therefore, this column is for a 4-diam length of free jet preceded by an orifice that forms a portion of the transition length.

D. *Properties of Jets Produced by Fully Developed Laminar Flow*

The pressure distributions produced by a jet formed with near-fully developed laminar flow are shown in Fig. 8. The data presented there include distributions for two different Reynolds numbers, with a free-jet length of 4 diameters and distributions obtained for free-jet lengths of 15 and 65 diameters. In the latter case, it was necessary to reduce the jet velocity (and, hence, the Reynolds number) somewhat in order to retain a stable jet for that length. It is seen, however, that, as with the turbulent jet, the pressure distribution, and therefore the velocity profile, changes quite rapidly within the free jet. This process is illustrated in Fig. 9, which shows the variation in the centerline stagnation pressure with free-jet length. It is clear from the latter data that the velocity profile at the orifice exit was very near parabolic (at least insofar as

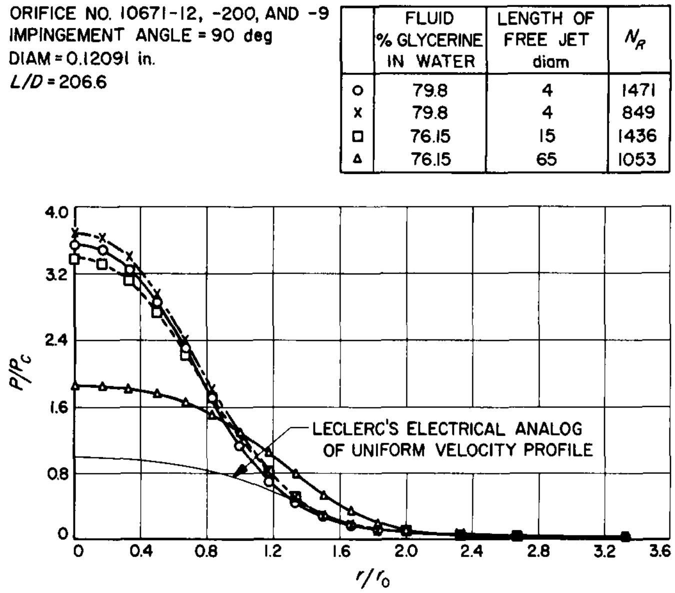


Fig. 8. The pressure distribution produced on a flat plate by the impingement of a free-liquid jet formed from fully developed laminar flow

the centerline pressure can be utilized to characterize the profile) and that the decay in the centerline velocity was approximately 70% complete within the first 60 diameters of free jet. Although jet breakup precludes the extension of these measurements to longer jet lengths, it is apparent that here, too, the characteristic length required for transition is similar to the length required for development of FDLF in the inlet of a pipe.

It should be noted that an attempt was made to determine the turbulence level that might exist in these

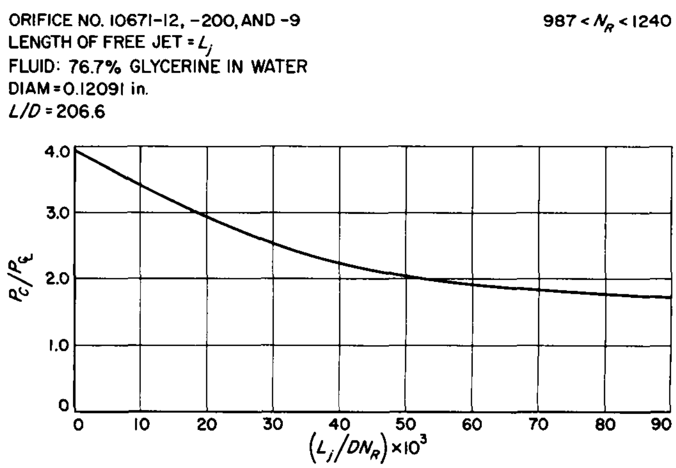


Fig. 9. The variation of centerline stagnation pressure with jet length for a jet produced by fully developed laminar flow

laminar jets and that at *no time* in the course of these experiments was it possible to detect a disturbance that was greater than the noise level inherent in the monitoring system. This background noise was attributable to the Photocon oscillator–detector and was on the order of 0.0013 RMS. This represents approximately 1% of the maximum voltage produced by a fully developed turbulent jet. It is noted that the voltmeter used for these measurements could easily detect variations of 0.001 v in the range from 0.001 to 0.01 v.

These measurements also indicated that the magnitude of large-scale disturbances present within the continuous portion of the jet was very low and, as a result, serve to substantiate the contention that breakup associated with these jets must be a consequence of the changing velocity profile rather than hydrodynamic noise arising in the upstream system.

It is interesting to note that "laminar flow" usually connotes the ultimate in stability to most fluid dynamicists but that in this particular case—i.e., for *fully developed* laminar flow—the disturbance arising in the free jet as the velocity profile decays is more violent than for any other "constant-area" flow regime. Also, it should be recognized that this comment applies to the jet prior to the time the disruptive breakup occurs as well. Thus, in addition to the practical limitations that such jets have with regard to Reynolds numbers and the difficulties in forming them, they tend to be the least tractable of the several available flow regimes. On the other hand, if laminar flow were really desirable, and if the velocity profile of such a jet could be made uniform, then it would be reasonable to expect that the instability associated with the fully developed laminar jet could be eliminated. Since jets are historically produced by relatively short orifices, so that the flow is definitely within the transition length, it is seen that the laminar jet with a uniform velocity profile can serve as a third reference configuration.

E. Properties of Jets Produced by Laminar Flow And Having a Uniform Velocity Profile

The pressure distribution produced by a laminar free-liquid jet having a near-uniform velocity profile is presented in Fig. 10, which includes for comparison (as do Figs. 5, 7, and 8) the pressure distribution inferred by LeClerc from an electrical analog solution of the potential flow model for jet impingement. Although it is recognized that these two techniques are radically different and the experiments are completely independent, it was expected that the agreement would be appreciably better than the approximately 5–6% of the maximum value indicated here. On the other hand, no obvious experimental discrepancies were discovered. In fact, it was found that distributions obtained at different Reynolds numbers and at various distances from the orifice exit were essentially duplicates of those shown in Fig. 10. These data are summarized in Table 3, where the distribution of Fig. 10 is directly compared with similar data taken for a different length of free jet with the same N_R and at the same length but for a different value of N_R. It is seen that the distributions for the different jet lengths are identical within experimental accuracy and that even at the higher N_R (where upstream conditions could influence the jet), the maximum change in local pressure is less than 1%. Data are also included to show that the centerline stagnation pressure varies less than 1% over jet lengths up to 50 diameters. Thus, it must be concluded that the distribution is either real and quite stable or that one or more of the constants utilized in obtaining the pressure ratio is in error. With regard to the latter, it is seen that an error in computing P_c, resulting from an erroneous evaluation of jet diameter, for example, could have a significant effect on the pressure ratio. If the value taken for the jet diameter were 1% too large, then P_c would be 4% too low. However, this would account only for the differences observed near the jet centerline and would tend to aggravate the differences observed for values of $r/r_0 > 0.8$. And since, as indicated in the Appendix, it is believed that the jet diameter was determined to an accuracy of about 0.2%, there is no justification in assuming an error as large as 1%. However, even though the data do not conform to the LeClerc solution, it is clear that it is possible

ORIFICE: SHARP EDGE
IMPINGEMENT ANGLE = 90 deg
LENGTH OF FREE JET = 0.583 in.; i.e., 5.81 diam
FLUID: WATER

	DIAM, in.	L/D	N_R
ORIFICE	0.128	1/10	34,986
JET	0.1003	NOTED	44,648

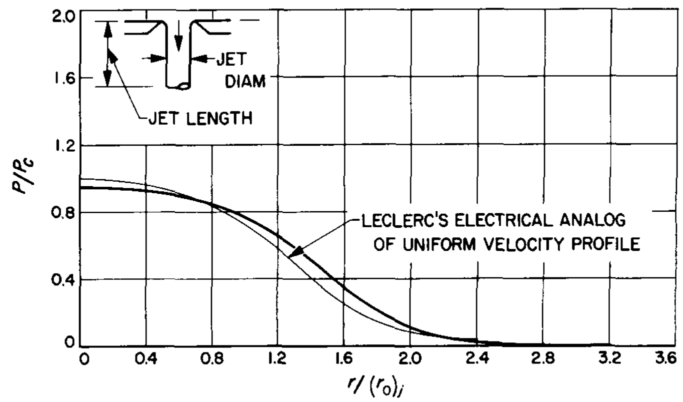


Fig. 10. The pressure distribution produced on a flat plate by the impingement of a laminar free-liquid jet having a near-uniform velocity profile

to produce jets having the characteristics associated with a *near*-uniform velocity profile.

As with the fully developed laminar jets, it was impossible to detect pressure fluctuations in these jets that could be associated with turbulence. However, it was noted that they are extremely susceptible to disturbances that arise in the upstream system. As was shown by C. V. Boys in 1889–1890 (Ref. 36), for example, a jet of this type responds not only to a disturbance as small as the ticking of a watch but is faithfully compliant to the resonance associated with the musical note of a clock's chime. In a similar manner, these jets respond to any random disturbance that arises in the system which produces them. It is, therefore, absolutely essential that the reservoir from which the jet discharges be completely quiescent and that there be no mechanical disturbance of the system itself. These processes become extremely important in jets of low viscosity formed from short orifices, where there are no dissipative mechanisms available to mask or minimize such disturbances. Thus, practical difficulties inherent in achieving stability with these jets indicate that this would not be a very suitable configuration for an application such as a rocket-motor injector element if jet stability is a consideration.

The jets formed by these several limiting flow regimes can serve as limiting cases for which the dynamic properties and certain of the transient characteristics are known. However, a great number of intermediate configurations are possible and, in fact, are probably the most important in practical instances in which incorporation of very long orifices introduces serious design complications. Thus, it appeared pertinent to evaluate the jet properties produced by orifice designs that, at least conceptually, could be incorporated in the usual injection scheme and, at the same time, produce jets that could conform to the usual design specifications.

Table 3. The variation of centerline stagnation pressure and flat-plate pressure distributions with jet length for a laminar jet having a uniform velocity profile[a]

Jet length, diam	5.82		15.24	9.14	25.4	50.8
$(N_R)_{jet}$ →	44,648	83,460	44,648	44,650	44,650	44,650
$(N_R)_{orifice}$ →	34,986	65,399	34,986	34,988	34,988	34,988
r/r_0	P/P_c			$P_{\not{L}}/P_c$		
0	0.949	0.962	0.952	0.949	0.949	0.952
0.199	0.946	0.959	0.949			
0.399	0.930	0.943	0.933			
0.598	0.900	0.911	0.901			
0.798	0.846	0.868	0.848			
0.997	0.768	0.773	0.767			
1.196	0.656	0.664	0.656			
1.396	0.516	0.515	0.512			
1.595	0.357	0.358	0.358			
1.795	0.216	0.215	0.216			
1.994	0.115	0.118	0.115			
2.193	0.058	0.063	0.060			
2.393	0.038	0.037	0.032			
2.792	0.012	0.018	0.013			
3.190	0.006	0.012	0.008			
3.988	0.003	0.009	0.004			

[a]Orifice diameter = 0.1273 in.
Jet diameter = 0.1003 in.
Orifice length = 1/10 diam
Impingement angle = 90 deg
Jet fluid = water at 58–60°F

VII. PROPERTIES OF JETS FOR ROCKET-MOTOR APPLICATIONS

One of the principal limitations to the design of orifices for liquid-propellant injectors is the available orifice length. In some instances, this is simply a space limitation; in others, it is due to cooling requirements; and, in many cases, it is a consequence of a compromise to achieve simplicity in manifold design. Therefore, it appeared that the greatest benefits would be gained if an orifice could be constructed with a relatively short L/D and yet produce jets that are stable, similar, symmetrical, and reproducible. Since it had already been demonstrated that jets produced by very short orifices were extremely susceptible to disturbances arising in the upstream system, it appeared that these requirements were inconsistent. On the other hand, some previous experience (Ref. 27) with orifices incorporating very rough turbulence-inducing sections near the orifice inlet had indicated that the transition length could be reduced substantially and suggested that jets having characteristics very similar to those produced by fully developed turbulent flow could be formed with relatively short orifices. Therefore, an empirical evaluation of a number of different orifice configurations was conducted in order to define, at least in part, the minimum length–roughness combinations that could be incorporated into an orifice which would then produce a jet having these characteristics. It is thus implied that such a jet will be suitable for use in rocket-motor injectors.

The pressure distributions and the superimposed fluctuations that were obtained for some eight different orifice configurations are shown in Figs. 11 and 12, which include combinations of four different orifice lengths (from 5 through 45 diameters in 10-diameter increments) with relative roughness factors of 0 and 0.333 in the turbulence-inducing section, which represents the initial 5 diameters of orifice length. In addition, Fig. 13 presents data for three more orifices, 5 diameters long, with relative roughness factors of 0.0417, 0.0833, and 0.167, respectively. The orifice diameter was constant at 0.1200 in. for all of these tests and the Reynolds number nearly so at approximately 40,000 (a slight variation due to small temperature changes). In the case of the 5-diameter-long orifices with roughness, the exit was formed with a smooth bore section 1/10 diameter long, having a sharp downstream edge.

The variation of the velocity profile with orifice length and the gradual increase in turbulence intensity that are usually associated with the entrance of a smooth pipe are clearly illustrated in Fig. 11. The increasing centerline velocity, the increasing intensity of turbulence, and the diffusion of turbulence toward the center are evident, and a comparison of these data with Fig. 5 shows that only for the 42.5-diameter orifice length are the properties of fully developed turbulent flow approximated. This is particularly true with regard to the turbulent characteristics of the jet. On the other hand, it is seen from Fig. 12 that very similar characteristics can be achieved with an orifice incorporating 5 diameters of rough section and an additional 10 diameters of smooth bore. It is further noted that the subsequent changes in jet properties produced by this latter group of orifices are relatively small; it can therefore be inferred that the transition to fully developed turbulent flow can be "forced" to occur within a substantially shorter length by controlling the boundary geometry.

The visual characteristics of several of the jets associated with the data of Figs. 11, 12, and 13 are shown in Figs. 14 and 15, which include high-speed flash plotos of jets produced at two different Reynolds numbers with two different orifice lengths (5.0 and 42.5, respectively, for Figs. 14 and 15) and roughness factors of 0 and 0.333 in the initial 5 diameters of orifice. The influence of higher Reynolds numbers and surface roughness in promoting turbulence is particularly evident in the series of jets from the short orifice. Note that the higher velocity associated with the higher Reynolds number does tend to degrade the photographic resolution; this must be considered when interpreting these characteristics. On the other hand, as indicated by the pressure measurements, only the Reynolds-number effect (or velocity) is discernible in the series of jets formed by the 42.5-L/D orifice, and, at least insofar as visual characteristics are concerned, these jets are essentially identical to the one produced by fully developed turbulent flow.

It is customary to presume that the varying velocity profile associated with flows of high Reynolds numbers in the inlet section of a straight pipe is asymptotic to an ultimately stable configuration and is essentially complete in some 20 to 40 diameters (see, for example, Ref. 29). As long as the allowable tolerance for defining the ultimate configuration is on the order of 5–10%, this presumption tends to be substantiated by the information presented here. However, a close examination of the data in Figs. 11 through 13 reveals that, in several instances,

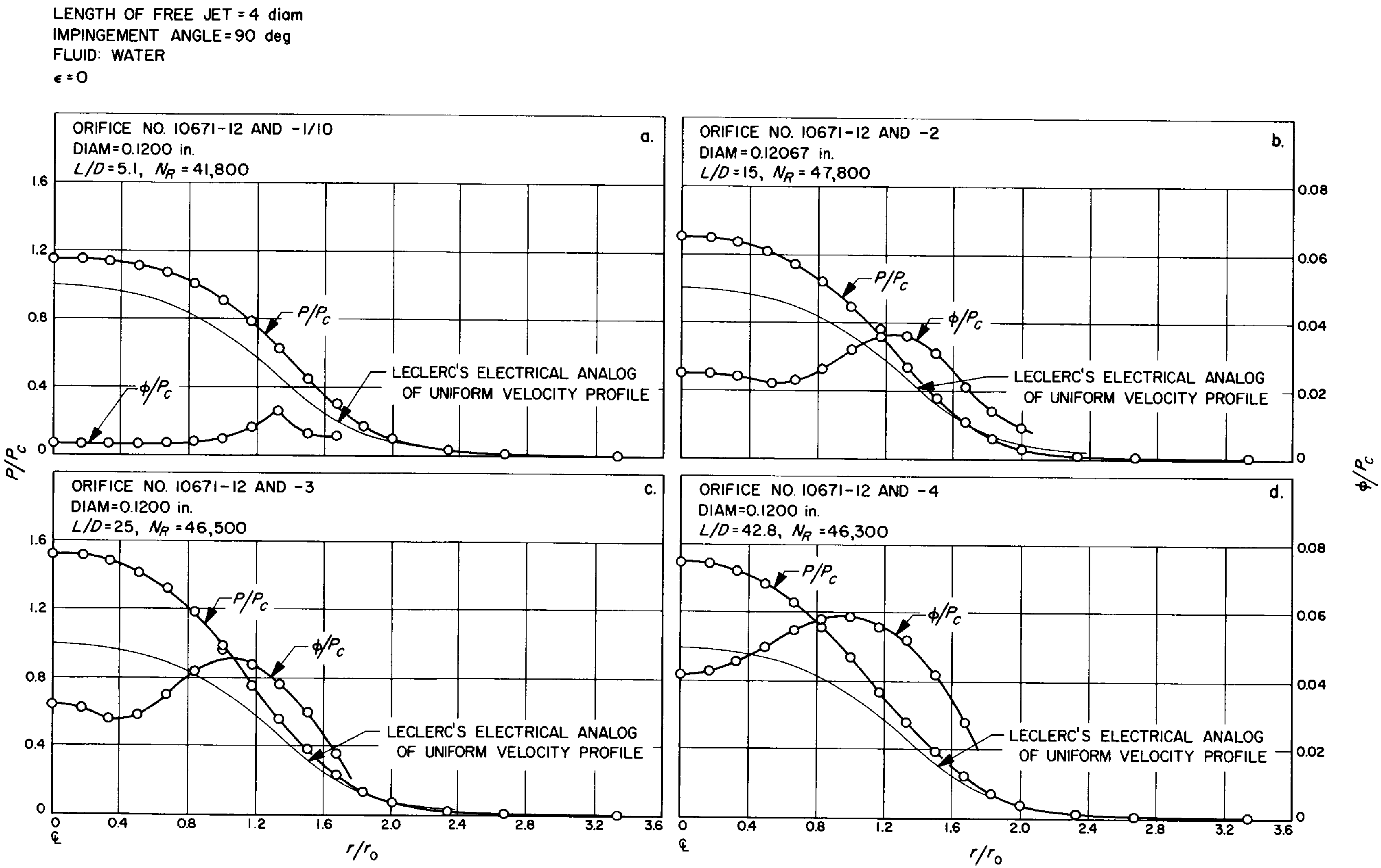


Fig. 11. The variation in flat-plate pressure distributions with orifice length for jets formed with smooth-bore orifices, where $\epsilon \cong 0$

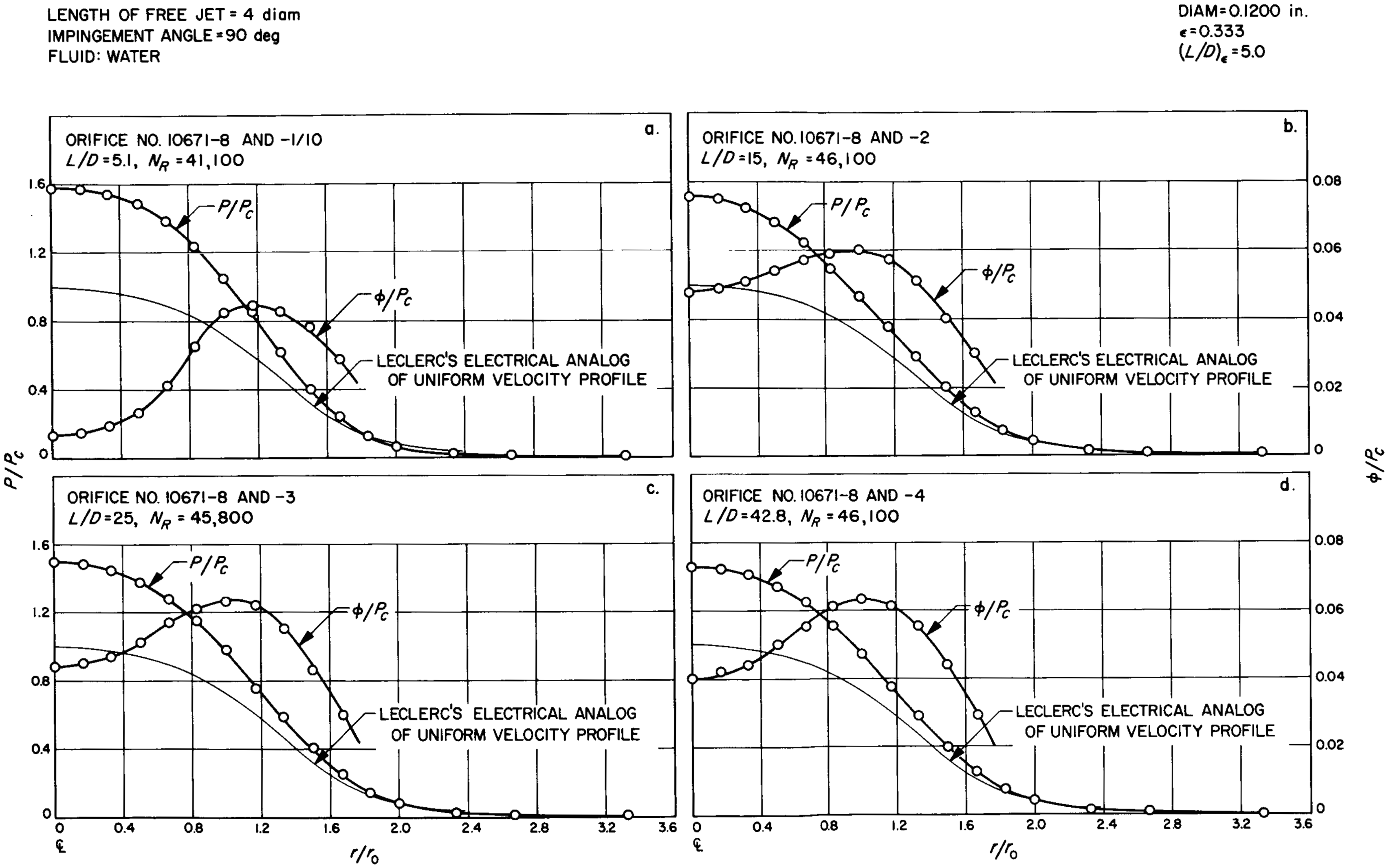


Fig. 12. The variation in flat-plate pressure distributions with orifice length for jets formed from an orifice incorporating an initial 5 diameters of rough bore, where $\epsilon = 0.333$

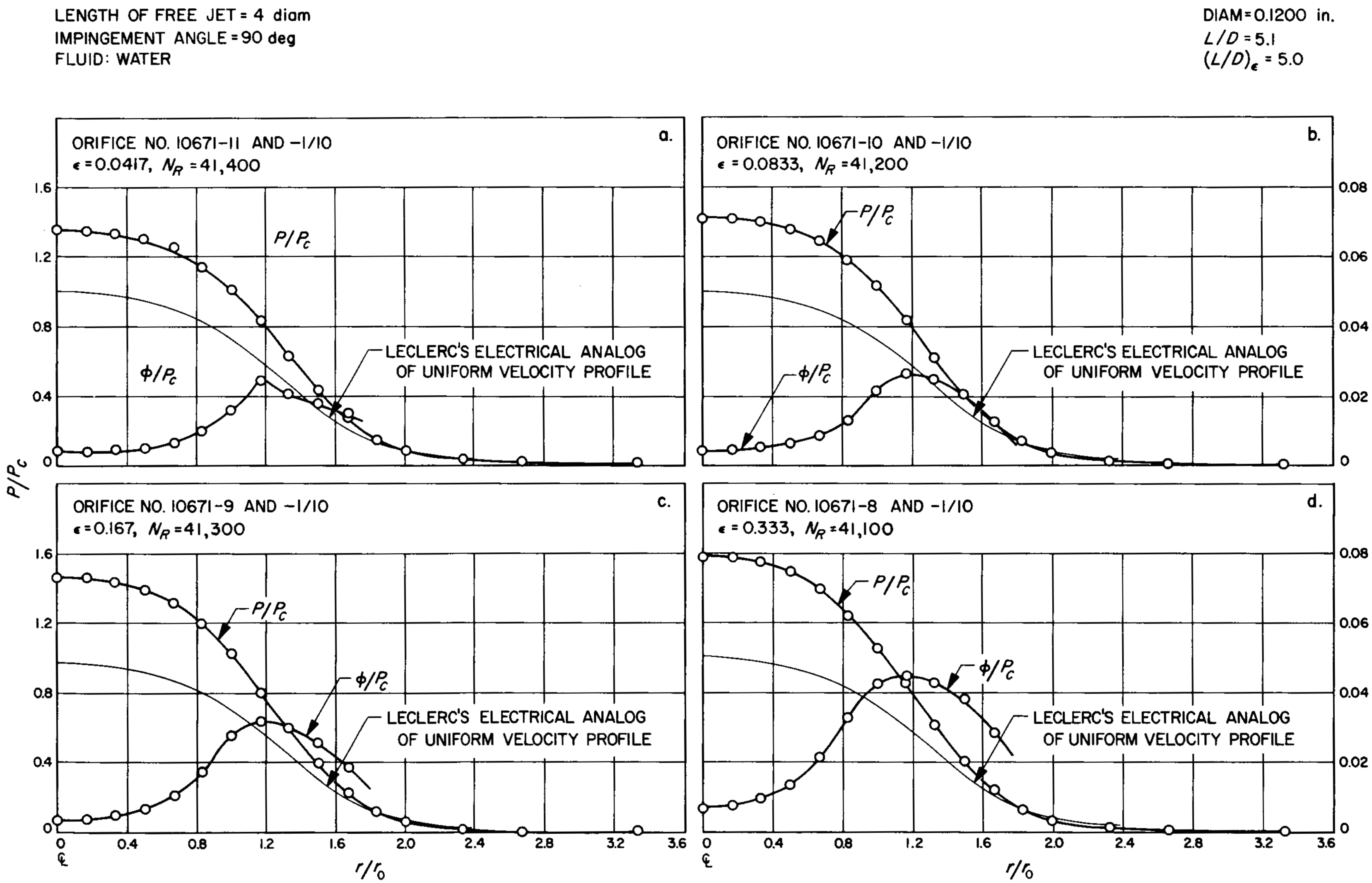


Fig. 13. The variation in flat-plate pressure distributions with orifice roughness for jets formed from a 5.1-diameter-long orifice

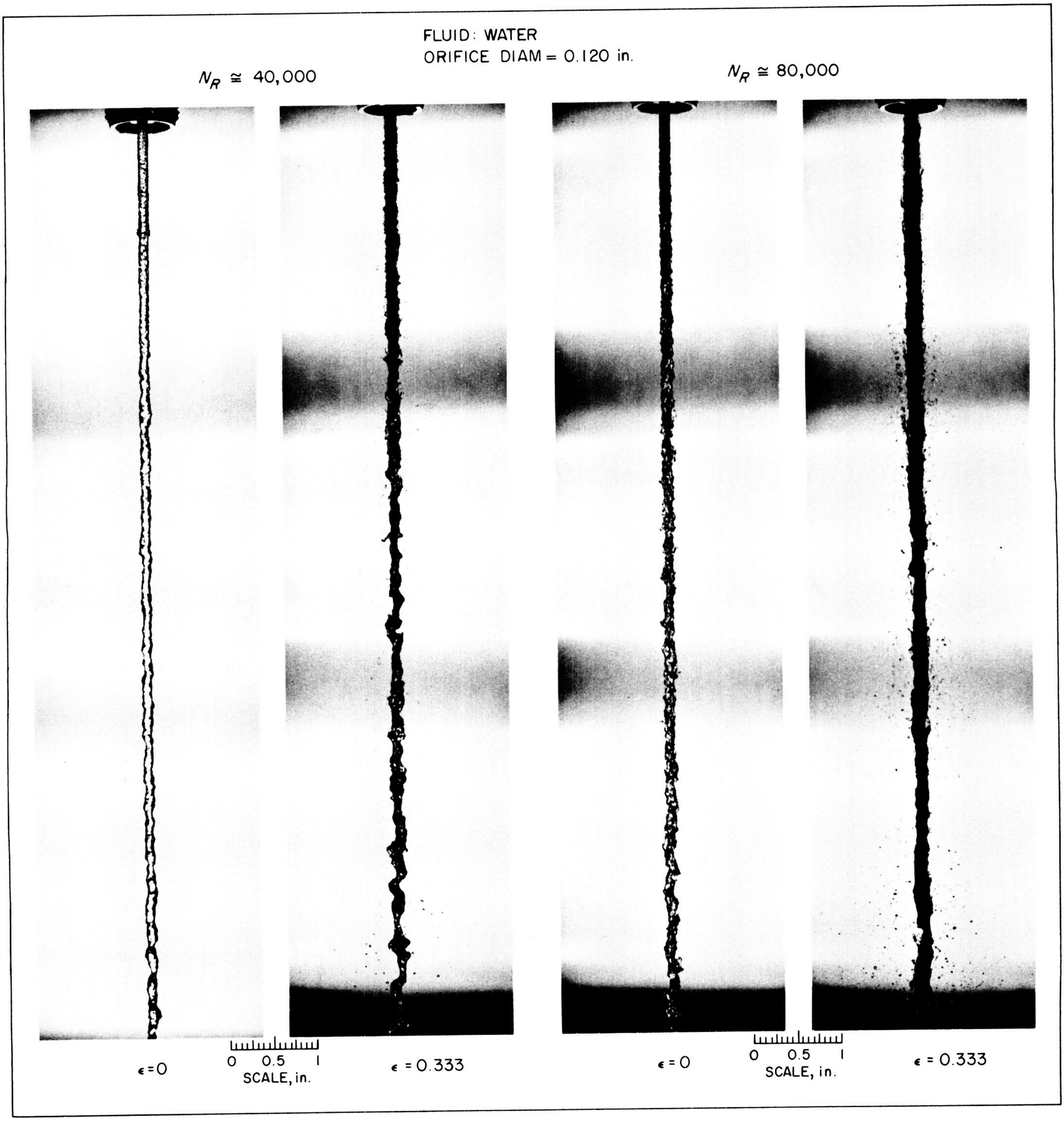


Fig. 14. Visual characteristics of jets produced by 5-diameter-long orifices with and without roughness

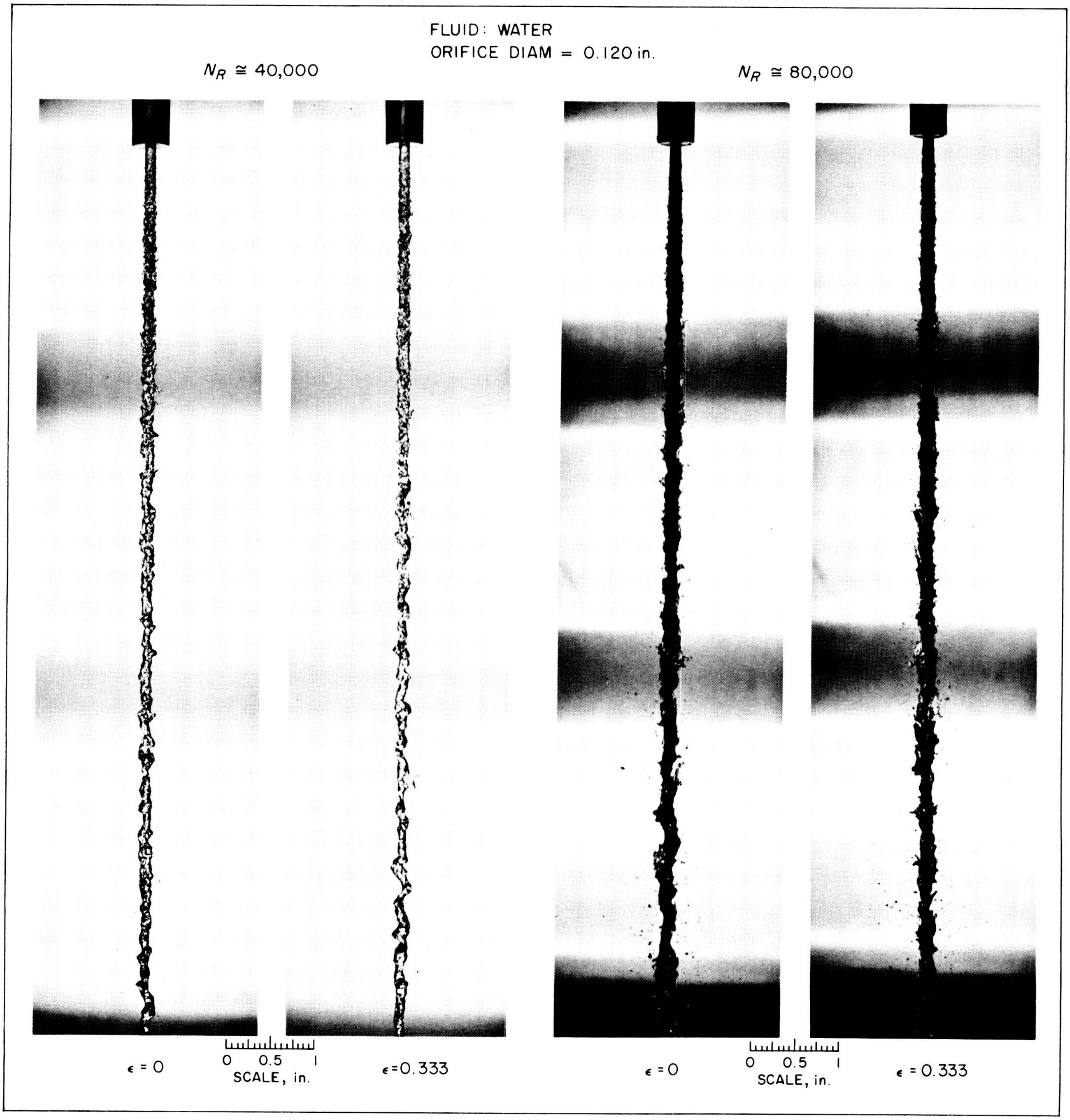


Fig. 15. Visual characteristics of jets produced by 42.5-diameter-long orifices with and without roughness

the centerline stagnation pressure exceeded the value expected for fully developed turbulent flow. Although the discrepancy was only 3–5%, it was found that this apparent anomaly was reproducible and could not be attributed to experimental difficulties. This was true even in orifices that contained a uniformly smooth bore. Therefore, in an effort to explain these apparent discrepancies, a more complete evaluation of the relation between centerline stagnation pressure and orifice length was undertaken.

VIII. JET PROPERTIES VERSUS ORIFICE LENGTH

The centerline stagnation pressure produced by the perpendicular impingement of a free-liquid jet on a flat plate has been used as a singular-characteristic parameter for purposes of correlating jet properties with orifice configuration. The data obtained with the orifice configurations described in Section VII were supplemented with data from several additional orifices. These include two orifices having only 1.0 diameter of straight bore (i.e., JPL No. 10671-14 and 10671-16) which incorporate roughnesses of 0 and 0.150, respectively; a series of 0.120-in. ID tubes varying in length from about 45 to 206 diameters, to which a common exit could be appended (see Fig. 2); and a so-called "decreasing-length" orifice which covered the range from 6.8 to 45 diameters. The term, decreasing length, referred to a single-orifice extension that achieved a total length of 45 diameters when appended to the -12 entry and which had been bored and honed to the proper ID of 0.1200 in. As can be seen in Fig. 3, this orifice could be adapted to the 10671-12 entry section in a fashion similar to that used for the -2, -3, and -4 extensions. In addition, however, it was proportioned into sixteen segments, so that the *inlet* segment could be successively machined off after a set of data had been obtained at a given length. Thus, the orifice length (including the -12 entry) was gradually reduced to 6.8 diameters; yet, the exit geometry was unchanged for this range of orifice lengths in which the greatest transient is observed. In all cases, a great deal of attention was given to controlling the exit geometry in order to assure a sharp burr-free exit having a truly cylindrical section. Also, in this latter case, the discontinuity at the junction between the entry and the extension was held to less than 0.0001 in., as determined from measurements with pin gages. It should be noted again that the duplication of orifice-exit geometries with the accuracies required to produce duplicate jet properties is extremely difficult. Even though every conceivable precaution was taken, no absolutely reliable technique for controlling the geometry was found. Therefore, it is doubtful whether the data comparing similar configurations but for different orifices can be expected to be duplicated to better than 0.5%.

The data obtained with these several sets of orifices are summarized in Figs. 16 and 17. Figure 16 compares the transients produced by the smooth-bore tube with one containing a very rough surface in the inlet 5 diameters, and Fig. 17 presents similar information for three additional configurations having various roughness factors in the inlet 5 diameters. The very marked influence of the turbulence-inducing sections on the transition is obvious, but the most interesting feature of the data is

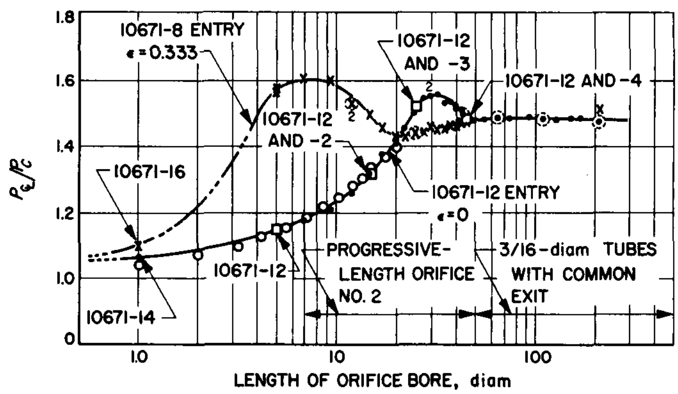


Fig. 16. A comparison of the centerline stagnation pressure vs free-jet length for a smooth-bore orifice and one containing a rough surface in the inlet 5 diameters

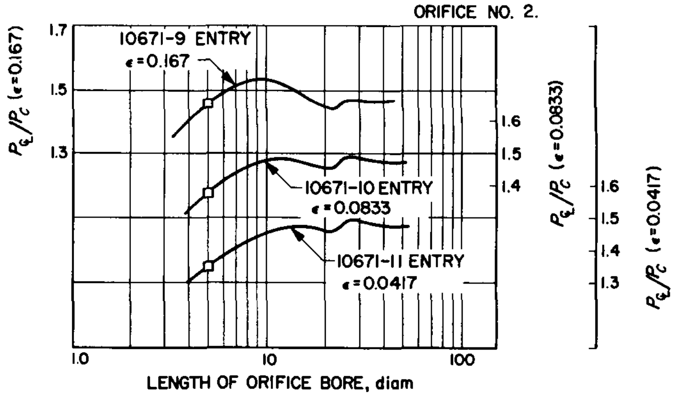


Fig. 17. Centerline stagnation pressure vs free-jet length for orifices having varying roughness factors in the inlet 5 diameters

exemplified by those for the smooth-bore tube. These data definitely show that the variation in centerline velocity associated with the transition from a uniform velocity profile is not monotonic for Reynolds numbers that are well into the turbulent range. It is, in fact, quite clear that the centerline velocity passes through at least one measurable maximum and a lesser minimum before stabilizing at the conventional steady-state value. Thus, it is inferred that the radial-velocity components must first have a real value toward the center and then reverse prior to decaying to zero. This concept is consistent with continuity considerations. It is interesting to note that the magnitude of the overshoot reported here is, in all probability, related to the stability of the particular system used in these experiments. This follows from the conceptual possibility that it represents the initial phases of the transition to fully developed laminar flow and that, if the system could be made sufficiently quiescent — as for instance was indicated by Schweitzer (Ref. 15), this centerline-stagnation-pressure ratio would asymptotically approach 4.0 even though the Reynolds number is well above the laminar regime. Of course, once the transition to turbulence is triggered, it becomes the stable mode of flow.

The orifices containing the rough inlet sections also exhibit similar characteristics. It can be argued here that the increased drag forces on the wall require higher (and hence, sooner) radial accelerations, so that the centerline velocity increases faster. However, it is also true that the centerline velocity for the ultimate stable velocity profile for a pipe having *uniform* roughness increases with increasing roughness (at constant N_R), and the absolute contribution of this effect cannot be separated from the observations. It could, for instance, be argued that drastic changes in roughness alone could produce the observed maximum. Such a statement, however, cannot explain the experiments with the "smooth" tubes, and it must be concluded that the observed departure from a monotonic variation of the centerline velocity is characteristic of the transition length.

It is further noted that a proper combination of orifice roughness and length can produce, within a relatively short length, a transition that is asymptotic to the properties of fully developed turbulent flow. This is illustrated here, for example, with the 10671-11 orifice entry, which had a roughness factor of 0.0833 in the inlet 5 diameters. It can be seen that the centerline stagnation pressure achieves its ultimate stable value in about 10 diameters total and that subsequent variations in the centerline velocity ratio are less than $\pm 2\%$. Thus, these data tend to substantiate the inference that was suggested by the pressure-distribution data presented in Fig. 12.

IX. CONCLUSION

1. The dynamic characteristics of a free-liquid jet are largely dependent upon the physical properties of the orifice that produced it and the dynamic characteristics of the upstream system.

2. Substantial forces can be generated within a free-liquid jet whenever the initial velocity profile is nonuniform. These forces can play an important part in jet disintegration.

3. The experimental determination of the pressure distribution produced by impinging a free jet upon a flat plate is an effective method of obtaining a comparative evaluation of free-jet velocity profiles.

4. The incorporation of a suitable turbulence-generating section in the initial length of cylindrical orifices having a reasonable entry geometry and having a total length of less than ten diameters will produce a free jet whose characteristics are essentially identical to those of fully developed turbulent pipe flow.

5. Attainment of fully developed turbulent flow at an orifice exit can be utilized as an effective means of minimizing upstream disturbances as well as producing jets with predictable dynamic properties.

6. The initial length of a free-liquid jet is characterized by a changing velocity profile that is analogous to the transient associated with the transition length of a pipe.

NOMENCLATURE

D diameter

f friction coefficient in a pipe

L length of constant-diameter portion of orifice

L_j length of free jet from orifice exit to probe location

N_R Reynolds number

P static pressure at a given station

P_c stagnation pressure of jet having a uniform velocity profile

$P_{\mathfrak{c}}$ stagnation pressure of jet at its centerline

r radius to point of measurement

r_0 radius of orifice exit (i.e., mean value for free jet)

u local axial velocity

$\bar{u}$ mean axial velocity

x transition length

ϵ roughness factor

ϕ RMS value of $P - P_{ave}$ for bandwidth of 10 cps to 2.0 kc

Subscripts

j jet

ave average

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APPENDIX

The calculation of the equivalent stagnation pressure of a free-liquid jet involves an experimentally measured flow rate, an orifice diameter, and fluid density, which are related by the following expression:

$$P_c = \frac{\delta \bar{u}^2}{288g} \text{ psi}$$

where

δ = weight density of fluid, lb/ft^3

P_c = stagnation pressure produced by mean velocity, lb/in.^{2}

g = gravitational constant = 32.17 ft/sec^2

and

$$\bar{u} = \frac{W}{\delta A}$$

where

W = weight flow rate, lb/sec

A = orifice area, ft^2

Thus, since

$$\bar{u} = \frac{576}{\pi} \frac{W}{\delta D^2}$$

for D = jet diameter in inches,

$$P_c = 3.6283 \frac{W^2}{\delta D^4} \text{ psi}$$

It is obvious, therefore, that the value obtained for P_c is particularly sensitive to small variations in D and, to a lesser degree, to variations in W. Errors incurred in the determination of δ (for water) are normally small enough to be ignored.

The accuracy of the flow rate determinations could, in general, be maintained to better than ¼% (averaged over a sampling time of 100 sec or more) by a direct weighing technique, so that the effect of this measurement on P_c was ½% or less. However, the determination of D^4 with sufficient accuracy to keep the effect of that measurement to ½% or less (and, hence, to give an overall accuracy of about 1%) was substantially more difficult. This was particularly true, since it was quite difficult to detect the presence of a very slight burr or bell-mouth at the orifice exit with the usual inspection techniques. Yet, the presence of such discontinuities was easily detectable in jet properties.

It is believed that adequate control of this parameter was ultimately achieved by combining a "volumetric" measurement, which is necessarily an average value, with a plane measurement at the orifice exit. The volume of the orifice bore was determined by weighing the orifice before and after filling with degassed water. This weight could, in most cases, be determined with an error less than 0.1% using an analytical balance, and since length could be ascertained to within 0.01%, the "average" diameter could be calculated to approximately 0.06% from the relation

$$D = C \left(\frac{\text{wt } H_2O}{\rho \times \text{orifice length}} \right)^{1/2}$$

where

$$C = \left(\frac{\pi}{4 \times (2.540)^3} \right)^{1/2}$$

or 0.278743 for weight H_2O in grams, ρ in g/cm^3, and orifice length in inches.

The values obtained in this manner were used as a control dimension on the exit diameters, which were determined with a comparator. In general, it was found that very careful machining (i.e., lapping and honing) of the orifice exit would yield an exit diameter that was essentially identical to the value obtained by weighing.

The diameters of the several orifices that were used in obtaining the data reported herein have been presented in Table 1. It is noted that whenever two or more orifices were added together to form a longer orifice, the diameter of the exit section was used to compute P_c. Hence, in the series of data obtained for Figs. 16 and 17, for example, it was assumed that the effective orifice diameter did not change as orifice lengths varied as long as the exit geometry remained constant.

For those cases in which a volumetric measurement was impossible (or impractical), the orifice diameter was determined by averaging several different diameters measured on the exit plane with the comparator.

The evaluation of the diameter of the jet formed by the sharp-edged orifice (i.e., uniform-velocity-profile laminar flow) represented a special problem, since the jet diameter is related to orifice diameter only through the vena contracta. Therefore, the actual jet diameter was determined by setting up a traveling microscope which viewed the jet at a magnification of 24 $\times$ and monitoring the displacement of the microscope as it was aligned first on one edge of the jet and then the other. Alignment was determined by matching the edge of the jet to a given line in the eyepiece scale, and the displacement was ascertained with a dial micrometer. These measurements were easily reproducible to within ± 0.0001 in. However, slight instabilities in the jet boundary precluded definition of the boundary to better than ½% (estimated as magnitude of observed diametric variations); thus, the overall measurement must be suspect to that extent.

With an orifice diameter as determined on the comparator of 0.12729 in., the measured jet diameter was $0.1003 \begin{smallmatrix} +0.0000 \\ -0.0001 \end{smallmatrix}$ in. It is noted that this yields a contraction ratio of 0.6208.