OBSERVATIONS RELATING TO THE EFFICIENCY OF MIXING IN RAPID REACTION FLOW DEVICES

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ABSTRACT The principle of dimensional analysis of liquid flow has been applied to the problem of rapid mixing in flow apparatus. A model of the Hartridge-Roughton mixing chamber and observation tube has been scaled approximately $1/1{,}000$ so that the times after mixing are approximately 6 s, the flow velocities are the order of 2 cm/s, and the distance from mixing to observation is 120 mm. Visual observation is employed to observe the end point of the mixing of acid-base with a color indicator, thymol blue. Quantitative estimates of the effect of the number of jets, the effect of screens placed in the flow stream, and the angle of jets, one with respect to another, lead to quantitative evaluations of these parameters for the scale model. The extent to which these parameters apply to the full-scale apparatus at faster flow velocities suggest that the general principles employed in the scale model are valid, although more emphasis is placed upon turbulence generation at the low flow velocities employed in this experiment than at the faster flow velocities employed in the full-scale apparatus.

INTRODUCTION

This paper attempts to apply the principle of dimensional analysis of liquid flow to the problem of rapid mixing in flow apparatus. By the term "dimensional analysis" it is meant simply that scale models may be used to reproduce the characteristics of the system under consideration. So far, scale models have not been employed in the study of mixing phenomena, and such a study seems appropriate in view of the pioneer works of Hartridge and Roughton in 1923 (1, 2) and the recent symposium to this point (3).

The scale factor employed in these studies is approximately $1/1{,}000$ in terms of time after mixing and with respect to the usual apparatus. For example, flow velocities of 2 cm/s and times after mixing of 6 s are characteristic of these studies while flow velocities up to 30 m/s and time after mixing of 10ths of msec are characteristic of the "full-scale" apparatus. One very useful consequence of the scaling employed here is that mixing extends over an interval of 120 mm downstream from the position of the mixer and can therefore be evaluated with considerable accuracy. The principal technique for observing mixing is to employ a color reaction and to adjust the flow velocity so that the mixing is completed at a fixed point downstream from the mixer (usually 120 mm).

EXPERIMENTAL METHODS

Mixing Test

A most favorable mixing test for visual observations was found to be that of 0.4% thymol blue in 0.01 N alkali mixed with 0.02 N acetic acid (0.1% vol/vol glacial acetic acid). The color changes from dark blue to orange. Usually aqueous solutions are employed. Occasionally, ethylene glycol at a concentration of 30% vol/vol is used. The experiments are carried out at room temperature. Two models were employed: (*a*) with a 2 mm bore observation tube, and (*b*) with a 10 mm bore observation tube on which the most definitive results were obtained and are repeated here. The design was such that the flow pattern could be observed anywhere along the tube, in the mixer itself, and down the bore of the tube as well. The view along the bore through the back plate allowed observation of the pattern of flow with jets as the liquid emerged from the mixer and seemed to provide all the visual access that was needed. All parts were made of Perspex with lapped faces between sections A, B, and C (Fig. 1). An outer sheet of nylon was later added as a result of leakage problems. This was screwed down onto the flow tube at the same time pressing the mixer and the back plate down on to the tube face. In practice even this sleeve arrangement was not completely satisfactory, and presumably some means of threading the sections into each other is preferable. The liquids were delivered to the mixer by separate lengths of 2 mm bore plastic tubing leading into an annular ring, one in A and one in C. In each mixer (unit B), the jets were drilled from the outside of the tube into the central bore. The opening to the outside was then sealed by inserting a short length of Perspex rod into each jet, and the holes were drilled at right angles to the lapped faces to open into each jet at the level of the annular rings A and C. In the mixers described here, the side drillings were made so that the liquid emerged into

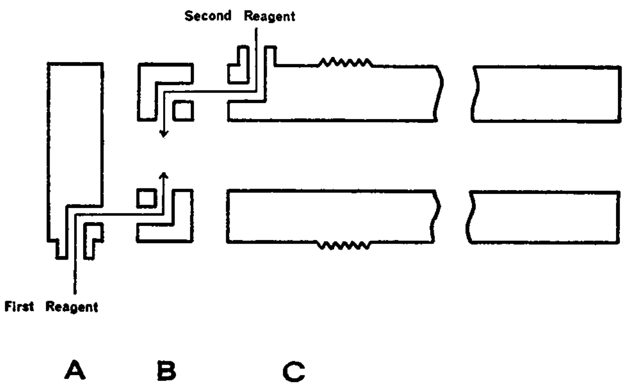

FIGURE 1 Section through model 2. Sections A, B, and C are held together by an outer cover which screws down on to C. The faces between them are lapped.

the main tube alternately from the A side and the C side, i.e., the reagents alternated from jet to jet. Three types of mixer were made, one set with radial jets (R) (directly opposed) and two with tangential jets (T_R and T_o). The configuration of tangential jets in which all have the same sense, i.e. to reinforce each other, is termed T_R. The configuration of tangential jets in which adjacent jets oppose each other is termed T_o. Each set of jets from A and C, respectively, were displaced 15° from the vertical in opposite directions.

The ratio of the cross-sectional area of the observation to the corresponding total area of the jets was maintained close to 1; however, this cross-sectional area was considerably greater than that of the tube feeding the annular rings A and C, although this was not considered to be a significant factor in the particular test described. The exact ratios of jet area to observation tube area varied somewhat with the number of mixing jets, since with a large number of mixing jets, some enlargement of the jet area due to fusion of the holes occurs.

EXPERIMENTAL PROCEDURE

When the end point of mixing was taken at a fixed point, readings were taken at varying values of flow velocity until the mixing just appeared at this point. When estimates of mixing were made at a constant flow velocity, observations of the distance at which mixing was complete were made up to 200 mm, the length of the observation tube. All observations were taken after agreement by two observers working in conjunction.

In all cases, the reagents were sucked through the observation tube by a constant head centrifugal pump. The actual rate of flow was adjusted by a clamp downstream from the pump. Each of these tests was repeated with a nylon mesh placed inside the mixer just at the face of the observation tube. This mesh contains 400 holes and has a mesh size of 0.45 mm (width of a hole plus a bar).

EXPERIMENTAL RESULTS

Experimental results are shown in Table I, and several points are worthy of consideration.

TABLE I
EXPERIMENTAL RESULTS

Type of mixer	Fixed reference point (120 mm) rate of flow	
	Mixer alone	Mixer + mesh
	ml/min	
4-jet R A	160	120
T_R A	220	140
T_o A	110	65
10-jet R A	120	27
G	430	—
T_R A	100	65
T_o A	90	25
G	290	—
20-jet R	90	40
30-jet R	25	~20

Effect of the Number of Jets

Considering the results as a whole, there is a general trend, apparently in exponential form, to a greater efficiency with an increasing number of jets. It is of great interest that the maximum number of jets (30) that the mixing efficiency is not increased significantly further by the addition of the mesh.

Effect of Jet Angle

The order of relative efficiency observed in this table is $T_o > R > T_R$. One exception to this is the 10-jet T_R mixer which appeared to be better than the 10-jet R mixer when measured to a fixed reference point. This difference persisted in ethylene glycol solutions (G) and is attributed to the use of too large a drill resulting in the jets breaking into each other slightly at the surface of the main tube of the T_R mixer.

Effect of Mesh

The effect of the mesh is highly significant for mixers containing a low number of jets, being roughly equivalent to a two- to threefold increase in the number of jets. As mentioned above, when 30 jets are reached, the mesh can provide no further improvement.

DISCUSSION OF RESULTS

The trend of the results is that more jets give better mixing, and the mixing of small numbers of jets could be improved by the addition of mesh for the same number of jets, and opposed tangential arrangement is better than a radial one, and both are better than a tangential reinforcing one. An appropriate scale of the performance is 1–1.2–1.7.

One explanation for the better performance of vortex-opposing as compared with vortex-producing arrangements is that the scaled version here emphasizes turbulence generation in the mixer. Vortex generation at the low Reynolds numbers characteristic of these mixers may afford patterns of vortices of relative stability such as were observed by Trowse (4). Such patterns of stable vortices were observed at low flow velocities, but could not be seen at higher flow velocities where more vigorous turbulence damped out the oriented motion.

A number of predictions arise from this work. The first is the relatively great effectiveness of the mesh. It is possible that a very simple jet mixer followed by an appropriate size mesh would give highly satisfactory mixing combined with very economical construction. The use of the mesh in particular calls attention to the general principle of introducing roughness in the orifices of the mixer in order further to improve turbulent flow, an aspect of the mixing problem that has scarcely been considered by workers in the field.

Two sources of noise in the flow stream may be detected: first, the well-discussed cavitation problem, and second, the irregularities introduced by "flecks" of unmixed reactants. Such flecks are readily visible in the systems under observation. Whether or not they are significant at the higher flow velocities used in actual apparatus is not clear, but it is a point to be considered.

Some general criteria for the design of mixers can be inferred from the above results and may be briefly summarized along the following lines.

(*a*) The efficiency of mixing depends on the ability of the mixer to break up the streams of the two reactants into elementary blocks of the smallest size. This is greatly aided, for example, by mixers which alternate the agents in adjacent jets.

(*b*) Inadequate attention has been given to turbulence generation before and after the mixer to the use of rough tubes, sharp angles, and meshes.

(*c*) Cavitation often represents a limit on the rate at which turbulence can be induced per unit length of the flow tubes. It was not a phenomenon studied in this contribution, but certainly must be considered in scaling the mixers described here to higher flow velocity.

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