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Submerged jets in short cylindrical flow vessels

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Liquid-into-liquid jets in short cylindrical vessels have been investigated under conditions of uniform flow by using an aqueous blue tracer solution in conjunction with transparent cylindrical tanks. The vessels had diameters D of 3, 6, 12 and 24 in., length-to-diameter ratios L/D of 1, 2 and 3 and inlet diameters d between $\frac{1}{4}$ and 1 in. Reynolds numbers in the inlet tube, Re_i, ranged between 100 and 28,000. Four main types of jet were observed:

	dissipated-laminar jets	($Re_i < 300$ approx.);
	fully laminar jets	($300 < Re_i < 1000$ approx.);
	semi-turbulent jets	($1000 < Re_i < 3000$ approx.);
and	fully turbulent jets	($Re_i > 3000$).

The laminar length a of sub-turbulent jets was investigated and correlated with Re_i and the geometric parameters by the equation

$$a/d = 9{\cdot}97 \times 10^7 Re_i^{-2{\cdot}46} (D/d)^{-0{\cdot}48} (L/d)^{0{\cdot}74}.$$

1. Introduction

Very few observations of liquid-into-liquid jets have been reported for low values (< 5000) of jet Reynolds number. Reynolds (1962) has summarized some previous work and reports observations of his own. He worked with a jet 0·32 mm in diameter discharging axially into a cylindrical vessel 30 cm in diameter and 120 cm long. All the modes of breakdown of the parallel-sided laminar jet described in his paper have been observed in the present work. He presents his results as a plot of the length of the jet before breakdown against the flow rate through the jet.

The phenomena occurring in such jets have practical importance in the design of chemical reactors and other types of flow equipment. Batten (1961) has reported observations on such jets in a study concerned with errors in reaction-rate measurements in tubular reactors with axial inlets and outlets. He carried out most of his work with gas-into-gas jets in a cylindrical vessel 25 cm long and 5 cm in diameter with two sizes of inlet and outlet, 0·75 and 1 cm. He did some work with liquid-into-liquid jets in the same vessel and showed that similar flow patterns occur at equal values of Reynolds number for the gas and liquid systems. The types of breakdown observed in the laminar jet were similar to those mentioned by Reynolds and observed in the present work.

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2. Experimental details

Liquid-into-liquid jets were observed by establishing a flow of water through a cylindrical vessel with axial inlets and outlets and then switching to an equal flow of tracer solution which contained 22 p.p.m. of methylene blue dye in water. The transparent Perspex vessels were floodlit from behind and the jets could be easily observed and photographed.

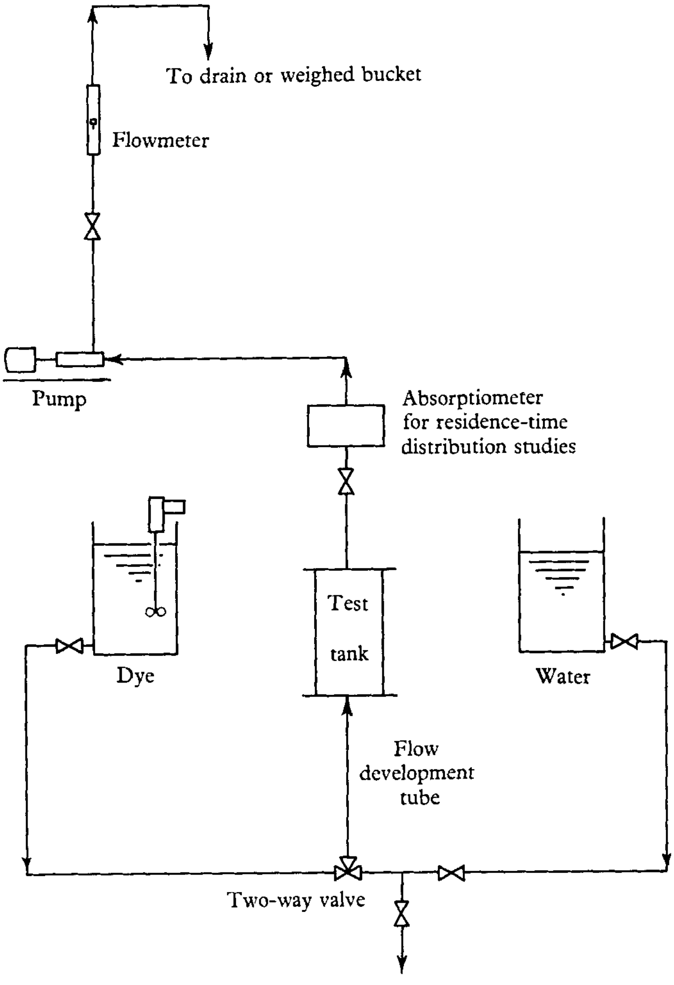

Figure 1. Equipment layout.

The layout of the equipment is shown in figure 1. Water and tracer solutions were held separately in 44-gallon head tanks. Lines from these tanks passed to a two-way valve, the position of which determined which of the two liquids would flow through the test tank. A flow-development tube was placed between the valve and the tank.

This tube was made of thick-walled precision-bore glass and a constant length-to-diameter ratio of 40 was maintained in all runs to ensure a consistent flow development. The end of the tube was ground flat and smoothed slightly with a flame to eliminate sharp uneven edges which might induce flow disturbances as the liquid entered the tank. Two 500 watt floodlamps were used behind sheets of opaque white Perspex to backlight the tank. A scale was suspended in front for the measurement of characteristic jet lengths.

The whole flow system was placed on the suction side of a pulsationless, positive displacement pump to prevent premixing of the dye–water interface before entry to the test vessel. The discharge from this pump passed through a flow meter to a flow diverter which could quickly divert the whole of the flow from the drain, for collection and weighing over a precisely measured period of time. Inlet diameters of $\frac{1}{4}$–1 in. were used and the test tanks varied in diameter between 3 in. and 2 ft. with length-to-diameter ratios of 1, 2 and 3. The Reynolds number in the inlet tube, Re_i, ranged between 100 and 28,000.

Before each run, a small amount of dye solution was run into the test tank and then drained out again to ensure that the first dye solution to enter the tank would be fresh. The inlet tube was flushed several times with water and then the test tank was filled with water. The pump was then switched on and the desired flow of water through the test tank was established. About 10 min were allowed for the flow pattern to become established and then the two-way valve was operated. Photographs of the emerging jets were taken with a 35 mm camera on f4 at $\frac{1}{250}$ sec.

It was found that all sub-turbulent jets had a laminar portion where the flow was parallel-sided and non-eddying. This laminar length a was found to be a useful characterizing parameter for investigating laminar–turbulent transitions. Measurements of a were made under a variety of conditions. When a particular jet had become stabilized, measurements of its laminar length were estimated at 15 sec intervals over a 4 min period and these values were plotted against time. The laminar length fluctuated slightly but, if these fluctuations were fairly uniform over the 4 min period, an average laminar length was determined from the sixteen values.

The flow rate was then increased and the new laminar length was measured. In this way, it was possible to determine the variation of the laminar length of sub-turbulent jets with Reynolds number, for various tank and inlet sizes.

3. Types of jet

The changes in the jet characteristics, as the Reynolds number in the inlet tube Re_i increased, are described below for the case of a tracer solution with a density equal to that of the liquid being displaced from the tank. Other cases will be discussed later. Note that $Re_i = \rho v d/\mu$, where v is the velocity of fluid in the inlet tube whose diameter is d.

1. For Re_i less than about 300, a parallel-sided, non-eddying jet rose a short distance into the vessel and then mushroomed [figure 2(a), plate 1]. As Re_i increased, the jet rose higher before mushrooming [figure 2(b), plate 1]. This is termed a dissipated laminar jet and it has a characteristic laminar length at a particular value of Re_i. The phenomenon is similar to the pedal breakdown described by Reynolds.

2. At a value of Re_i which depended on the dimensions of the vessel, the laminar length of the jet became equal to the length of the vessel and the jet passed straight through to the exit [figure 3, plate 1]. This type of jet was observed over a considerable range of flow rates in each vessel and the value of Re_i for which this condition was obtained was in the range 300–1000.

There was no apparent entrainment by the fully laminar jet nor any transfer of material between the jet and the vessel contents by eddy diffusion. However, due to slight misalignment of the jet axis and the tank axis and slight sinuous disturbances in the jet there was a small amount of mixing at the exit which ultimately caused a complete exchange of tracer with the original contents of the vessel. In one run, an 18 in. long, fully laminar jet from a $\frac{1}{2}$ in. nozzle was maintained in a 6 in. diameter vessel for 8 h before it became indistinguishable from the surrounding liquid.

3. As Re_i increased still further, turbulent eddies appeared at the top of the laminar jet [figure 4 (*a*), plate 2]. In the upper turbulent region, the surrounding fluid was entrained and well mixed with the jet. Consequently, the volumetric flow rate of the jet increased. At the exit, an amount of fluid equal to that entrained recirculated in a direction contrary to the flow of the jet, in the annular space surrounding it. The recirculation was fairly uniform at right angles to the tank axis and a 'recirculation front' moved down the backflow region towards the inlet. Rapid mixing took place in the turbulent section of the tank with a slower dispersion of tracer throughout the remainder. A stage in this mixing process is shown in figure 4 (*b*) (plate 2).

As Re_i increased further, the point at which turbulence set in moved closer to the inlet nozzle [figure 4 (*c*), plate 2]. We term this type of jet semi-turbulent, and, like the dissipated laminar jet, it has a characteristic laminar length at any particular value of Re_i.

4. At Re_i equal to 3000, the laminar length became negligible for all combinations of vessel and inlet sizes tested and the jet became fully turbulent [figure 5, plate 3]. Although Reynolds numbers as high as 28,000 were achieved, no further change in jet geometry could be observed. Above Re_i 3000, the flow pattern was always comprised of two regions: the forward-moving, conical, turbulent-jet region, and the slower moving backflow region which surrounded the jet.

The four jet types observed may be summarized as follows:

1. Dissipated-laminar jet ($Re_i < 300$ dependent on vessel dimensions).
2. Fully laminar jet ($300 < Re_i < 1000$ dependent on vessel dimensions).
3. Semi-turbulent jet ($1000 < Re_i < 3000$ dependent on vessel dimensions).
4. Fully turbulent jet ($Re_i > 3000$ independent of vessel dimensions).

4. Laminar length

Since a laminar length is characteristic of all types of jet other than the fully turbulent one, it is very useful as a descriptive parameter. For purposes of comparison and correlation the ratio of laminar length to nozzle diameter (a/d) has been used. The variation of a/d with Re_i is shown in figure 6, where the experimental points from observations in an 18 by 6 in. tank are presented. The length of the dissipated-laminar jet increased with Re_i until, at Re_i equal to 500, it reached a length of 18 in. Since this was the length of the vessel, a fully laminar jet persisted until turbulence set in at Re_i equal to 800 and the laminar length of the semi-turbulent jet began to decrease. At Re_i equal to 3000 the laminar length had become negligible and the jet was fully turbulent.

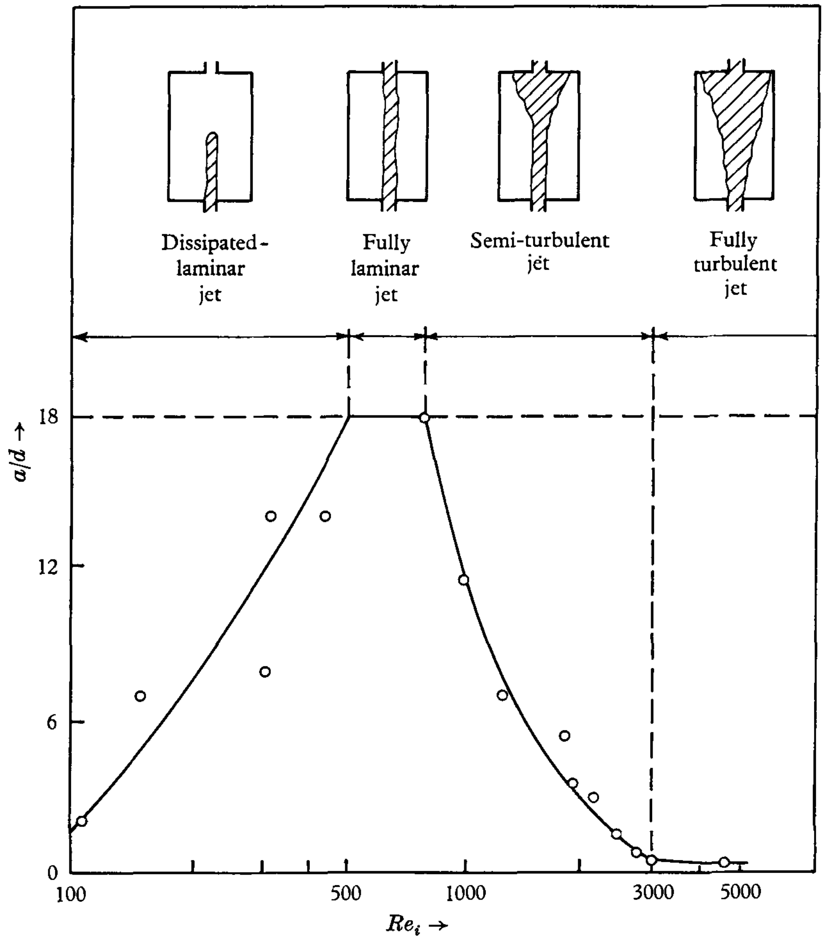

FIGURE 6. Laminar length of a sub-turbulent jet. a/d against Re_i. Experimental points ○ and sketches are for a tank with $D = 6$ in., $L = 18$ in., $d = 1$ in.

The scatter of points prior to the fully laminar stage in figure 6 indicates the difficulty of obtaining precise measurements in this region. This is mainly due to the relative significance of minor density differences between the tracer solution and the original tank contents at such low flow rates. No extensive work was done on dissipated-laminar jets but work has been carried out to determine the laminar length of semi-turbulent jets for a few combinations of vessel length, vessel diameter and inlet diameter. All the results for laminar lengths up to 80 per cent of the vessel length are shown in figure 7, where a/d is plotted against Re_i. The end effects when a/L is greater than 0·8 are discussed later. For $500 < Re_i < 2000$ the data of figure 7 are correlated by the relationship

$$a/d = 9{\cdot}97 \times 10^7 Re_i^{-2{\cdot}46} (D/d)^{-0{\cdot}48} (L/d)^{0{\cdot}74}. \tag{1}$$

Points derived from results presented by Batten and Reynolds are also plotted in figure 7, but these were not used in determining the correlation.

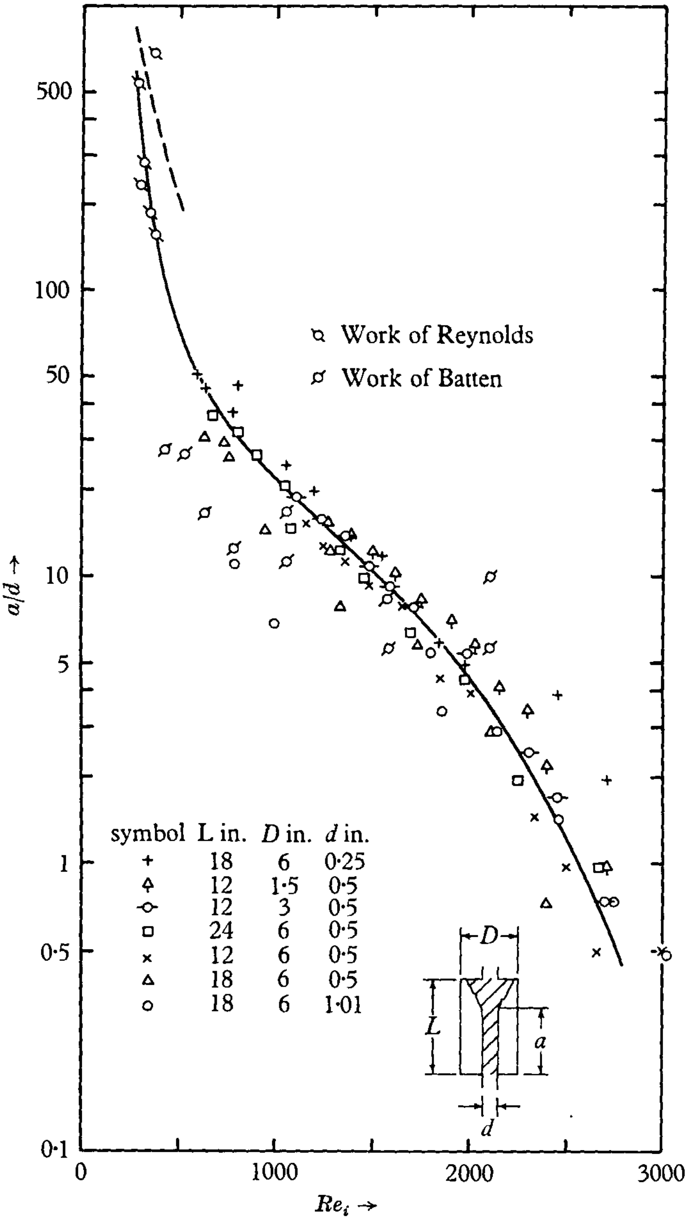

FIGURE 7. Laminar length of a semi-turbulent jet. a/d against Re_i. Data for which $a/L > 0{\cdot}8$ have been omitted, see figure 8.

Batten did not measure laminar length directly. He presented his results in tabular form, referring to six different patterns of flow which were photographed and shown in the paper. It was possible to estimate from these only six discrete

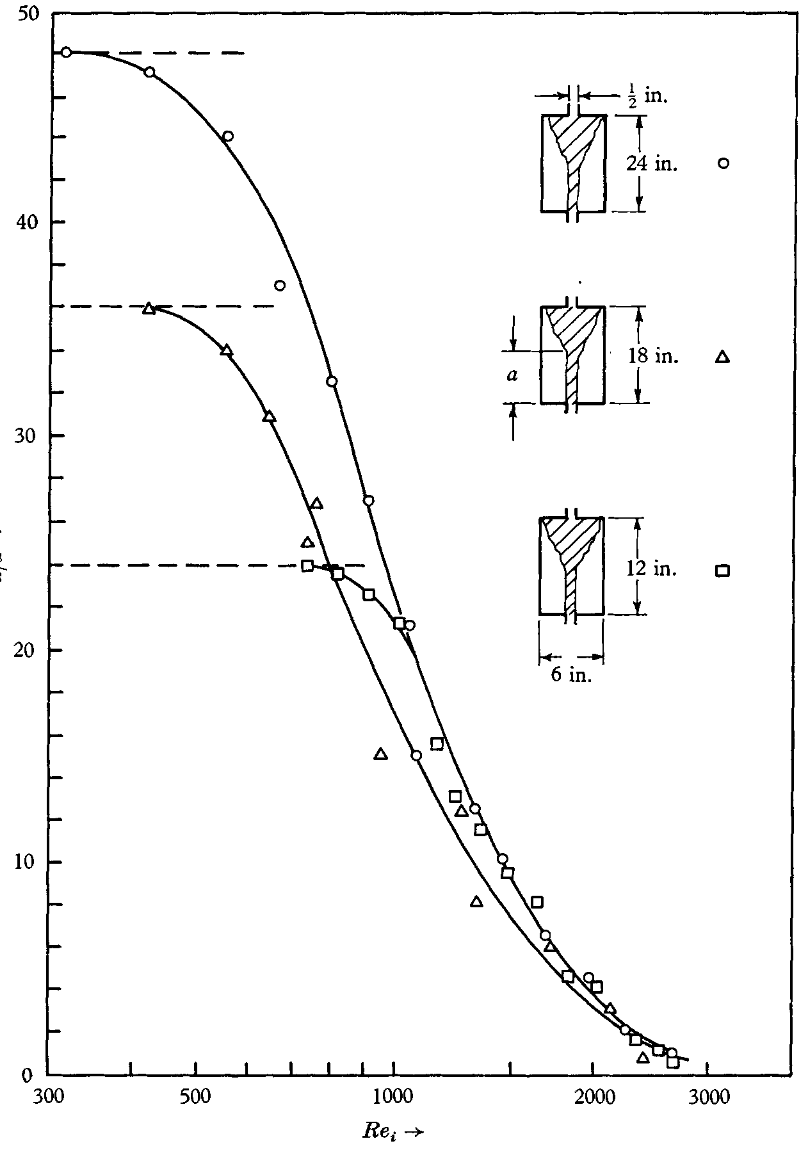

FIGURE 8. Tank end effects on laminar length. a/d against Re_i.

values of the ratio a/L. Bearing this in mind, the differences between Batten's results and those presented in this paper are not significant. The points taken from Reynolds's paper are those which correspond to his 'confused breakdown' flow pattern. This corresponds to our semi-turbulent flow. Since the Reynolds number at which this phenomenon occurred did not overlap in Reynolds's and our studies, it is not possible to say that they directly confirm the results presented here. However, as is shown, a smooth curve may be drawn through the two sets of results.

The heavy broken line is a plot of equation (1) for Reynolds's conditions. In view of the ratio of over 20 to 1 of jet diameters used in the present and Reynolds's work, the discrepancies are not unexpected.

The results obtained for a jet emerging into an infinite fluid would be expected to differ from the results obtained for bounded jets as investigated in this work. The effect of the tank length is shown in figure 8, which shows the laminar length of semi-turbulent jets emerging from a $\frac{1}{2}$in. nozzle into a 6in. diameter tank. Tank lengths of 12, 18 and 24in. were used. The end of the tank has the effect of inducing turbulence at a lower value of Re_i than would be the case in a longer tank.

5. Density differences

In this work it was found that very small differences in density between the tracer solution and the original contents of the vessel noticeably affected the behaviour of the jet. Drops of tracer solution with only 22p.p.m. of dye were found to have a terminal velocity of 0·4in./min in pure water at the same temperature. This was one of the reasons why the results for the very slow-moving dissipated-laminar jets were not reliable.

Great care was taken in the rest of the experimental work to ensure that the temperature of the tracer solution was the same as the temperature of the tank contents. Slight differences in temperature cause density differences which can easily upset the natural flow pattern. Where the density of the tracer is such as to cause it to move towards the outlet, the effect on the flow pattern is shown in figure 9(*a*), (*b*) and (*c*) (plate 4). With zero density difference, one would expect dissipated-laminar jets at corresponding values of Re_i.

The density difference causes the jet to thin out with a consequent increase in the Reynolds number of the jet. This, together with the acceleration of the fluid, significantly affects the flow pattern at high density differences [figure 9(*a*), plate 4]: there is an immediate breakdown into a fully turbulent flow pattern. As the density difference decreases the laminar length of the jet increases and various forms of instability arise. Figures 9(*b*) and (*c*) (plate 4) show examples of these phenomena at successively lower density differences.

Where the density of the tracer is such as to cause it to move towards the inlet, the laminar length is smaller than it would otherwise have been and the tracer drifts towards the inlet [figure 10(*a*), plate 5]. In this latter case, a horizontal interface between the slightly diluted tracer solution and the original contents of the vessel moves slowly from the inlet, passes the dissipation length of the jet and eventually reaches the outlet. Stages in this process, which chemical engineers call 'plug flow', are shown in figures 10(*b*) and (*c*) (plate 5).

Since all experiments were carried out in tanks with the axis of inlet and outlet vertical, no observations were made of tracer drifts to the side walls. However, this phenomenon has been treated by several authors, including Bosanquet, Horn & Thring (1961).

Of the four types of jet listed previously, only the dissipated-laminar jet is significantly affected by these density differences. So it is necessary to add two sub-groups to type 1.

1 (*a*) Dissipated-laminar jet—drift to outlet.
1 (*b*) Dissipated-laminar jet—drift to inlet.

6. Conclusions

When a fluid flows through a cylindrical vessel with an axial inlet and outlet at opposite ends, there are four main types of jet which may be set up inside the vessel. These are the dissipated-laminar jet, the fully laminar jet, the semi-turbulent jet and the fully turbulent jet. The transition Reynolds numbers between the first three régimes are of the order of 300 and 1000. Above a Reynolds number of 3000 all jets are fully turbulent and the flow pattern inside the vessel invariably consists of two regions—a forward-moving, turbulent, conical jet and a slower moving backflow region which surrounds the jet and moves towards the inlet.

Small density differences between the inlet solution and the original contents of the vessel can considerably affect the behaviour of the jets.

The laminar length a is a useful characterizing parameter for describing sub-turbulent jets and for investigating the transitions from laminar to turbulent flow. Between Reynolds numbers of 500 and 2000, the laminar length is related to the vessel dimensions and the Reynolds number by the following relationship:

$$a/d = 9{\cdot}97 \times 10^7 Re_i^{-2{\cdot}46} (D/d)^{-0{\cdot}48} (L/d)^{0{\cdot}74}.$$

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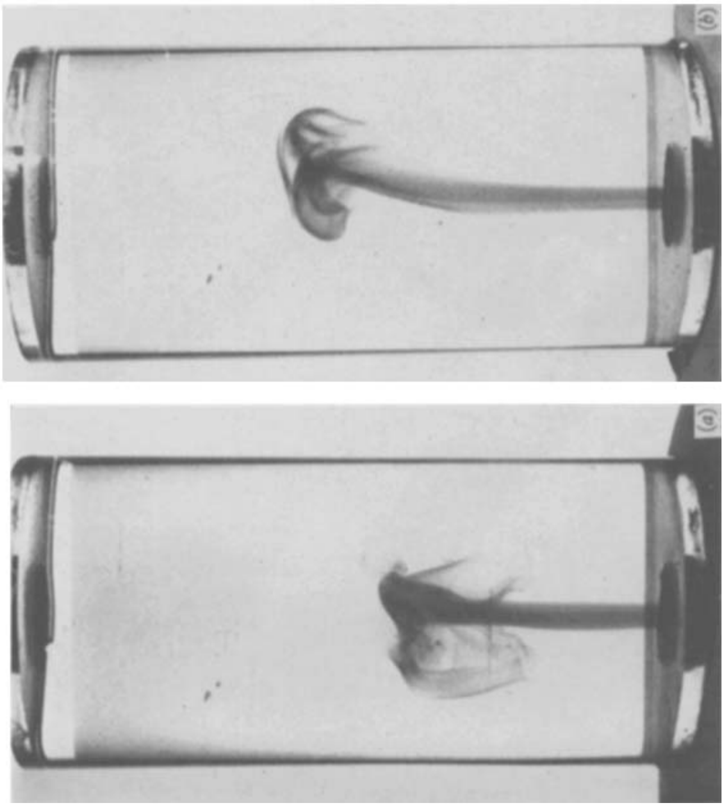

FIGURE 2. Dissipated-laminar jets: (*a*) $Re_i = 240$, (*b*) $Re_i = 256$.

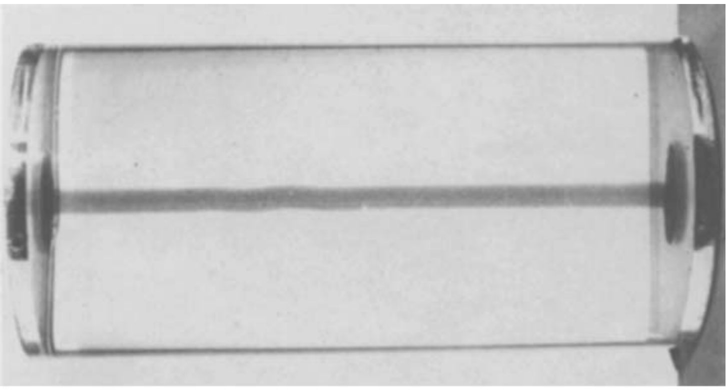

FIGURE 3. Fully laminar jet, $Re_i = 456$.

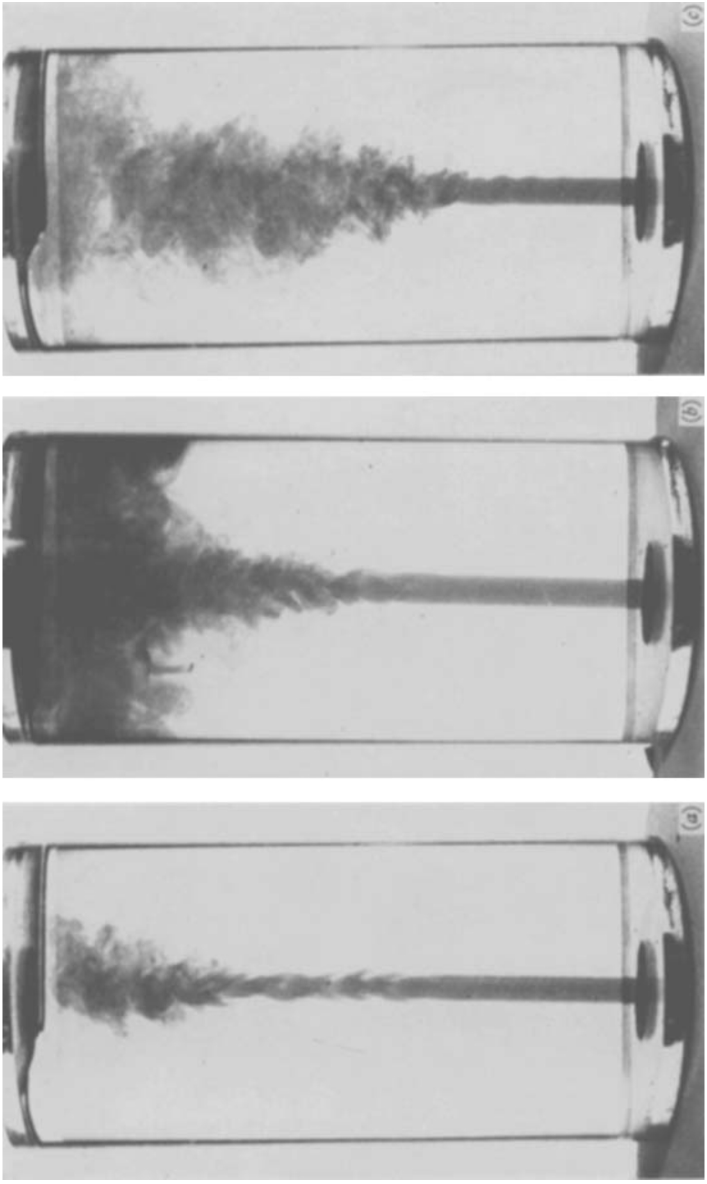

FIGURE 4. Semi-turbulent jets: (*a*) $Re_i = 1400$, (*b*) the same several seconds later, (*c*) $Re_i = 2000$.

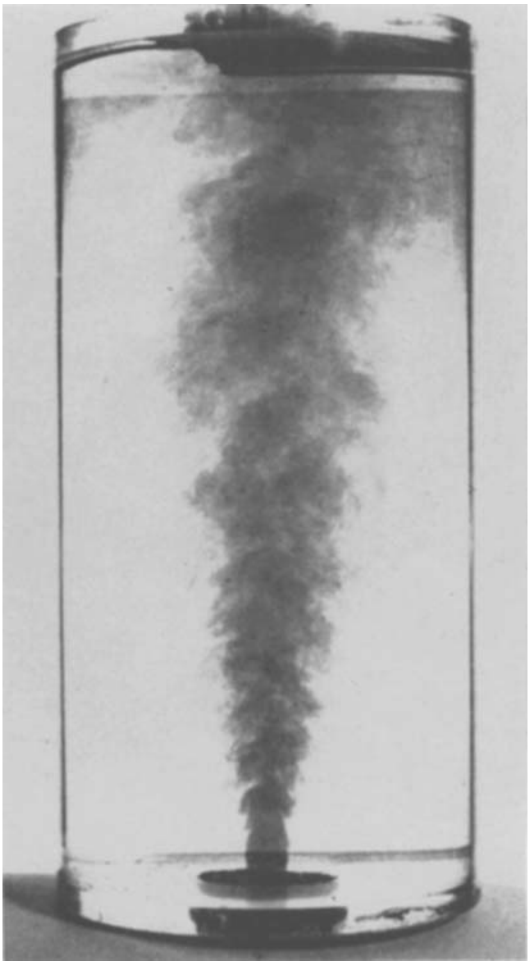

FIGURE 5. Fully turbulent jet, $Re_i = 3200$.

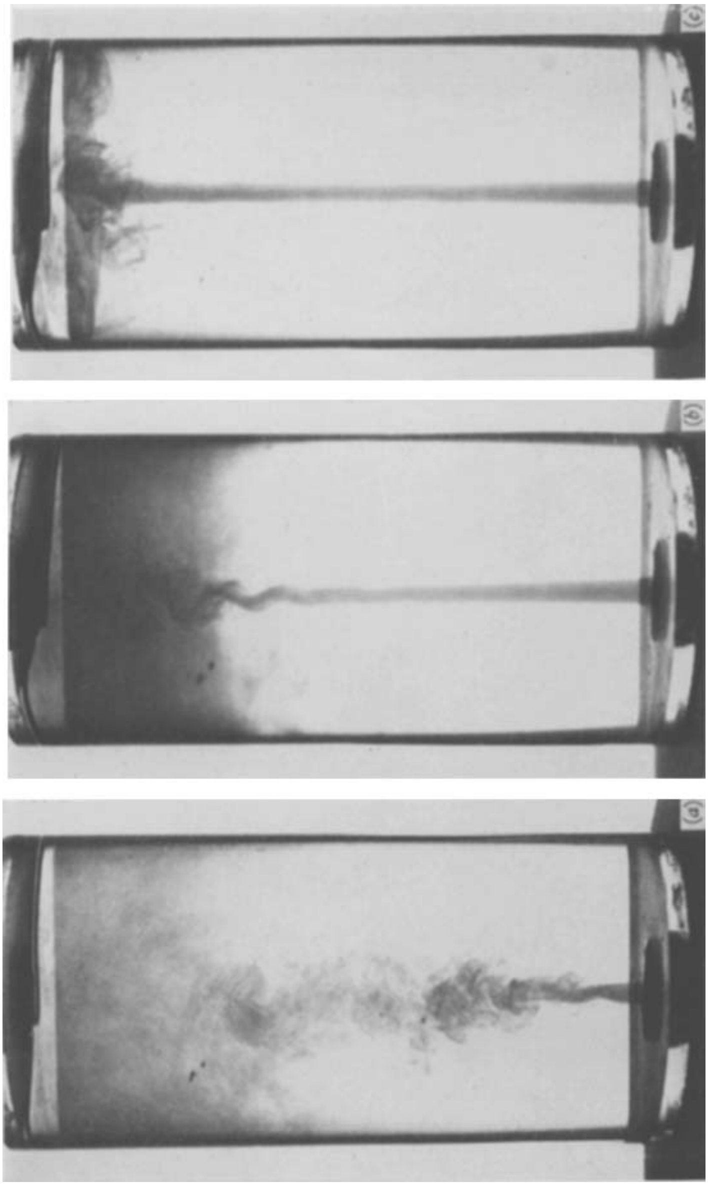

FIGURE 9. Effect of density difference; tracer drift towards outlet. (*a*), (*b*), (*c*), $Re_i = 208$. Normally dissipated jets became semi-turbulent, but to a lesser extent as the density difference becomes lower.

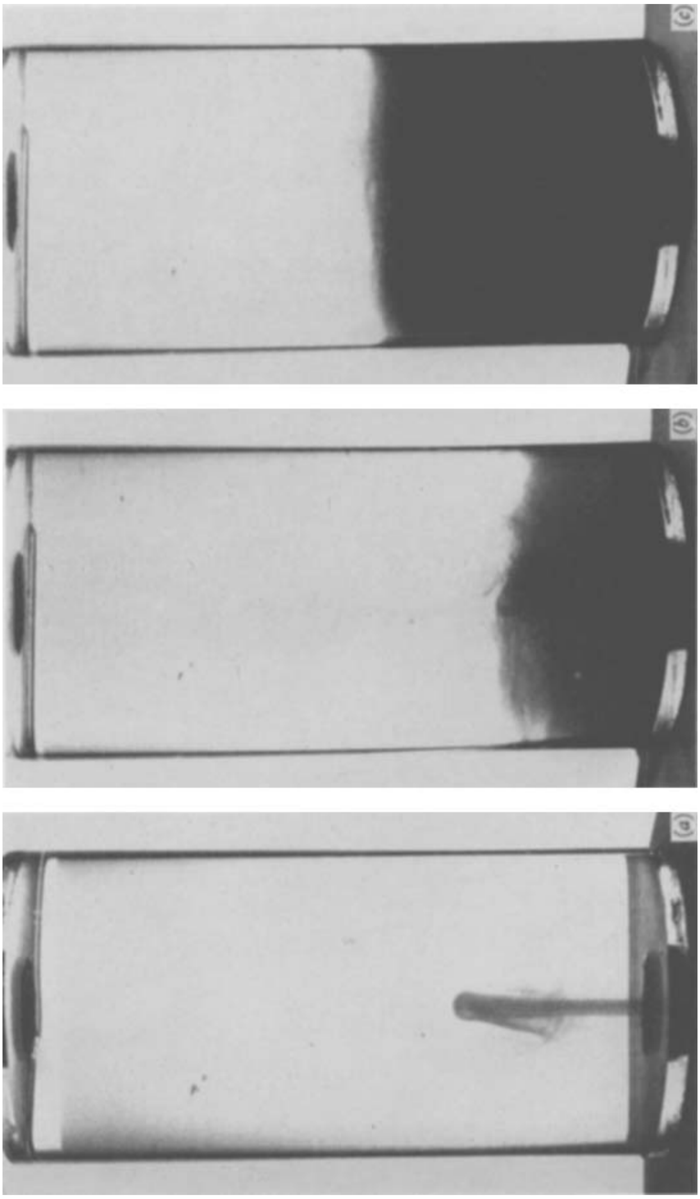

FIGURE 10. Effect of density difference on dissipated-laminar jets; tracer drift towards inlet. Tank gradually fills up in 'plug' or 'piston' flow.