



Measurements of the intensity of concentration turbulence in inline motionless mixing systems
by Arthur Kirk McCready

A thesis submitted in partial fulfillment of the requirements for the degree of DOCTOR OF
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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_{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 I_{CONC} and viscosity ratio.

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

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 I_{CONC} to $\ln(\text{mix ratio})$ was a function of the viscosity ratio. 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 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.

MEASUREMENTS OF THE INTENSITY OF CONCENTRATION TURBULENCE
IN INLINE MOTIONLESS MIXING SYSTEMS

by

ARTHUR KIRK McCREADY

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of

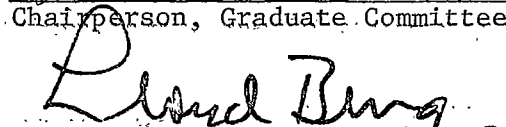
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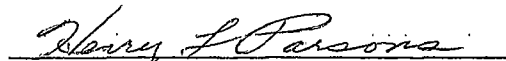
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TABLE OF CONTENTS

	<u>Page</u>
VITA	ii
ACKNOWLEDGEMENT.	iii
LIST OF TABLES	vii
LIST OF FIGURES.	ix
ABSTRACT	xiii
I. INTRODUCTION	1
A. THEORY OF OPERATION	1
1. KENICS STATIC MIXER	1
2. ROSS ISG MIXER.	2
3. ROSS LPD MIXER.	2
4. KOCH STATIC MIXING SYSTEM	3
B. APPLICATIONS.	9
C. PREVIOUS WORK	11
D. RESEARCH OBJECTIVES	13
II. TECHNICAL BACKGROUND	15
A. MEASURE OF MIXEDNESS.	15
B. CONCENTRATION MEASUREMENT	22
C. FREQUENCY CONSIDERATIONS.	23
D. FLUID PROPERTIES.	29
III. EQUIPMENT, MATERIALS, AND PROCEDURE.	33

	<u>Page</u>
A. SYSTEM OVERVIEW	33
B. CONDUCTIVITY MEASUREMENTS	33
C. FLOW SYSTEM	35
D. ANALOG INSTRUMENTATION.	41
E. DIGITAL INSTRUMENTATION	46
F. PROCEDURE OF DATA ACQUISITION	48
G. VISCOSITY MEASUREMENTS.	53
IV. EXPERIMENTAL RESULTS AND DISCUSSION.	57
A. THE DATA.	57
B. DISCUSSION OF THE KENICS STATIC MIXER	79
1. VISUAL OBSERVATIONS	79
2. AVERAGED INTENSITY OF CONCENTRATION TURBULENCE.	84
3. RADIAL DISTRIBUTIONS.	93
C. DISCUSSION OF THE ROSS LPD MIXER.	95
1. AVERAGED INTENSITY OF CONCENTRATION TURBULENCE.	95
2. RADIAL DISTRIBUTIONS.	104
D. DISCUSSION OF THE ROSS ISG MIXER.	106
1. AVERAGED INTENSITY OF CONCENTRATION TURBULENCE.	106
2. RADIAL DISTRIBUTIONS.	116

	<u>Page</u>
V. CONCLUSIONS AND RECOMMENDATIONS	117
A. CONCLUSIONS.	117
B. RECOMMENDATIONS.	119
VI. NOMENCLATURE.	122
VII. APPENDICES.	126
APPENDIX A - SIGNAL ELECTRONICS.	126
APPENDIX B - COMPUTER PROGRAM LISTINGS	134
APPENDIX C - DERIVATION OF CONCENTRIC CYLINDER VISCOMETRIC RELATIONSHIPS	150
VIII. BIBLIOGRAPHY.	155

LIST OF TABLES

<u>Table</u>	<u>Page</u>
III-1 ELECTRICAL CONDUCTIVITY DATA	36
III-2 MIXER SYSTEM SPECIFICATIONS.	38
III-3 SPACING OF PROBE TIP CENTERS, MEASURED IN INCHES FROM INSIDE TUBE WALL WHERE THE PROBE LEADS EXIT THE SYSTEM	43
III-4 CMC VISCOSITY PARAMETERS	53
IV-1 AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, \overline{I}_{CONC} , WITH WATER ONLY PASSING THROUGH THE MIXING SYSTEMS.	61
IV-2 AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, \overline{I}_{CONC} , IN $\frac{1}{2}$ " KENICS MIXER WITH 1% CMC SOLUTION.	62
IV-3 AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, \overline{I}_{CONC} , IN $\frac{1}{2}$ " KENICS MIXER WITH 2% CMC SOLUTION	64
IV-4 AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, \overline{I}_{CONC} , IN $\frac{1}{2}$ " KENICS MIXER WITH 3% CMC SOLUTION	65
IV-5 AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, \overline{I}_{CONC} , IN $\frac{1}{2}$ " KENICS MIXER WITH 4% CMC SOLUTION	66
IV-6 AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, \overline{I}_{CONC} , IN $\frac{3}{4}$ " KENICS MIXER WITH 1% CMC SOLUTION	67
IV-7 AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, \overline{I}_{CONC} , IN $\frac{3}{4}$ " KENICS MIXER WITH 2% CMC SOLUTION	68

<u>Table</u>	<u>Page</u>	
IV-8	AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I_{CONC}}$, IN 3/4" KENICS MIXER WITH 3% CMC SOLUTION	69
IV-9	AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I_{CONC}}$, IN 3/4" KENICS MIXER WITH 4% CMC SOLUTION	70
IV-10	AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I_{CONC}}$, IN ROSS LPD MIXER WITH 1% CMC SOLUTION.	71
IV-11	AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I_{CONC}}$, IN ROSS LPD MIXER WITH 2% CMC SOLUTION.	72
IV-12	AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I_{CONC}}$, IN ROSS LPD MIXER WITH 3% CMC SOLUTION.	73
IV-13	AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I_{CONC}}$, IN ROSS LPD MIXER WITH 4% CMC SOLUTION.	74
IV-14	AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I_{CONC}}$, IN ROSS ISG MIXER WITH 1% CMC SOLUTION.	75
IV-15	AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I_{CONC}}$, IN ROSS ISG MIXER WITH 2% CMC SOLUTION.	76
IV-16	AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I_{CONC}}$, IN ROSS ISG MIXER WITH 3% CMC SOLUTION.	77
IV-17	AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I_{CONC}}$, IN ROSS ISG MIXER WITH 4% CMC SOLUTION.	78
A-1	AMPLIFIER COMPONENT VALUES	133

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
I-1	SECTION OF KENICS STATIC MIXER.	4
I-2	ROSS ISG MIXING ELEMENT	5
I-3	SCHEMATIC REPRESENTATION OF A PORTION OF A ROSS LPD MIXER	6
I-4	KOCH STATIC MIXING ELEMENT.	7
II-1	TYPICAL WAVEFORM RESULTING FROM CONCENTRATION FLUCTUATIONS.	22
III-1	SYSTEM BLOCK DIAGRAM.	34
III-2	ELECTRICAL CONDUCTIVITY VERSUS CONCENTRATION FOR CMC SOLUTIONS	37
III-3	DETAIL OF CMC INJECTION NOZZLE.	40
III-4	SIGNAL PROCESSING BLOCK DIAGRAM	46
III-5	DEPTH CORRECTION FOR CONCENTRIC CYLINDER CONFIGURATION	56
IV-1	EXAMPLE OF DATA PRESENTATION.	59
IV-2	ORIENTATION OF PROBE ARRAY TO TRAILING EDGE OF LAST ELEMENT IN KENICS MIXERS (top view).	60
IV-3	\overline{I}_{CONC} VERSUS TOTAL FLOW RATE IN 3/4" KENICS STATIC MIXER AT LOW CMC INJECTION RATE (5.1 to 5.4 ml/min)	83
IV-4	\overline{I}_{CONC} VERSUS TOTAL FLOW RATE IN 3/4" KENICS STATIC MIXER WHILE INJECTING 3% CMC SOLUTION ($\lambda=2074$).	86

<u>Figure</u>		<u>Page</u>
IV-5	\overline{I}_{CONC} VERSUS MIX RATIO FOR 3/4" KENICS STATIC MIXER. . .	87
IV-6	\overline{I}_{CONC} VERSUS MIX RATIO FOR 1/2" KENICS STATIC MIXER. . .	89
IV-7	\overline{I}_{CONC} VERSUS TOTAL FLOW RATE IN 1/2" KENICS STATIC MIXER WHILE INJECTING 3% CMC SOLUTION ($\lambda=2024$)	90
IV-8	\overline{I}_{CONC} VERSUS TOTAL FLOW RATE IN 1/2" KENICS STATIC MIXER WHILE INJECTING 2% CMC SOLUTION ($\lambda=266$).	91
IV-9	\overline{I}_{CONC} VERSUS TOTAL FLOW RATE IN 1/2" KENICS STATIC MIXER AT LOW CMC INJECTION RATE (5.1 to 5.4 ml/min).	92
IV-10	TYPICAL CONCENTRATION TURBULENCE PROFILE BELOW 3/4" KENICS MIXER	94
IV-11	TYPICAL CONCENTRATION PROFILE BELOW 3/4" KENICS MIXER WHILE INJECTING 3% AND 4% CMC SOLUTION	94
IV-12	\overline{I}_{CONC} VERSUS TOTAL FLOW RATE IN ROSS LPD MIXER WHILE INJECTING 2% CMC SOLUTION ($\lambda=266$).	96
IV-13	\overline{I}_{CONC} VERSUS TOTAL FLOW RATE IN ROSS LPD MIXER WHILE INJECTING 4% CMC SOLUTION ($\lambda=13250$).	98
IV-14	\overline{I}_{CONC} VERSUS MIX RATIO FOR ROSS LPD MIXER.	100
IV-15	\overline{I}_{CONC} VERSUS TOTAL FLOW RATE IN ROSS LPD MIXER AT LOW CMC SOLUTION (5.3 to 5.8 ml/min)	101
IV-16	\overline{I}_{CONC} VERSUS TOTAL FLOW RATE IN ROSS LPD MIXER AT MIDDLE CMC INJECTION RATE (9.1 to 10.3 ml/min)	102

<u>Figure</u>	<u>Page</u>
IV-17	$\overline{I}_{\text{CONC}}$ VERSUS TOTAL FLOW RATE IN ROSS LPD MIXER AT HIGH CMC INJECTION (14.0 to 17.4 ml/min) 103
IV-18	TYPICAL CONCENTRATION PROFILE BELOW THE ROSS LPD MIXER. 105
IV-19	TYPICAL INTENSITY OF CONCENTRATION TURBULENCE PROFILE BELOW THE ROSS LPD MIXER 105
IV-20	$\overline{I}_{\text{CONC}}$ VERSUS TOTAL FLOW RATE IN ROSS ISG MIXER WHILE INJECTING 2% CMC SOLUTION ($\lambda=266$) 107
IV-21	$\overline{I}_{\text{CONC}}$ VERSUS TOTAL FLOW RATE IN ROSS ISG MIXER WHILE INJECTING 3% CMC SOLUTION ($\lambda=2074$) 108
IV-22	$\overline{I}_{\text{CONC}}$ VERSUS MIX RATIO FOR ROSS ISG MIXER. 110
IV-23	$\overline{I}_{\text{CONC}}$ VERSUS TOTAL FLOW RATE IN ROSS ISG MIXER AT LOW CMC INJECTION RATE (5.0 to 5.7 ml/min) 112
IV-24	$\overline{I}_{\text{CONC}}$ VERSUS TOTAL FLOW RATE IN ROSS ISG MIXER AT MIDDLE CMC INJECTION RATE (7.2 to 10.0 ml/min) 113
IV-25	$\overline{I}_{\text{CONC}}$ VERSUS TOTAL FLOW RATE IN ROSS ISG MIXER AT HIGH CMC INJECTION RATE (14.7 to 16.8 ml/min) 114
A-1	TYPICAL SIGNAL AMPLIFIER AND DEMODULATOR 128
A-2	CIRCUIT PROVIDING THE VARIOUS LEVELS USED IN THE SIGNAL PROCESSING 128
A-3	PEAK DETECTOR TRANSFER FUNCTION. 131

<u>Figure</u>		<u>Page</u>
C-1	PLOT USED TO DETERMINE PHYSICAL PARAMETERS OF A POWER LAW FLUID WITH A CONCENTRIC CYLINDER VISCOMETER . . .	154

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.

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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

preceding 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° 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

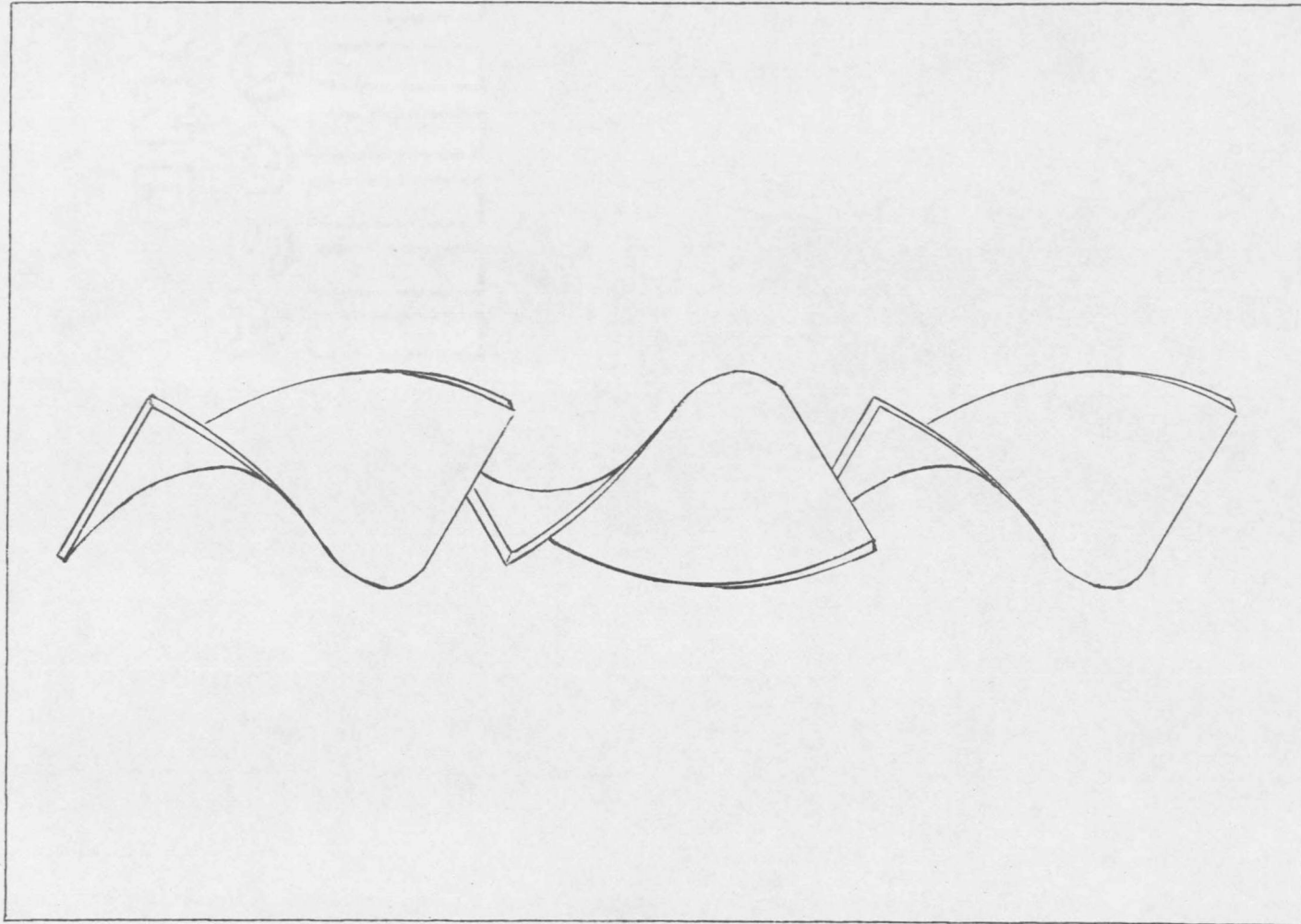


FIGURE I-1. SECTION OF KENICS STATIC MIXER

