Measurements of the intensity of concentration turbulence in inline motionless mixing systems

by Arthur Kirk McCready

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Abstract:
Concentration profiles were measured at intervals of 45 milliseconds in the exit streams of four inline motionless mixers using a ten position concentration probe array. These data were used to calculate a dimensionless parameter called the intensity of concentration turbulence, I CONC ten positions across the diameter of the exit stream. I CONC is defined as the ratio of the average magnitude of concentration fluctuations to the average concentration at a point, and the average of the values of I CONC across the diameter of the exit stream provided a direct quantitative measure of mixing performance. The data were sampled with a digital data acquisition system such that concentration fluctuations in the frequency range of 0.04 Hz to 10 Hz could be measured.

Sodium carboxymethylcellulose (CMC) solutions were injected into water streams at the entrance of 1/2 and 3/4 inch Kenics static mixers, a 1 inch Ross LPD mixer, and a 1 inch Ross ISG mixer. Five water flow rates ranging from 360 to 2080 ml/min and three different CMC flow rates ranging from 5 to 17 ml/min were used to determine I as a function of mix ratio (CMC flow rateiwater flow rate) and total flow rate. Also, four different CMC concentrations (1, 2, 3, and 4 wt. %) were used to determine the relationship between ICONC and viscosity ratio.

It was found that in all mixers ICON decreased with the onset of momentum turbulence and that at any given flow rate ICONC was generally greater with greater viscosity ratios. Also, the importance of mix ratio and viscosity ratio diminished as momentum turbulence developed.

ICONC was independent of flow rate in the Kenics mixers for laminar flow and was logarithmically related to the mix ratio. The slope of the line relating ICON to 1n(mix ratio) was a function of the viscosity ratio. ICONC was also found to be logarithmically related to mix ratio in the Ross ISG mixer, at high viscosity ratios, for any given flow rate, for both laminar and turbulent flow; although for laminar flow ICON increased with decreasing mix ratio and the trend reversed with turbulent flow.

Concentration and ICON profiles indicated that in the 3/4 Kenics mixer, CMC particles tended to migrate toward the center of each side of the mixer's elements. In the smaller Kenics mixer, the CMC stream tended to channel, undisturbed, through several mixer elements resulting in higher concentrations and turbulence on one side of the mixer. In the Ross LPD mixer, fluctuations were uniform across the diameter, but the concentrations were higher near the axis. In the Ross ISG mixer, the concentration profile became very flat at higher flow rates and fluctuation profiles were random.

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ABSTRACT

Concentration profiles were measured at intervals of 45 milliseconds in the exit streams of four inline motionless mixers using a ten position concentration probe array. These data were used to calculate a dimensionless parameter called the intensity of concentration turbulence, I_{CONC}, at ten positions across the diameter of the exit stream. I_{CONC} is defined as the ratio of the average magnitude of concentration fluctuations to the average concentration at a point, and the average of the values of I_{CONC} across the diameter of the exit stream provided a direct quantitative measure of mixing performance. The data were sampled with a digital data acquisition system such that concentration fluctuations in the frequency range of 0.04 Hz to 10 Hz could be measured.

Sodium carboxymethylcellulose (CMC) solutions were injected into water streams at the entrance of ½ and 3/4 inch Kenics static mixers, a 1 inch Ross LPD mixer, and a 1 inch Ross ISG mixer. Five water flow rates ranging from 360 to 2080 ml/min and three different CMC flow rates ranging from 5 to 17 ml/min were used to determine $\overline{I}_{CONC}$ as a function of mix ratio (CMC flow rate:water flow rate) and total flow rate. Also, four different CMC concentrations (1, 2, 3, and 4 wt. %) were used to determine the relationship between $\overline{I}_{CONC}$ and viscosity ratio.

It was found that in all mixers $\overline{I}_{CONC}$ decreased with the onset of momentum turbulence and that at any given flow rate $\overline{I}_{CONC}$ was generally greater with greater viscosity ratios. Also, the importance of mix ratio and viscosity ratio diminished as momentum turbulence developed.

$\overline{I}_{CONC}$ was independent of flow rate in the Kenics mixers for laminar flow and was logarithmically related to the mix ratio. The slope of the line relating $\overline{I}_{CONC}$ to ln(mix ratio) was a function of the viscosity ratio. $\overline{I}_{CONC}$ was also found to be logarithmically related to mix ratio in the Ross ISG mixer, at high viscosity ratios, for any given flow rate, for both laminar and turbulent flow; although for laminar flow $\overline{I}_{CONC}$ increased with decreasing mix ratio and the trend reversed with turbulent flow.

Concentration and I_{CONC} profiles indicated that in the 3/4 Kenics mixer, CMC particles tended to migrate toward the center of each side of the mixer's elements. In the smaller Kenics mixer, the CMC stream tended to channel, undisturbed, through several mixer elements resulting in higher concentrations and turbulence on one side of the mixer. In the Ross LPD mixer, fluctuations were uniform across the diameter, but the concentrations were higher near the axis. In the Ross ISG mixer, the concentration profile became very flat at higher flow rates and fluctuation profiles were random.

I. INTRODUCTION

A. Theory of Operation

Mixing is an important unit operation in the chemical process industries. There are many types of mixers, most of which involve some sort of rotating device. Since shortly before the beginning of this decade, a new class of mixing device has received some attention and application in the industry. The distinction between this class of mixer and all other mixing devices is that it utilizes no moving parts and requires no tank to perform the mixing operation As fluid flows through one of these in-line motionless mixers, the configurations of the mixer divert the flow field, so as to cause a mixing action.

Currently there are four motionless mixer designs on the market. Each of the mixers can be placed in a tube or pipe for in-line operation. Several articles have appeared in the literature (1, 3, 17, 21, 23, 31) which physically describe these mixers. Below is a brief description of each mixer:

1. Kenics Static Mixer

This is probably the most well known of the motionless mixers. Designed by the consulting firm of Arthur D. Little, Inc., and further refined and marketed by Kenics Corporation, the Static Mixer consists of a number of short right and left hand helices alternately welded together so that the leading edge of each helical element is oriented 90 degrees from the trailing edge of the preceeding element. The Kenics Static Mixer is shown in Figure I-1.

2. Ross ISG (Interfacial Surface Generator) Mixer

This mixer was developed by Dow Chemical Company and is manufactured and marketed under its license by Charles Ross & Sons Company. It consists of a number of identical elements placed in a pipe. A tetrahedral space is formed between adjoining elements. Four circular holes are machined through each element and the diameter on which the holes align is shifted 90 degrees both through each element and between successive elements. Also the two inner holes on the upstream side lead to the two outer holes on the downstream side of each element. A Ross ISG Mixer element is shown in Figure I-2.

3. Ross LPD (Low Pressure Drop) Mixer

This mixer was also developed by Dow and is manufactured and marketed by Charles Ross & Sons. It consists of a series of semi circular plates intersecting on a diagonal and welded to a rod which runs down the axis of the pipe. The end plates are then welded to the pipe wall so that, unlike the other three mixers, the Ross LPD mixer could not be removed from the flow system. The semi-circular plates were oriented to give alternate right and left hand motions as with the Kenics Static Mixer. Figure I-3 shows the configuration of the Ross LPD Mixer.

4. Koch Static Mixing System

This mixer was developed by the Sulzer Brothers of Winterthur, Switzerland and is marketed in the United States by Koch Engineering Company, Inc. It consists of a number of identical elements which are fitted into a conduit. Unlike the other mixers the Koch System may be placed into any shape of container, not just circular pipe. The elements consists of several layers of corrugated metal oriented so that the fluid is rotated 90^o between elements. The corrugation angle of adjacent layers in the element is reversed with respect to the mixer axis. Three Koch Static Mixing Elements are shown in Figure I-4.

The mechanism of mixing in these devices can be described by a combination of four processes (3, 6, 22, 31). These are:

1. Flow division: Each element divides the flow from the preceeding element. Hence, the number of divisions increases exponentially with the number of elements. For the Kenics Static Mixer and the Ross LPD Mixer the number of divisions, S, is given by the equation

$$S = 2^n \qquad \text{I-1}$$

where n is the number of elements. This action results from the fact that the flow is divided in half by each element. By a similar argument one could say that the number of divisions for the

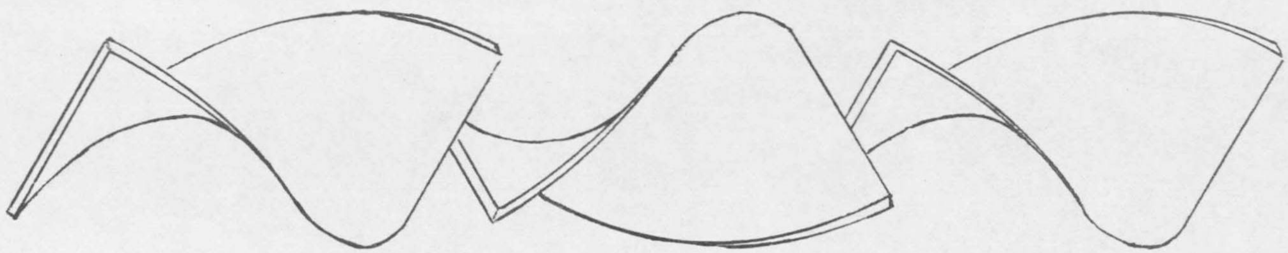

FIGURE I-1. SECTION OF KENICS STATIC MIXER