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Characteristics of Jet Mixers—Effect of Number of Jets and Reynolds Numbers

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If a passive tracer is added to some of the jets in a jet mixer, the root mean square concentration fluctuations of the tracer can be used to characterize the turbulent mixing.

While studying the influence of turbulent mixing on chemical reactions, data have been accumulated on five mixing devices; Device I, a 1.80-mm I.D. tube located concentrically in a 3.175-mm I.D. pipe; Device II, 14 tubes, 0.394-mm I.D., close packed in a 3.175-mm I.D. pipe; Device III, geometrically similar to Device II, 14 tubes, 0.84-mm I.D., close packed in a 6.76-mm I.D. pipe; Device IV, 188 tubes, 1.37-mm I.D., close packed in a 3.175-cm I.D. pipe; Device V, 100 tubes, 1.32-mm I.D., in a 3.175-cm I.D. pipe (Vassilatos and Toor, 1965; Shuck, 1971; Mao and Toor, 1971; Singh, 1973; Toor and Singh, 1973). Very rapid acid-base reactions were used to measure d by feeding the reactants in alternate jets. This measured value of d is equivalent to what would be obtained if a tracer were fed through alternate jets (Toor, 1962; Keeler, Petersen, and Prausnitz, 1965; Vassilatos and Toor, 1965; Toor, 1969). All the data are for equal flow rates of reactant streams, equivalent to equal flow rates of tracer and nontracer fluid. The data are used in this report to examine the effect of geometry and Reynolds Number on d.

PRELIMINARY CONSIDERATIONS

The mixing depends on the nature of the turbulent field downstream of the mixing devices and, except perhaps for Device I which is clearly a special case, the turbulence is generated primarily by the expanding, interacting jets. Since the turbulent field far downstream must decay to that field characteristic of fully developed pipe flow, one would expect that there is a region near the inlet where the mixing depends upon jet turbulence and one far downstream where the mixing depends upon pipe turbulence. However, the observable range of d^2 in the experiments is order 1 to 10^{-3} and in all cases the lower bound is reached in less than 3 pipe diameters. This distance is small compared to that required to establish fully developed pipe flow, which suggests that over the region of interest the jet turbulence would control. Hence, in comparing mixing devices which are not geometrically similar, one would expect the appropriate characteristic length to be jet diameter.

Furthermore, when comparing Device II (or III which is geometrically similar to II) with Device IV, the above arguments would suggest that both devices would be identical when scaled in terms of jet diameter since the pipe wall is presumably playing no role. Looked at another way, with enough jets present most of the jets should be unaware of the wall and the central portion of a hypothetical Device II′ which has the same diameter jets as Device IV but 14 jets (in a smaller pipe) should have the same central field as Device IV. But Device II′ is geometrically similar to Device II so that when scaled by jet diameter the central portions of Devices II and IV should be similar.

Since Device V does not have close packed tubes the above arguments do not necessarily hold.

COMPARISON OF MIXING DEVICES

Data for Devices II, III, and IV from various investigators (Mao and Toor, 1971; Shuck, 1971; Singh, 1973) at almost equal values of jet Reynolds number are plotted against dimensionless length in Figure 1. The data can be represented by a single curve, which confirms the earlier arguments that with a sufficient number of jets in the same array jet diameter is the proper scaling parameter. It is not possible to discern from the data an effect of pipe diameter, which indicates that up to values of $Z = 20$ the turbulent field is dominated by jet turbulence.

Data of Singh (1973) for Device I at a somewhat higher jet Reynolds number are also shown in Figure 1 for comparison. These data differ from those of the multiple jet devices (the difference in Reynolds numbers is not significant). Presumably, if we were to build multiple jet devices with decreasing numbers of jets n, a value of n (less than 14) would be found below which the characteristic behavior of the multiple jet devices would not be obtained, and as n decreased towards 1 the behavior would tend towards the behavior found for the single jet.

Data for Device V are available only at a jet Reynolds number of 3700 (Vassilatos and Toor, 1965). These data do not differ greatly from the data for Devices II, III, and IV.

EFFECT OF REYNOLDS NUMBER

Data for Devices II, III, and IV are shown in Figure 2. An attempt was made to determine the effect of Reynolds number even though the range is rather limited. The results are shown in Figure 3. The Reynolds number dependence in the initial region differs from that in the fully developed region and the data for the fully developed region are correlated by

$$d^2 = 3.52 \times 10^7 (\sqrt{N_{Rej}}\, Z)^{-3.45} \quad (1)$$

[Mao and Toor (1971), whose data are included, obtained exponents on z around -3.2] and for the initial region by

$$d^2 = (23.48 - 0.050 \sqrt{N_{Rej}}\, Z)\ N_{Rej}^{-0.47} \quad (2)$$

Examination of Figure 2 shows that the Reynolds number effect in the initial region is quite pronounced [and is correlated quite well by Equation (2)], but it is less pronounced in the fully developed region. The scatter in Figure 3 is visibly less than in Figure 2 in the fully developed region for $d^2 > 0.01$, but there is little improvement for smaller values of d^2. This lack of improvement may be due to the larger experimental errors in this region. The squared correlation coefficient for the best straight line fit to the data in Figure 2 for $d^2 < 0.25$ is 0.82, while the same coefficient for Equation (1) is 0.92 for the same range. We conclude that there is indeed an effect of Reynolds number on d, but it is clear that data on a wider range of Reynolds number is needed.

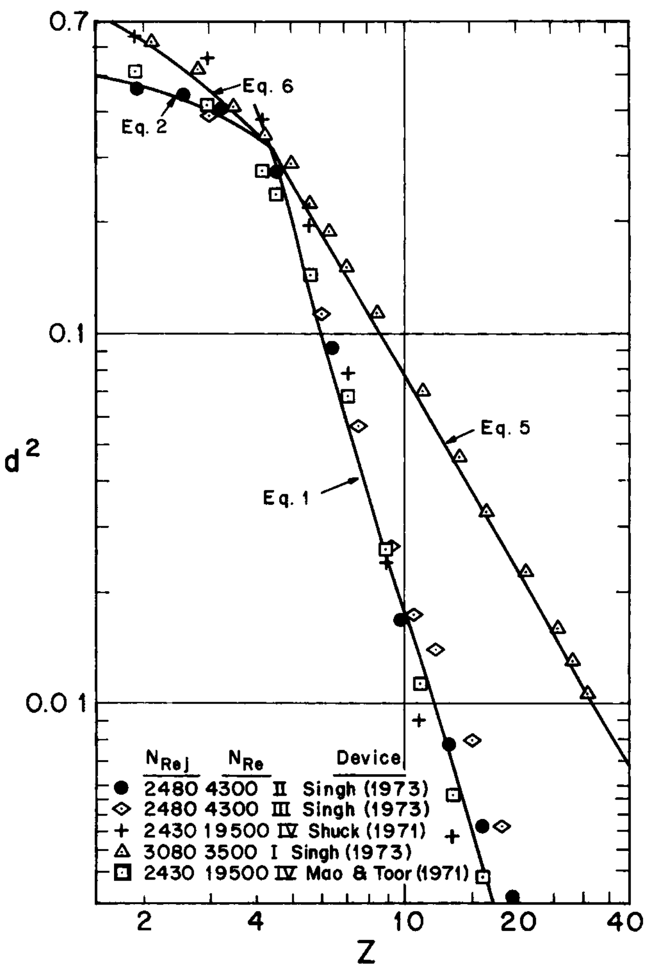

Fig. 1. d^2 vs. Z, multiple and single jet devices.

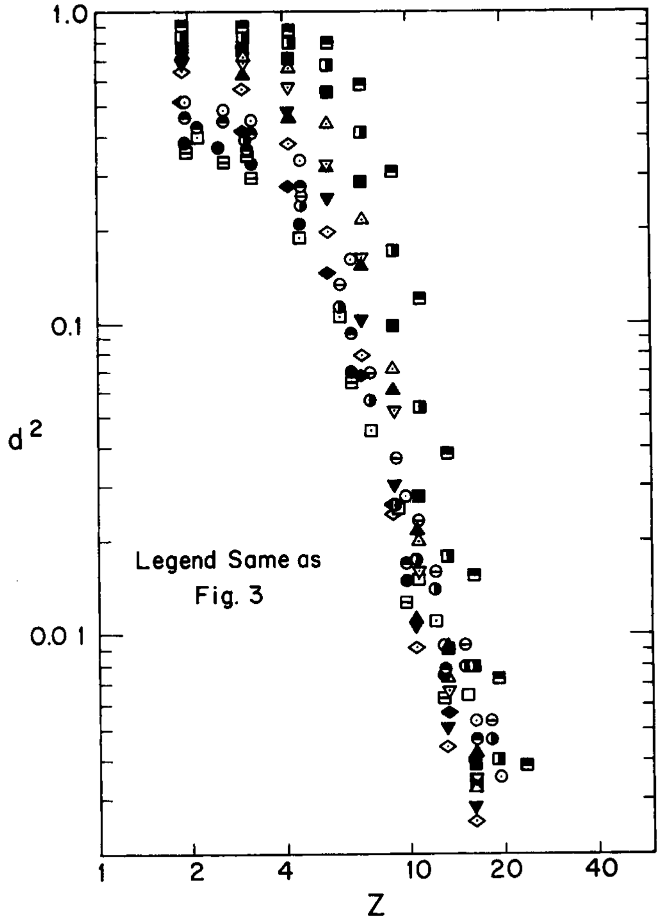

Fig. 2. d^2 vs. Z, multiple jet devices.

Equation (2) does not extrapolate to a value of $d^2 = 1$ at $Z = 0$. The lowest value of $\sqrt{N_{Rej}}\, Z$ measured was about 25 (corresponding to $Z = 0.95$). The fluid in the region is quite nonuniform since the jets have not yet lost their identities at this short distance. Indeed here the measured values of d are averages over the region of the centerline (Singh, 1973). This leads to some ambiguity since the theoretical underpinning to the experiments are inherently one-dimensional (Toor, 1962). However, it has been found to be satisfactory (Vassilatos and Toor, 1965; Mao and Toor, 1971) to retain the one-dimensional viewpoint and to recognize that d^2 suffers a rapid decrease from one at $Z = 0$ to the value given by Equation (2) at $\sqrt{N_{Rej}}\, Z = 25$.

The mixing time (the time moving with the fluid and assuming plug flow) required to reduce d to a given value is obtained from Figure 3 and a material balance,

$$(\theta_m v / d_j^2)\ (A_j/A) = N_{Rej}^{-3/2}\, X \quad (3)$$

where X is the abscissa in Figure 3 corresponding to the desired value of d. X depends only on d in the fully developed region, $d \lesssim 0.5$. Alternately,

$$\theta_m = d_j^{1/2}\, u_j^{-3/2}\, \nu^{1/2}\, X\, A/A_j \tag{4}$$

As mentioned earlier, a single jet device does not show the same behavior as the multiple jet devices. Not only is the form of the decay law different, as seen in Figure 1, but the Reynolds number dependence is also different. This is shown in Figure 4 where data of Singh (1973) for three Reynolds numbers are shown. In the fully developed region, these data are fit by the equation

$$d^2 = 0.062\, (N_{Rej}^{-0.3}\, Z)^{-1.75} \tag{5}$$

and in the initial region

$$d^2 = 60\, N_{Rej}^{-0.4} \exp\left(-3.2 \sqrt{N_{Rej}^{-0.3}\, Z}\right) \tag{6}$$

The mixing time is given by

$$(\theta_m \nu / d_j^2)\, (A_j/A) = N_{Rej}^{-0.7}\, X' \tag{7}$$

where X' is the value of $N_{Rej}^{-0.3}\, Z$ corresponding to a given value of d. X' depends only on d in the fully developed region. Alternately,

$$\theta_m = d_j^{1.3}\, u_j^{-0.7}\, \nu^{-0.3}\, X'\, A/A_j \tag{8}$$

Equations (5) through (8) are based on a rather narrow range of Reynolds numbers.

ACKNOWLEDGMENT

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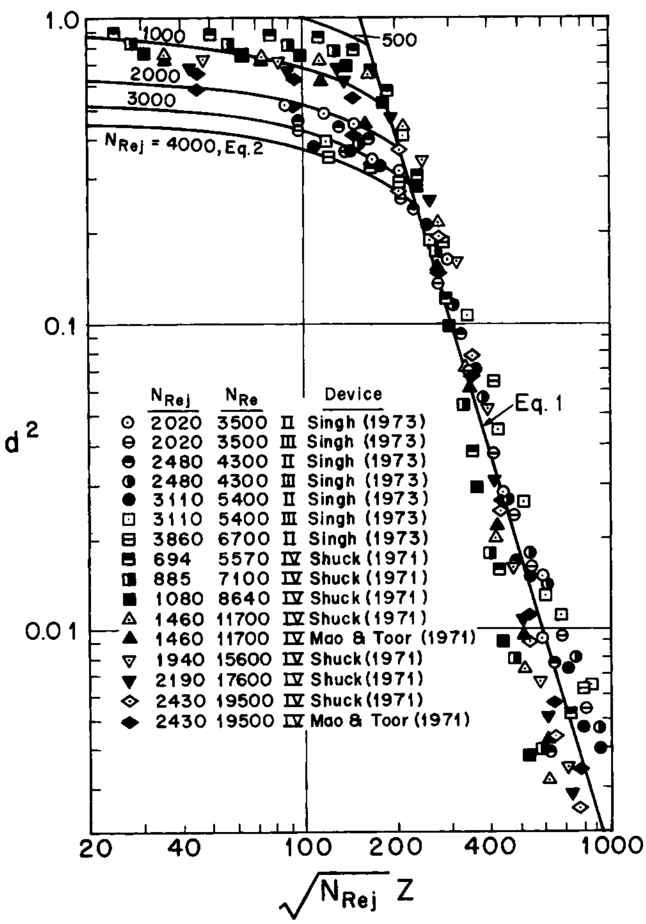

Fig. 3. d^2 vs. $\sqrt{N_{Rej}}\, Z$, multiple jet devices.

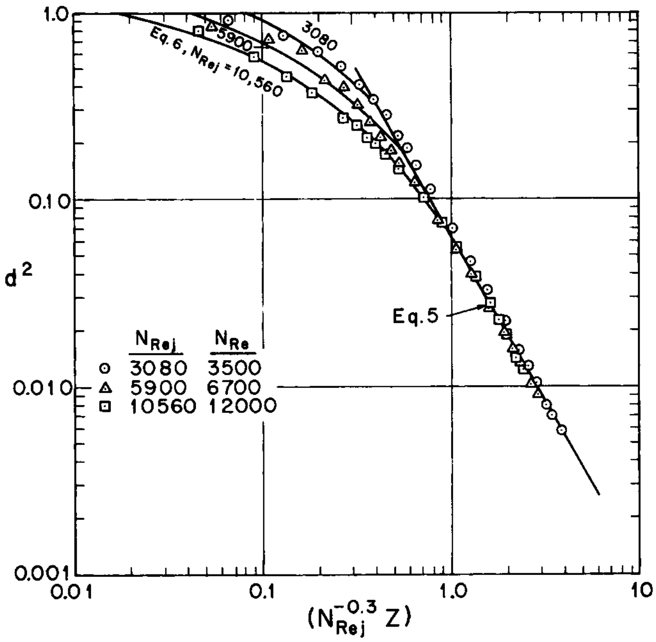

Fig. 4. d^2 vs. $N_{Rej}^{-0.3}\, Z$, single jet device.

NOTATION

A = cross section of pipe
A_j = total initial cross section of jets
c = tracer concentration fluctuation
d = $\sqrt{\overline{c^2}/\overline{c^2}|_0}$
d_j = initial jet diameter
L = characteristic length
N_{Re} = pipe Reynolds number
N_{Rej} = jet Reynolds number
u_j = initial velocity of jet
X = $\sqrt{N_{Rej}}\, Z$
X' = $(N_{Rej})^{-0.3}\, Z$
z = distance from inlet
Z = z/d_j
θ_m = mixing time
ν = kinematic viscosity
— = time average

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