



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
PHILOSOPHY in Chemical Engineering
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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 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

A thesis submitted in partial fulfillment
of the requirements for the degree

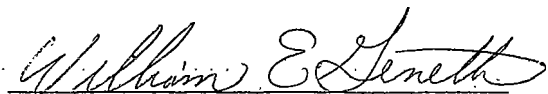
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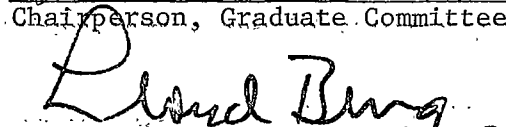
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ABSTRACT

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 $\frac{1}{2}$ and $\frac{3}{4}$ 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 $\frac{3}{4}$ 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° 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

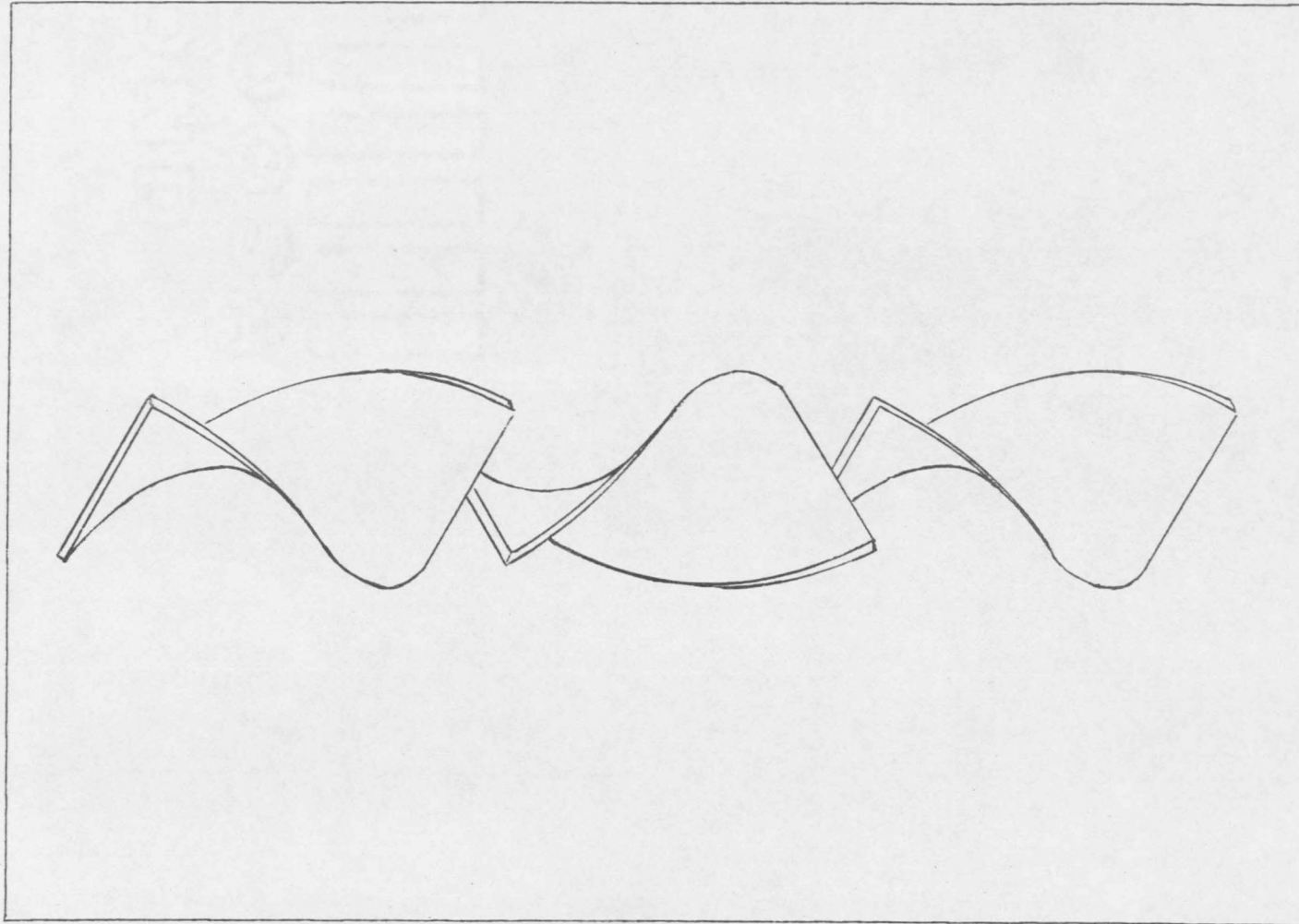


FIGURE I-1. SECTION OF KENICS STATIC MIXER

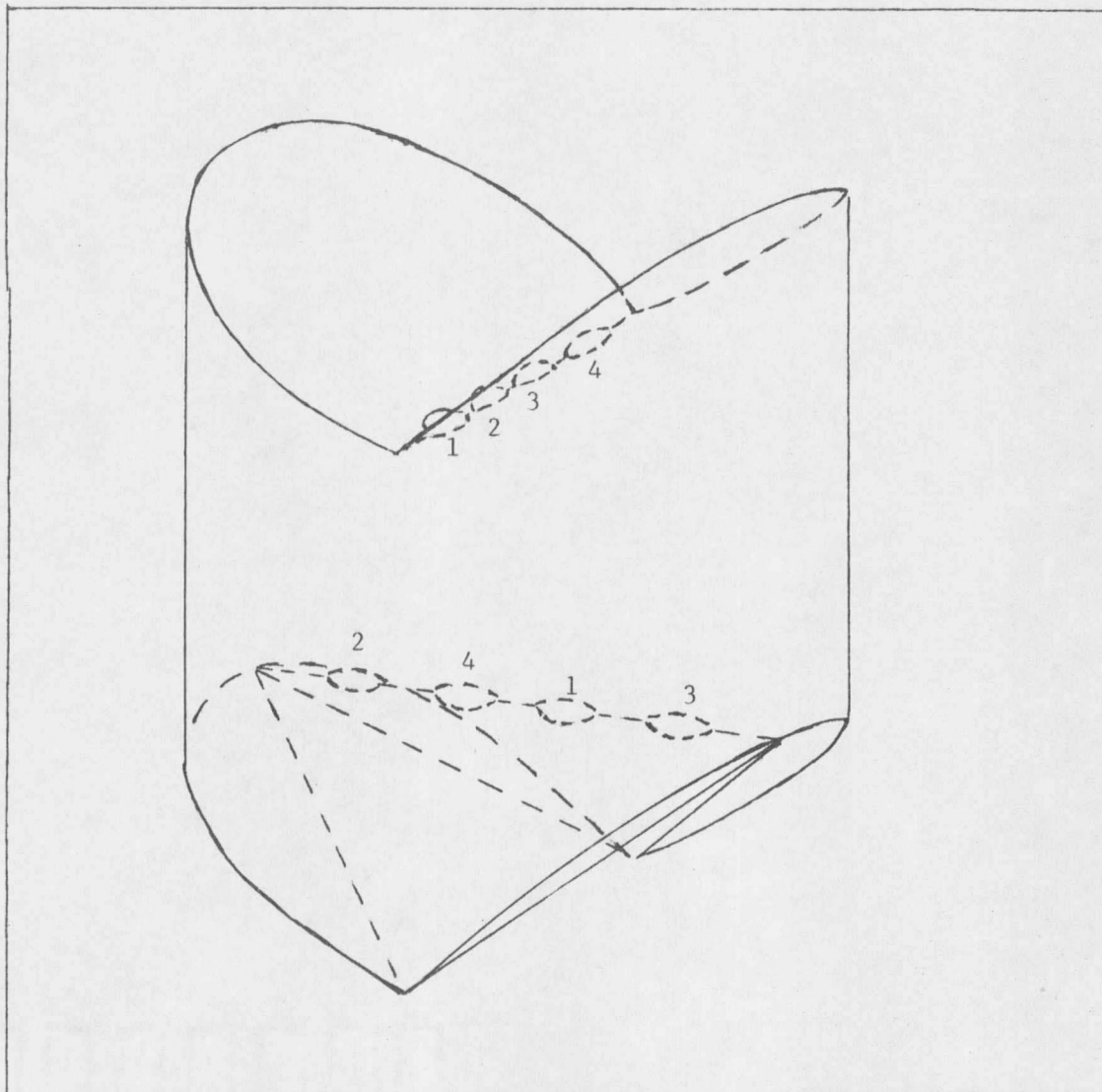


FIGURE I-2. ROSS ISG MIXING ELEMENT

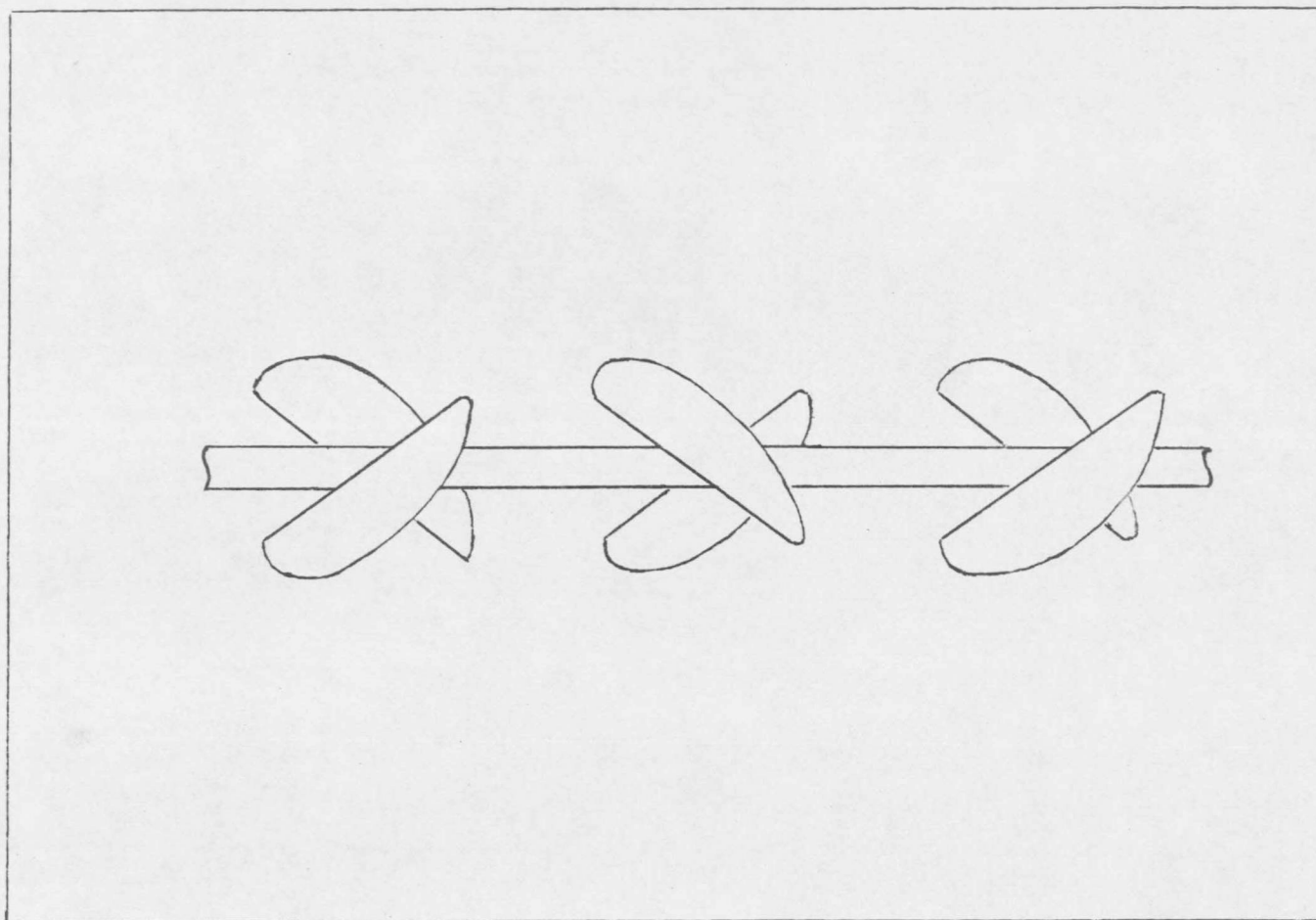


FIGURE I-3. SCHEMATIC REPRESENTATION OF A PORTION OF A ROSS LPD MIXER

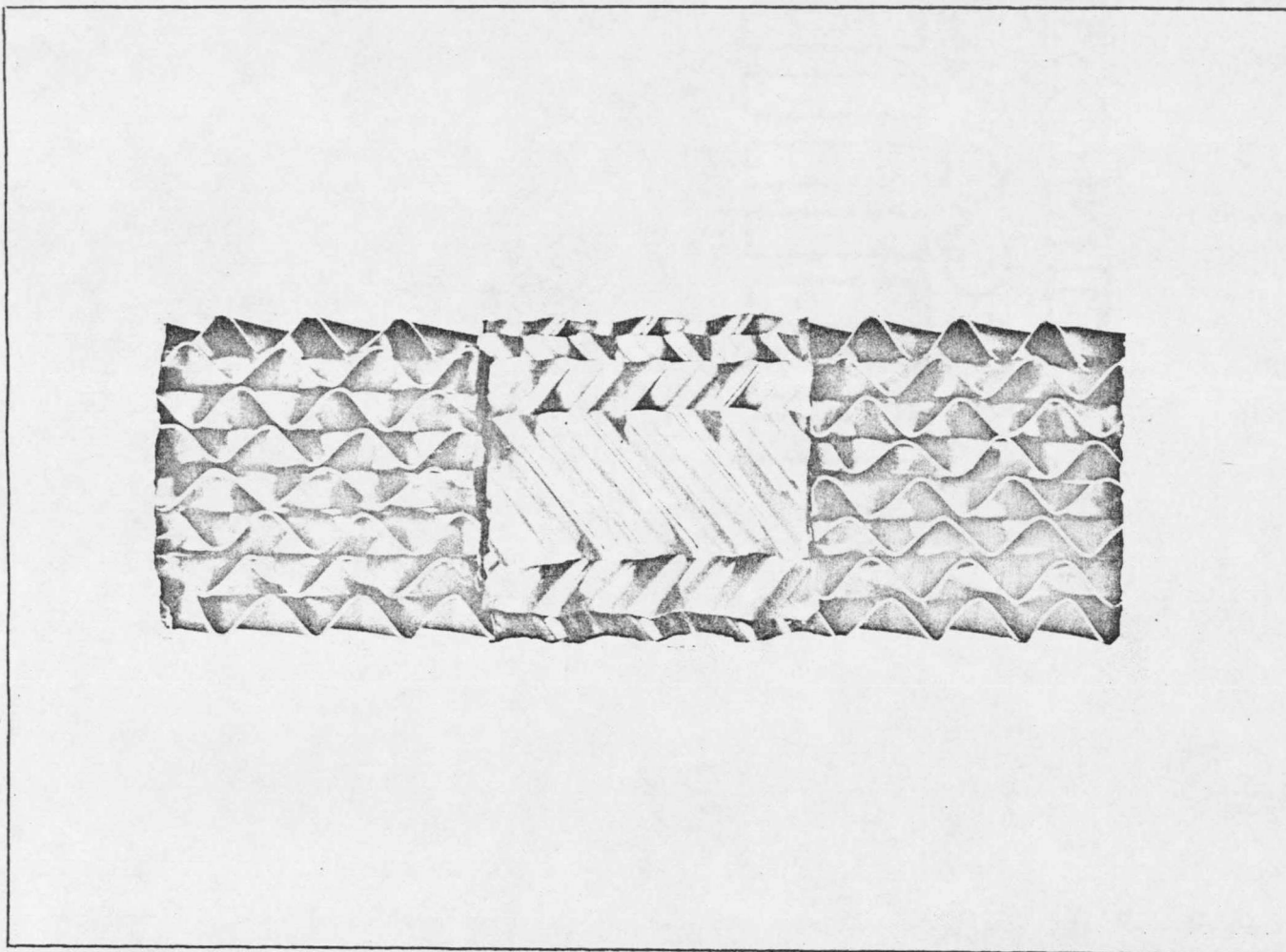


FIGURE I-4. KOCH STATIC MIXING ELEMENTS. REPRODUCED WITH PERMISSION FROM KOCH ENGINEERING COMPANY, INC.

Ross ISG mixer is given by the relation

$$S = 4^n \quad \text{I-2}$$

since each element divides the flow into four streams. Equation I-2 is probably only an approximation, however, because of the tetrahedral chamber between successive elements which results in the recombination of the four streams exiting an element before the stream is redivided. For the Koch Static Mixing System, the number of layers formed can be predicted by equation I-3,

$$S = \frac{m}{2} (2m)^{n-1} \quad \text{I-3}$$

where m is the number of corrugations per element (26).

2. Flow reversal: The configuration of adjacent elements causes the direction of flow to alternate. In the Ross LPD and the Kenics Static mixers the circular flow alternates because of the alternate right and left hand element configuration. In the Koch system the flow path is rotated 90 degrees upon encountering each element. In the Ross ISG mixer, the fact that the diameter on which the holes on the exit align are displaced 90 degrees from the diameter of the entrance holes probably contributes to this mixing action between elements, but, because each element of the Ross ISG mixer is identical, this action is probably not as important in that mixer.

3. Flow inversion: This action causes particles to travel

from the tube center to the wall and back. In the Kenics mixer this action makes heat transfer units 60-300% more efficient than straight tubing. It is also responsible for the self-cleaning, anti-fouling properties of the Kenics Static and Ross LPD mixer. This flow action is even more pronounced in the Koch System.

This action is not as important with the Ross ISG mixer. Its heat transfer properties come from the large amount of surface area in the mixer in which the fluid contacts a surface with a high thermal conductivity.

4. Back mixing: This action is especially important in the Ross ISG mixer. Upon encountering each new element the relative particle velocity is constantly changing and the velocity profile changes giving both an axial and a lateral mixing action. This action is probably the main reason that constituents injected in controlled cyclical pulses mix as evenly as those injected continuously. Hence these mixers are good for evening out minor feed fluctuations.

B. Applications

Some applications of these mixers are:

Heat exchange (8, 10, 11, 23, 25) where improvement of 300% in inner film coefficients have been observed and scaling and crystallization problems have been eliminated.

Single and multiphase reactions, where, because plug flow is

approached, multistage reactions are often unnecessary; for reactions requiring a certain order of reagent addition, the proper reagent is simply injected at the proper point of reaction. Also, with more complete mixing the reactions take less time so retention time is reduced.

Catalytic reforming, where the mixers prevent hot spots and subsequent catalyst deterioration, allowing the process to be carried out at higher temperatures with higher yields.

Polymerization processes (6, 8, 22, 23) especially with simultaneous heating or cooling, where the unique mixing action lessens the danger of thermal damage to temperature sensitive liquids by eliminating hot spots. This also helps in overcoming the control problems caused by high heats of polymerization and the often low thermal conductivities of polymer melts. Also, the problem of mixing inhibitors or additives of much different viscosity than the main stream fluid and often in very low mass ratios, can be solved with these mixers.

Gas-liquid contacting (19, 31) resulting in more economical aeration of water and possibly a clinically safe blood oxygenator.

Liquid-liquid mixing (6, 8, 9, 19, 22, 24, 31) of miscible or immiscible fluids, high viscosity fluids, and fluids of vastly different viscosities and mix ratios.

Liquid-solid mixing (3), where there is no change in composition from inlet to exit, the exit composition is uniform, and the problems previously involved in the operation (e.g., height of suspension, tank bottom motion, filleting, settling) no longer apply.

Solid-solid mixing (7, 15, 28) of fertilizers, grains and catalysts.

C. Previous Work

Although using these motionless mixers can provide superior performance in many applications, the mechanism of mixing is not fully understood. Work supported by the mixers' manufacturers (6, 25, 31) has yielded valuable information concerning energy requirements, heat transfer and residence time distributions. T. Tung and R. Laurence (27) performed a residence time distribution study with the Kenics Static Mixer. Work done at Lowell Technological Institute (22, 23) has yielded some pressure drop, thermal homogenation, heat transfer and color dispersion information with the Koch Static Mixing System.

Besides the above mentioned studies, other work has been done in the area of heat transfer with motionless mixers, especially the Kenics Static Mixer. Grace (11) provides correlations, experimental heat transfer coefficients and pressure drop correlations: Genetti and Priebe (10) used their own data and the data of Sununu (25) to obtain correlations for heat transfer coefficients, pressure drop

and j factor. Morris and Mission (19) investigated mass transfer and flow resistance in the Kenics Static Mixer.

Although these studies have yielded valuable information about the transport phenomena involved with these mixers, very little work has been done to quantitatively evaluate the performance of these systems as mixers. Some studies (7, 15, 28) have given information on the mixing of solid particles, but the work done to determine the mixing characteristics in combining fluids of highly different viscosities and/or mix ratios consists of a single Masters' thesis at Montana State University. In this study, Fyock (9) combined various concentrations of sodium carboxymethylcellulose (CMC) with water in a Kenics Static mixer at various flow rates and evaluated mixing performance in terms of "criteria levels" which corresponded to magnitudes in the levels of concentration fluctuations measured with a conductivity probe. This study, however, produced some rather questionable results, probably due to magnitude of noise in the electronics and variations in the flow system (flow rates and temperatures) during the runs. Also, the rate at which data could be acquired in the study was fixed by the teleprinter used as an output device. This meant that the highest data rate possible was about 1.5 samples per

second. However, since the corner¹ frequency on the low pass filter he used was 3.3 KHz, the significance of his sampled data is questionable because the sampling rate was far below the Nyquist rate.

D. Research Objectives

Because an understanding of the mixing characteristics of these mixers, especially under the adverse conditions of high viscosity and mix ratios, would be valuable to anyone wishing to apply one of the systems and because so little work has been done in the area, the present project was initiated.

The objective of the work is to quantitatively evaluate the mixing performance and limitations of three motionless mixer designs as a function of flow rate, mix ratio and viscosity ratio. Also it was desired to determine if the degree of mixing was a function of the radial position in the tube at the outlet of the mixer section. The three mixers studied were the Ross ISG, the Ross LPD, and the Kenics Static Mixer. Since two different sizes of Kenics mixers were used, the study also provides some scale-up information.

In order to meet the objectives of the study, it was necessary to develop a method of measuring "mixedness" and a system capable of

¹Also called the half power or 3 dB frequency, the corner frequency is the frequency at which the voltage output from the low pass filter is 0.707 times the voltage output at a lower frequency in the pass band. Frequencies above the corner frequency are further attenuated, resulting in the effect of filter passing essentially the frequencies below the corner frequency.

acquiring the data necessary to make the measurements. It was also required that the data acquisition system be general purpose so that it could easily be used for other studies.

II. TECHNICAL BACKGROUND

A. Measure of Mixedness

How does one measure mixedness? The reason that mixing is such a difficult operation to study is that there is no method of measuring mixedness that can be used even in a majority of mixing situations. The results of mixing studies usually depend on how mixing is defined by the experimenter, and all too often the results of these studies are far from reproducible.

The most frequent method of studying mixing is visual; for example: color change of an indicator in liquid-liquid mixing and interference phenomena to follow the blending of gases. For inline mixers one often finds photographs of cross sections at several positions down the axis of a mixer, through which two different colored fluids are being pumped. The trouble with visual methods is that they are either difficult or expensive to quantitatively evaluate.

Before a quantitative measure of mixedness can be obtained it is necessary to define mixing. For this study a suitable definition is: mixing is the physical integration of constituents with different physical properties into a blend with more uniform properties. This definition, of course, assumes that no reactions are occurring. It includes all physical properties (temperature, concentrations, color, density, etc.).

Uniformity is the key measure of mixedness. Using the above definition of mixing one can define perfectly mixed, in a continuous

mixer, as the total absence of variation of any physical property with respect to position and, with steady inputs, with respect to time. Then a measure of the degree of mixedness can be determined in terms of the magnitude of deviations in a mix's physical properties, with respect to position and time. Since it would be impossible to measure all of a mix's physical properties with respect to position or time it is necessary to modify the definition of perfect mixing so that a meaningful measure of mixedness can be obtained for the system being studied. In the mixing of liquids, chemical engineers are usually most concerned about achieving uniform concentration in the mix. Then perfect mixing could be defined as the absence of variations in a mix's concentration with respect to position and time.

Hence, for a perfectly mixed solution

$$C_i(x,y,z,t) = \bar{C}_i = \text{constant} \quad \text{II-1}$$

where C_i is the concentration of component i of a multicomponent system. Equation II-1 should hold true for all time and positions in the fluid.

Equation II-1 expresses an ideal situation; one that can only be approached in real systems. If one were to monitor the concentration of some component at a point (x_1, y_1, z_1) in the outlet stream of a continuous mixing system, the concentration could be described by the following equation:

$$C_i(x_1, y_1, z_1, t) = \bar{C}_i(x_1, y_1, z_1, t) + C'_i(x_1, y_1, z_1, t) \quad \text{II-2}$$

where $\bar{C}_i$ is the local average concentration, over some period of time as given by the following definition:

$$\bar{C}_i = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} C_i(x_1, y_1, z_1, t) dt \quad \text{II-3}$$

C'_i is the instantaneous deviation in concentration from $\bar{C}_i$. Hence, C'_i will have both negative and positive values such that

$$\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} C'_i(x_1, y_1, z_1, t) dt = 0 \quad \text{II-4}$$

If the mixing system has inputs that are steady with time, $\bar{C}_i$ will not be a function of time and the concentration at the point can be described by the relation

$$C_i(x_1, y_1, z_1, t) = \bar{C}_i(x_1, y_1, z_1) + C'_i(x_1, y_1, z_1, t) \quad \text{II-5}$$

Equation II-5 will be used to describe the concentration at a point for this study, because all inputs were steady.

Because all concentration measurements taken in this study were at fixed points as a function of time, it will no longer be necessary to indicate the concentrations as functions of position and time. All that is necessary is to indicate the position. Also this study involved the mixing of an ionic polymer with water. Since there are only two components, for the remainder of this paper, C will indicate the concentration of the polymer; so the subscript i can be dropped.

Hence Equation II-5 can be rewritten

$$C_1 = \bar{C}_1 + C'_1 \quad \text{II-5}$$

where the subscript 1 denotes the position (x_1, y_1, z_1) .

Because C' has an average value of zero, it is desirable to express the magnitude of C' in terms of a root mean square value.

C'_{rms} , given by

$$C'_{\text{rms}} = \left(\frac{1}{t} \int_0^t C'^2 dt \right)^{1/2} \quad \text{II-6}$$

represents the value of the average fluctuation from $\bar{C}$. C'_{rms} will be some fraction of this average concentration. This fraction is an important factor and is a measure of the degree of mixedness. The fraction can be called the intensity of concentration turbulence and is defined as

$$I_{\text{CONC}} \equiv \frac{C'_{\text{rms}}}{\bar{C}} \quad \text{II-7}$$

The velocity in direction k at a point is given by

$$v_k = \bar{v}_k + v'_k \quad \text{II-8}$$

The equation of continuity of the polymer, with no reaction occurring is

$$\frac{\partial C}{\partial t} = - \left(\frac{\partial}{\partial x} v_x C + \frac{\partial}{\partial y} v_y C + \frac{\partial}{\partial z} v_z C \right) + D \nabla^2 C \quad \text{II-9}$$

Assuming that molecular diffusion is much slower than convective diffusion makes the last term of equation II-9 negligible and yields

equation II-10.

$$-\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} v_x C + \frac{\partial}{\partial y} v_y C + \frac{\partial}{\partial z} v_z C \quad \text{II-10}$$

Substituting equations II-5 and II-8 into II-10 gives

$$\begin{aligned} -\frac{\partial (\bar{C} + C')}{\partial t} &= \frac{\partial}{\partial x} (\bar{v}_x + v'_x) (\bar{C} + C') + \frac{\partial}{\partial y} (\bar{v}_y + v'_y) (\bar{C} + C') \\ &+ \frac{\partial}{\partial z} (\bar{v}_z + v'_z) (\bar{C} + C') \end{aligned} \quad \text{II-11}$$

With steady inputs $\bar{C} = \text{constant}$, hence $\frac{\partial \bar{C}}{\partial t} = 0$. Therefore, expanding equation II-11 gives

$$\begin{aligned} -\frac{\partial C'}{\partial t} &= \frac{\partial}{\partial x} (\bar{v}_x \bar{C} + v'_x \bar{C} + \bar{v}_x C' + v'_x C') + \frac{\partial}{\partial y} (\bar{v}_y \bar{C} + v'_y \bar{C} + \bar{v}_y C' + v'_y C') \\ &+ \frac{\partial}{\partial z} (\bar{v}_z \bar{C} + v'_z \bar{C} + \bar{v}_z C' + v'_z C') \end{aligned} \quad \text{II-12}$$

Multiplying both sides of equation II-12 by $\frac{C'}{\bar{C}^2}$ yields the relation

$$\begin{aligned} -\frac{\partial}{\partial t} \left(\frac{C'^2}{\bar{C}^2} \right) + C' \frac{\partial}{\partial t} \left(\frac{C'}{\bar{C}^2} \right) &= \frac{\partial}{\partial x} \left(\frac{\bar{v}_x C'}{\bar{C}} + \frac{v'_x C'}{\bar{C}} + \frac{\bar{v}_x C'^2}{\bar{C}^2} + \frac{v'_x C'^2}{\bar{C}^2} \right) \\ &+ \frac{\partial}{\partial y} \left(\frac{\bar{v}_y C'}{\bar{C}} + \frac{v'_y C'}{\bar{C}} + \frac{\bar{v}_y C'^2}{\bar{C}^2} + \frac{v'_y C'^2}{\bar{C}^2} \right) + \frac{\partial}{\partial z} \left(\frac{\bar{v}_z C'}{\bar{C}} + \frac{v'_z C'}{\bar{C}} + \frac{\bar{v}_z C'^2}{\bar{C}^2} \right. \\ &\left. + \frac{v'_z C'^2}{\bar{C}^2} \right) - (\bar{v}_x \bar{C} + v'_x \bar{C} + \bar{v}_x C' + v'_x C') \frac{\partial}{\partial x} \left(\frac{C'}{\bar{C}^2} \right) - (\bar{v}_y \bar{C} + v'_y \bar{C} \\ &+ \bar{v}_y C' + v'_y C') \frac{\partial}{\partial y} \left(\frac{C'}{\bar{C}^2} \right) - (\bar{v}_z \bar{C} + v'_z \bar{C} + \bar{v}_z C' + v'_z C') \\ &\frac{\partial}{\partial z} \left(\frac{C'}{\bar{C}^2} \right) \end{aligned} \quad \text{II-13}$$

Time smoothing equation II-13, and incorporating the fact that $\bar{C}' = \bar{v}_k' = 0$ by definition,

$$\begin{aligned}
 -\frac{\partial}{\partial t} \frac{\overline{C'^2}}{\bar{C}^2} &= \frac{\partial}{\partial x} \left(\frac{\overline{\bar{v}_x' C'^2}}{\bar{C}^2} + \frac{\overline{\bar{v}_x' C'}}{\bar{C}} + \frac{\overline{\bar{v}_x' C'^2}}{\bar{C}^2} \right) + \frac{\partial}{\partial y} \left(\frac{\overline{\bar{v}_y' C'^2}}{\bar{C}^2} \right. \\
 &\quad \left. + \frac{\overline{\bar{v}_y' C'}}{\bar{C}} + \frac{\overline{\bar{v}_y' C'^2}}{\bar{C}^2} \right) + \frac{\partial}{\partial z} \left(\frac{\overline{\bar{v}_z' C'^2}}{\bar{C}^2} + \frac{\overline{\bar{v}_z' C'}}{\bar{C}} + \frac{\overline{\bar{v}_z' C'^2}}{\bar{C}^2} \right)
 \end{aligned} \quad \text{II-14}$$

But, by definition, $\overline{C'^2} = (C'_{\text{rms}})^2$. Utilizing this fact and substituting equation II-7 into II-14 gives

$$\begin{aligned}
 -\frac{\partial}{\partial t} (I_{\text{CONC}}^2) &= \frac{\partial}{\partial x} \left(\bar{v}_x' I_{\text{CONC}}^2 + \frac{\overline{\bar{v}_x' C'}}{\bar{C}} + \frac{\overline{\bar{v}_x' C'^2}}{\bar{C}^2} \right) + \frac{\partial}{\partial y} \left(\bar{v}_y' I_{\text{CONC}}^2 \right. \\
 &\quad \left. + \frac{\overline{\bar{v}_y' C'}}{\bar{C}} + \frac{\overline{\bar{v}_y' C'^2}}{\bar{C}^2} \right) + \frac{\partial}{\partial z} \left(\bar{v}_z' I_{\text{CONC}}^2 + \frac{\overline{\bar{v}_z' C'}}{\bar{C}} + \frac{\overline{\bar{v}_z' C'^2}}{\bar{C}^2} \right)
 \end{aligned} \quad \text{II-15}$$

But I_{CONC} should not vary with time with steady inputs. Hence

$$\begin{aligned}
 \frac{\partial}{\partial x} \left(\bar{v}_x' I_{\text{CONC}}^2 + \frac{\overline{\bar{v}_x' C'}}{\bar{C}} + \frac{\overline{\bar{v}_x' C'^2}}{\bar{C}^2} \right) &+ \frac{\partial}{\partial y} \left(\bar{v}_y' I_{\text{CONC}}^2 + \frac{\overline{\bar{v}_y' C'}}{\bar{C}} + \frac{\overline{\bar{v}_y' C'^2}}{\bar{C}^2} \right) \\
 + \frac{\partial}{\partial z} \left(\bar{v}_z' I_{\text{CONC}}^2 + \frac{\overline{\bar{v}_z' C'}}{\bar{C}} + \frac{\overline{\bar{v}_z' C'^2}}{\bar{C}^2} \right) &= 0
 \end{aligned} \quad \text{II-16}$$

Equations II-15 and II-16 show that I_{CONC} is not only a function of position, but that its magnitude depends on average velocities in all directions and interactive product terms of the instantaneous velocity and concentration fluctuations. It should also be noted that every term contains some form of the ratio $\frac{C'}{\bar{C}}$. This emphasizes the

fact that the intensity of concentration fluctuations is not proportional to the magnitude of the fluctuations but rather the ratio of the magnitude of the fluctuations to the average concentration.

Because of the interactive velocity terms in equation II-16, one would expect that the degree of mixedness, indicated by the magnitude of I_{CONC} , depends not only on inlet concentrations, but also the instantaneous stresses in the fluid. For a turbulent flow situation a time-smoothed equation of motion can be used. This is the same time-smoothing operation that was used to form equation II-14. Using vector notation, the time-smoothed equation of motion can be written

$$\rho \frac{D\bar{v}}{Dt} = -\nabla\bar{p} - \nabla \cdot \bar{\tau} - \nabla \cdot \bar{\tau}^t + \rho g \quad \text{II-17}$$

$\bar{\tau}$ is the time-smoothed average momentum flux tensor. For example, components of $\bar{\tau}$ for an incompressible fluid are:

$$\bar{\tau}_{xx} = -2\eta \frac{\partial \bar{v}_x}{\partial x}, \quad \bar{\tau}_{yx} = \bar{\tau}_{xy} = -\eta \left(\frac{\partial \bar{v}_x}{\partial y} + \frac{\partial \bar{v}_y}{\partial x} \right), \quad \bar{\tau}_{yz} = \bar{\tau}_{zy}$$

$$= -\eta \left(\frac{\partial \bar{v}_y}{\partial z} + \frac{\partial \bar{v}_z}{\partial y} \right) \text{ etc., where } \eta \text{ is the viscosity. } \bar{\tau}^t \text{ is the}$$

time-smoothed turbulent momentum flux tensor. Components of $\bar{\tau}^t$ are:

$$\bar{\tau}_{xx}^t = \rho \overline{v'_x v'_x}, \quad \bar{\tau}_{xy}^t = \rho \overline{v'_x v'_y}, \quad \bar{\tau}_{yz}^t = \rho \overline{v'_y v'_z}, \text{ etc., and are usually called the Reynolds stresses.}$$

The major difference between these stresses is that the molecular contribution is expressed in terms of a fluid property,

viscosity, and a derivative of a mean velocity, while the turbulent contribution is expressed in terms of the fluctuating properties of the flow, the momentum fluctuations.

The molecular contribution will depend on the viscosities of the inlet fluids and their flow rates. The Reynolds stresses, however, will depend almost solely on the configurations of the mixer. For turbulent flows, the magnitude of the Reynolds stress is much greater than the molecular contribution except near the walls.

Hence, the parameters that affect the degree of mixing are the inlet concentrations, the inlet flow rates, the viscosity of the inlet streams, and the configurations of the mixer. In this study, the intensity of concentration turbulence was determined at ten positions across the diameter of the tube, about an inch below the exit of the mixers, for various flow rates, inlet polymer concentrations and polymer viscosities. The performance of the mixer was then evaluated by the average of the ten values of I_{CONC} . The lower the value of I_{CONC} the better the mixing.

B. Concentration Measurement

The concentration of a component in a fluid at a point is a difficult thing to measure directly. Because of this, concentration is usually determined by measuring some fluid property that is directly related to concentration. For this study it was decided to mix an ionic polymer, sodium carboxymethylcellulose (CMC), with

water. It was determined experimentally that the electrical conductivity of CMC solutions was directly related to the CMC concentration. This relationship is shown graphically in Figure III-2. The relationship was approximately linear for solutions of CMC with deionized water of concentrations from 0.2% to at least 3.5% and could be expressed by the equation

$$\sigma = .01925 + .04962C \quad \text{II-18}$$

where σ is the electrical conductivity in millimhos per meter and C is the CMC concentration in weight percent.

The probes and probe electronics used in the study were constructed to produce a d.c. output voltage directly proportional to the electrical conductivity, and hence the CMC concentration, of the fluid immediately surrounding the probe tip.

C. Frequency Considerations

Figure II-1 illustrates the concentration versus time waveform that might typically be found at a point at the exit of one of the motionless mixers. Because the probe electronics outputs a voltage directly proportional to the CMC concentration, Figure II-1 also illustrates a typical waveform output from the signal electronics. Only the scale and units of the ordinate need to be altered.

Any concentration or voltage waveform that can actually be produced can be described as a periodic function. Given a function $f(t)$ such that

$$f(t) = f(t + T), \quad \text{II-19}$$

$f(t)$ is a periodic function with a period T . The Fourier theorem states that a periodic function $f(t)$ can be represented by the infinite series

$$f(t) = a_0 + \sum_{n=1}^{\infty} (a_n \cos n\omega_0 t + b_n \sin n\omega_0 t) \quad \text{II-20}$$

where the fundamental frequency ω_0 is related to the period T by

$$\omega_0 = \frac{2\pi}{T} \quad \text{II-21}$$

It can be shown that

$$a_0 = \frac{1}{T} \int_0^T f(t) dt \quad \text{II-22}$$

Hence a_0 is simply the average value of $f(t)$ over a period. This corresponds to the d.c. voltage component, V_0 , or the average concentration, $\bar{C}$. Also

$$a_k = \frac{2}{T} \int_0^T f(t) \cos k\omega_0 t dt \quad \text{II-23}$$

$$b_k = \frac{2}{T} \int_0^T f(t) \sin k\omega_0 t dt \quad \text{II-24}$$

where a_k and b_k are the amplitudes of the waveform at the frequency $k\omega_0$.

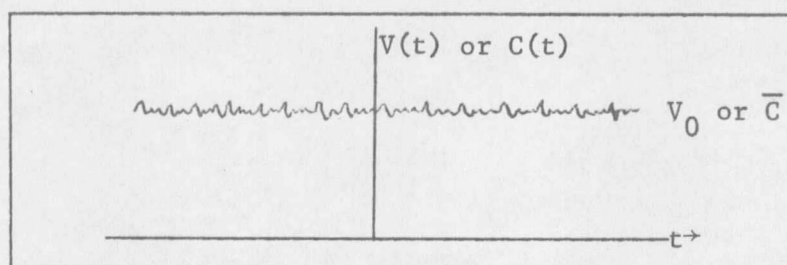


FIGURE II-1. TYPICAL WAVEFORM RESULTING FROM CONCENTRATION FLUCTUATIONS

The waveform shown in Figure II-1 can be described by

$$V(t) = V_0 + \sum_{n=1}^{\infty} (a_n \cos n\omega_0 t + b_n \sin n\omega_0 t) \quad \text{II-25}$$

where values of a_n and b_n for specific $n=j$ are given by equation II-23 and II-24 respectively, with $f(t) = V(t)$.

For any waveform that can be physically produced, the values of the coefficients a_n and b_n become very small as n becomes very large. Because of this, an accurate representation of a function can be obtained without having to evaluate an infinite number of terms. Hence a reasonably accurate representation of the function $V(t)$ can be obtained from the equation

$$V(t) = V_0 + \sum_{n=1}^q (a_n \cos n\omega_0 t + b_n \sin n\omega_0 t) \quad \text{II-26}$$

This is the mathematical equivalent of putting the function $V(t)$ through a "low pass" filter. The highest frequency component allowed to pass, $\omega_{\max}$, is given by

$$\omega_{\max} = q\omega_0 \quad \text{II-27}$$

As discussed in the first chapter, flow division is an important mechanism of mixing in motionless mixers. Because of this action, and to some extent due to the other mechanisms, the output stream from these mixing devices will contain regions or domains of varying concentration. These domains will have a three dimensional instantaneous velocity that is a function of the configurations of the mixer, the total flow rate, and the viscosities of the domains and

adjacent domains. As these regions pass near the probes they cause the function $V(t)$ shown in Figure II-1 to be generated. Hence the frequency components of $V(t)$ will depend on the instantaneous velocity and the size of the domains of concentration. The higher the instantaneous velocity and the smaller the domains of concentration, the higher q in equation II-27 must be to accurately describe $V(t)$ or the proportional function $C(t)$.

As the solution gets more completely mixed the domains of concentration get smaller and more numerous. This effect produces higher frequency concentration fluctuations of lower amplitude. Also, as the solution becomes more uniform, adjacent regions of much different viscosity become smaller and the viscosity differences from region to region will not be as extreme. Again, the smaller regions will tend to create higher frequency velocity fluctuations, however the smaller concentration differences should provide some attenuation of all frequency components. Therefore, as a solution becomes more well mixed, not only do the concentration fluctuations become smaller, but they will also be made up of higher frequency components.

In evaluating the performance of a mixer by measuring the fluctuations of concentration (or any physical property) at a point with respect to time, it is necessary to determine what frequency components are important. Higher fluid velocities will result in generally higher frequency components, as will a smaller conductivity

probe. To measure the turbulent mixing of two low viscosity liquids would require a larger value of q in equation II-26 than to measure the laminar mixing of two high viscosity liquids.

Theoretically it is an easy matter to measure the $\bar{C}$ and C'_{rms} of equations II-5 and II-6 by measuring the proportional $\bar{V}$ and V'_{rms} with a d.c. and an a.c. voltmeter, respectively. The problem is that a.c. voltmeters are not sensitive to frequencies as low as the frequency components of concentration fluctuations. A very good a.c. voltmeter will respond to frequencies as low as 10Hz; however, at the velocities found in many in-line mixing situations, only a small fraction of the fluctuations will have that high a frequency.

For the present study, the range of frequency components included was set by equipment limitations. The upper frequency limit was set at 10Hz largely because the fastest rate at which voltage profiles could be converted to digital numbers and stored was slightly faster than 50 milliseconds per profile¹, which corresponds to a sampling frequency of 20Hz. Since the sampling frequency must be at least twice that of the highest signal frequency component, all signal frequency components greater than 10Hz were filtered out. The lower frequency limit was set by the length of time that the signal was measured, which was established by the number of profiles

¹The system will actually operate at 30 milliseconds/profile. Runs were taken at 45 milliseconds/profile to lengthen the runs.

that could be fit into a computer memory with programs for analysis. The length of the runs was 27 seconds. This would allow one period of a 0.037 Hz frequency component to be included. Hence ω_0 in equation II-21 equals 0.037 Hz for this study.

It is necessary to point out that because the data taken in this study were sampled rather than continuous, it does not give information about the energy content of all frequencies in the range from .037 Hz to 10 Hz. Rather, the data contains information, in the form of amplitudes, at discrete, equally spaced intervals of 0.037 Hz in the frequency spectrum as described by equation II-26. In order to obtain a closer spacing and a lower ranging frequency response it would be necessary to increase the time of the runs. Also, because the data were sampled, it was not possible to directly measure $V'_{k_{rms}}$ or $\bar{V}_k$. Instead, the value used for $\bar{V}_k$ was the average of all the data points taken at position k over a single run as given in the following equation:

$$\bar{V}_k = \frac{\sum_{n=1}^q V_{k_n}}{q} \quad \text{II-28}$$

where q is the number of samples taken during a run. Then the value used for $V'_{k_{rms}}$ was the standard deviation of the data points from $\bar{V}_k$ as given by

$$V'_{k_{rms}} = \left[\frac{\sum_{n=1}^q (V_{k_n} - \bar{V}_k)^2}{q-1} \right]^{1/2} \quad \text{II-29}$$

Then the values of I_{CONC} , as presented in Chapter IV, were calculated by the equation

$$I_{CONC_k} = 100 \frac{V_k \text{ rms}}{\bar{V}_k} \quad \text{II-30}$$

and represented the magnitude of the standard deviation of the concentration data as a percentage of the average concentration.

The range of frequencies examined is perhaps the biggest limitation in this study, largely because the amplitudes of frequency components outside this range were not measured or known. It is believed, though, that this frequency range will include a large percentage of the frequency components necessary to evaluate the voltage (concentration) function as described by equation II-26. The fact that the data were reproducible also supports this belief. However, anyone wishing to perform a similar study should heed the recommendations given in Chapter V of this thesis.

D. Fluid Properties

The fluids used were water and solutions of sodium carboxymethylcellulose (CMC) and deionized water in various concentrations. Sodium carboxymethylcellulose was chosen because it forms an ionic solution with water, giving the solution a conductivity proportional to the CMC concentration as discussed in section B, and because the viscosity of solutions is a function of the CMC concentration. Also, the CMC solutions are completely miscible with water. The CMC was obtained

from Hercules, Inc.

One drawback to the use of CMC solutions is that they are visco-elastic fluids. Because it was desired to investigate the effect of viscosity ratio on the mixing performance, it was necessary to obtain some sort of relation to describe viscosity of the CMC solutions. It was decided to model these solutions as power law fluids, following the relation:

$$\tau = m \dot{\gamma}^n \quad \text{II-31}$$

where τ is the shear stress and $\dot{\gamma}$ is the shear rate. The power law equation involves only two rheological parameters: the consistency index m , and the flow behavior index, n . Although this relation is not a perfect model for the CMC solutions, it does fairly accurately describe the non-Newtonian behavior of these solutions with respect to shear as a function of steady shear rates (not to transient shear rates).

For a Newtonian fluid, m is a constant often designated η , and $n = 1$, yielding the expression

$$\tau = \eta \dot{\gamma} \quad \text{II-32}$$

η is the ratio of the shear stress to the shear rate and is called the viscosity. For a power law fluid the ratio of shear stress to shear rate is not constant and is called the apparent viscosity, η_A . The apparent viscosity is the viscosity a fluid exhibits at a specific shear rate. Rearranging equation II-31 can give

$$\tau = (m \dot{\gamma}^{n-1}) \dot{\gamma} \quad \text{II-33}$$

Comparing equation II-32 and II-33 it can be seen that the apparent viscosity of a power law fluid is given by the relation

$$\eta_A = m \dot{\gamma}^{n-1} \quad \text{II-34}$$

at steady values of $\dot{\gamma}$.

In the mixing system there is no way to determine what the shear rate is. Indeed, in any given cross section there are many shear rates all of which are constantly changing. Because equations II-31 and II-34 will model the viscoelastic CMC solutions only at constant shear rates, even if the values of the shear rates were known it would not be possible to determine the exhibited viscosity of the CMC solutions in the mixing system. For this reason no attempt was made in this study to correlate the data as a function of the viscous properties of the fluids as they exist in the mixing system (for example, using Reynolds numbers). Instead, the effects of the inlet viscosity ratio were examined. Actually the parameter to characterize the CMC solutions' viscosities was not the apparent viscosity at the inlet conditions but rather the generalized viscosity coefficient, γ , developed by Metzner and Reed (19) and defined by

$$\gamma = g_c m' 8^{n'-1} \quad \text{II-35}$$

where

$$n' = n \quad \text{II-36}$$

and

$$m' = m \left(\frac{3n' - 1}{4n} \right) n'$$

II-37

The water used exhibited Newtonian behavior with a measured viscosity of 1.15 cp at the room temperature of 23°C.

III. EQUIPMENT, MATERIALS, AND PROCEDURE

A. System Overview

Figure III-1 shows an overall view of the flow and signal systems used in this study. In the flow system, water was always used as the main stream fluid and the sodium carboxymethylcellulose (CMC) solution was injected just above the mixer. The fluids then exited the mixer, flowed through a probe array, then through a large screen electrode and then out of the system.

The signal system originates with a signal generator which injects a constant voltage sine wave into the fluid system at the large screen electrode. The sine wave is detected at the probes, amplified, rectified and filtered to yield a voltage, the d.c. value of which is proportional to the resistivity of the fluid immediately surrounding the probe tips. This voltage is then converted to a digital number and stored into a computer buffer. As the computer buffer fills, the data is transferred to a flexible disc mass storage unit.

B. Conductivity Measurements

In order to measure the conductivity of the inlet water and of the various concentration CMC solutions, a small conductivity cell was made. This cell consisted of a $\frac{1}{2}$ " I.D. plastic tube with a metal plate glued to the bottom. Three inches above the bottom, a small hole was drilled through the side of the tube. The solution, whose conductivity was to be measured, was put into the cell, then a $\frac{1}{2}$ " diameter steel rod was lowered into the cell until it was visible

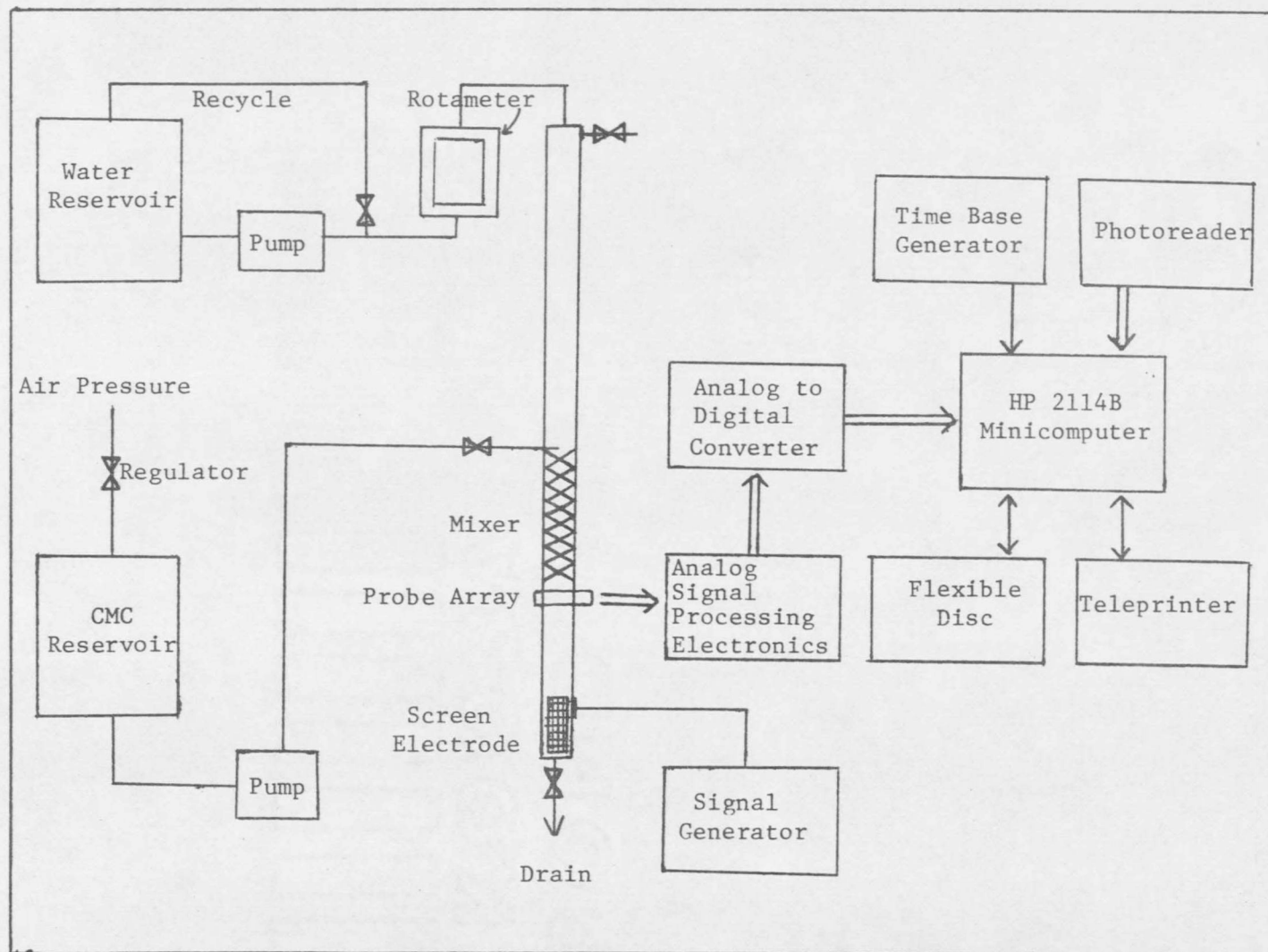


FIGURE III-1. SYSTEM BLOCK DIAGRAM

through the hole in the side of the tube. Any excess fluid escaped through the hole.

The filled cell then consists of a 3-inch column of fluid, $\frac{1}{2}$ inch in diameter, in contact on each end with a material having a very high electrical conductivity. The conductance of the column of fluid can be measured by placing a voltage potential across the column and measuring the current through it. Then the conductance, G , is given by equation III-1,

$$G = \frac{I}{V} \quad \text{III-1}$$

where I is the current through the cell and V is the potential across the cell. Then the conductivity, σ , can be calculated by the equation

$$\sigma = \frac{GL}{A} \quad \text{III-2}$$

where L is the length of the column and A is the area normal to the flow of current.

In all cases the potential across the column was kept at 5 V when the current was measured. The voltage was measured with a Hewlett-Packard Model 3440A Digital Voltmeter; the current was measured with a Fluke Model 8000A Digital Multimeter. The results of the measurements are tabulated in Table III-1 and the conductivities are shown graphically in Figure III-2.

C. Flow System

Four separate flow systems were used, one for each mixer studied. A schematic of the flow system is shown in the left side of

TABLE III-1. ELECTRICAL CONDUCTIVITY DATA

Materials	Current With 5V Across Cell	Conductance, G	Conductivity, σ
Hot Tap Water	139 μ A	2.78×10^{-5} Ω^{-1}	16.7 m Ω /m
Cold Tap Water	95	1.90×10^{-5}	11.4
Deionized Water	4.5	9.00×10^{-7}	0.54
0.10 wt% CMC*	117	2.34×10^{-5}	14.1
0.20	198	3.96×10^{-5}	23.8
0.25	254	5.08×10^{-5}	30.6
0.50	476	9.52×10^{-5}	57.3
1.00	562	1.12×10^{-4}	67.6
1.50	800	1.60×10^{-4}	96.2
2.00	990	1.98×10^{-4}	119.1
2.50	1185	2.37×10^{-4}	142.6
3.00	1420	2.84×10^{-4}	170.8
3.50	1580	3.16×10^{-4}	190.1

*All CMC solutions were made with deionized water.

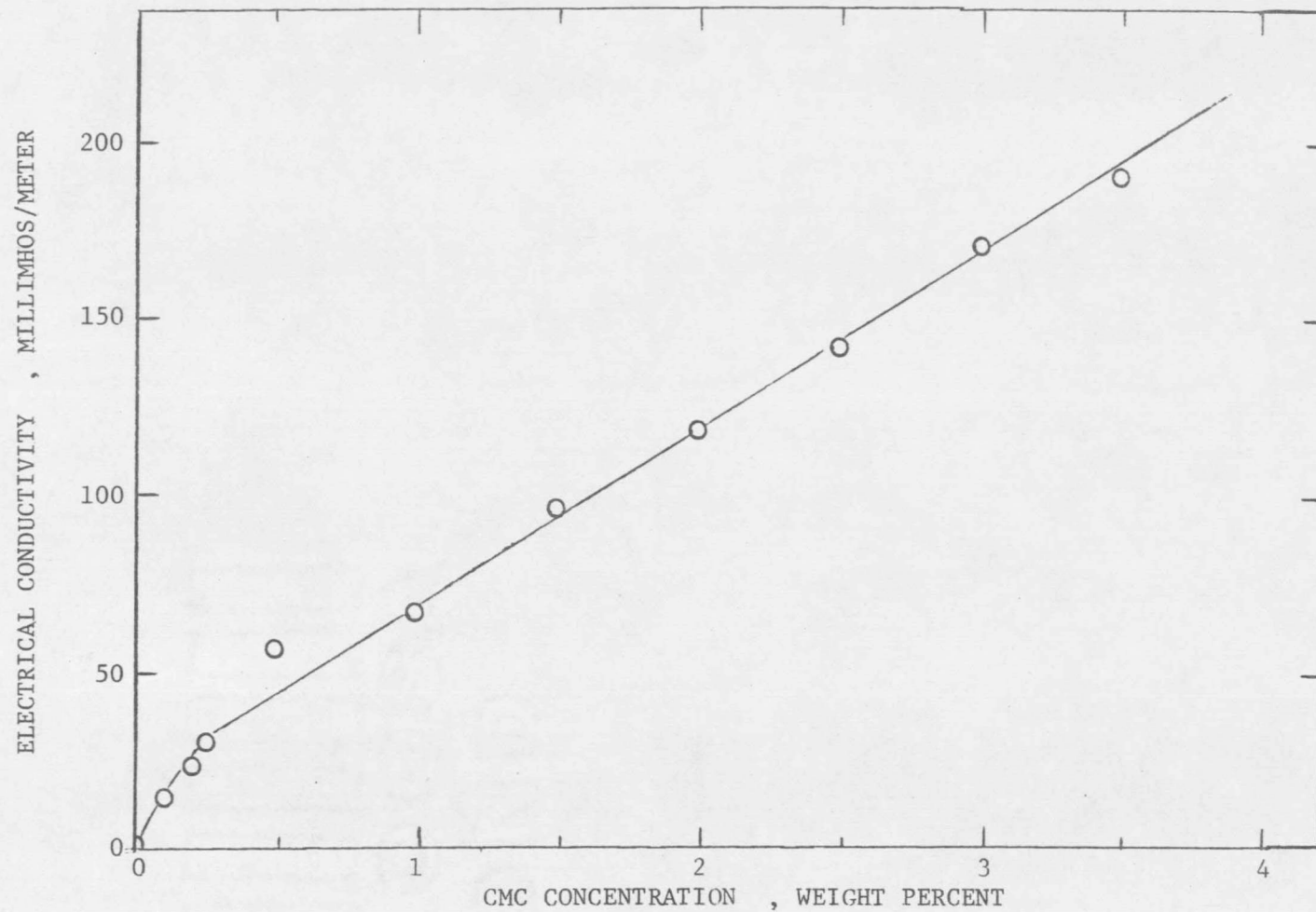


FIGURE III-2. ELECTRICAL CONDUCTIVITY VERSUS CONCENTRATION FOR CMC SOLUTIONS

Figure III-1. All the columns were constructed of extruded acrylic tubing. Table III-2 gives the specifications of each of the systems. In the table, entrance section refers to the section from the top of the column to the top of the mixer; the exit section refers to the section from the bottom of the mixer to the bottom of the column and includes the 3/4" for the probe system. At the top of each column was a valve which was used to empty the air from the column when it was first filled. This valve was kept closed after all the air was removed.

TABLE III-2. MIXER SYSTEM SPECIFICATIONS

Mixer	Mixer Diameter (tube I.D.)	Mixer Length	No. of Elements	Entrance Section Length	Exit Section Length
Kenics Static	1/2"	15.75"	21	42"	12"
Kenics Static	3/4	23.5	21	71	12
Ross LPD	1	19.0	10	83	13
Ross ISG	1	10.0	10	92	13

The water was stored in a fifty-five gallon drum and allowed to reach room temperature (always 20° to 23° C) before runs were made. The inside of the drum was painted with chemical resistant paint to retard rust formation. The drum was almost filled with de-ionized water and then tap water was added to give the water a conductivity of 1.5 to 2.0 millimhos/meter. The mixture of deionized

and tap water was necessary for two reasons: 1) The degree of deionization, and hence the conductivity of the deionized water supply varied somewhat from day to day, so it is necessary to adjust the conductivity of the water solution to keep it more uniform from run to run; 2) The amplifiers are adjusted before each run series, and occasionally during a run series, to give approximately the same reading from each probe position with only the water running through the system. Hence it is necessary that the water be conductive enough to give a high enough reading to give good resolution when adjusting the amplifiers. Even with the addition of the tap water the conductivity of the water was much lower than the conductivity of any of the CMC solutions used in the mixing study (see Table III-1). During a run, the water was pumped through a rotameter to the top of the vertical column with a constant displacement pump. A recycle line was placed from the discharge side of the pump to the water reservoir to prevent excessive pressure build-up in the system.

The CMC reservoir consisted of a 5 foot long, $1\frac{1}{2}$ inch diameter cast acrylic tube. The top of the column was attached to a constant pressure air source. From the bottom of the column the CMC flowed to the suction side of a Zenith gear pump and then through the pump to an inlet nozzle in the center of the column just above the mixer. A detailed diagram of the inlet nozzle is shown in Figure III-3. It was necessary to pressurize the CMC reservoir to prevent the pump

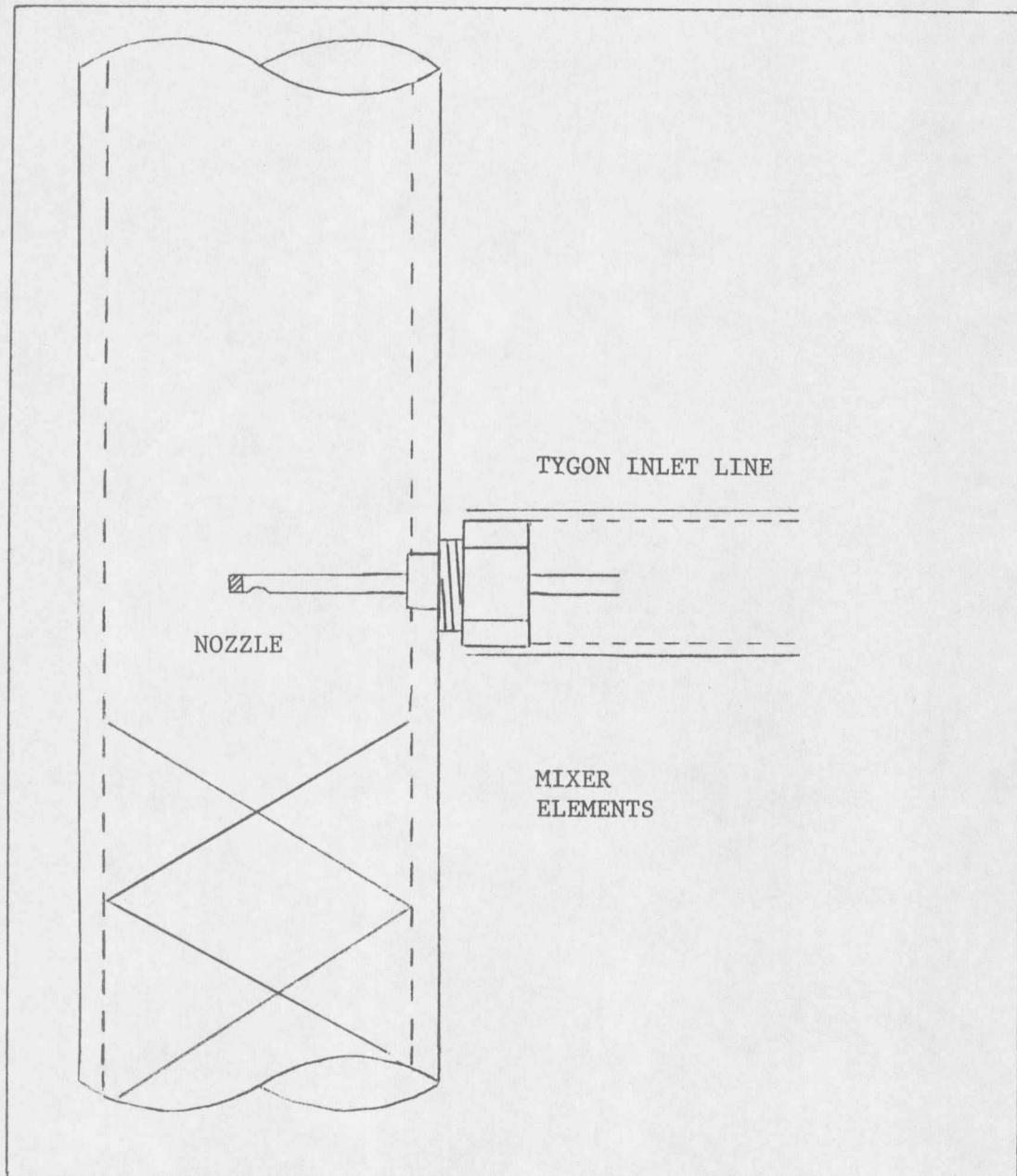


FIGURE III-3. DETAIL OF CMC INJECTION NOZZLE

from cavitating. The CMC solution flow rate was determined by measuring the rate at which the level in the column dropped during a run. The fluids then flowed through the column and out the bottom to a drain.

All the interconnecting lines in the flow system were of 3/8 inch I.D. Tygon tubing. All pressurized lines were 9/16 inch O.D.; the other lines (exit stream and water recycle) were 1/2 inch O.D.

D. Analog Instrumentation

A block diagram of the instrumentation system is contained in Figure III-1. The driving signal, a 5 kHz sine wave, originates from a Heathkit Model IG-18 Sine-Square Audio Generator and is applied to a 6" X 1½" coiled steel screen¹ in the bottom of the exit section of the column. The signal generator was externally loaded by a 1 KΩ shunting resistor. The input voltage was varied with each run. (This will be discussed later in the procedure section).

This signal is picked up by the probes in the probe array located just below the mixing section. The array consists of a piece of 1/16" copper clad circuit board, etched to give ten separate foils. The etching mask was provided by a photographic negative

¹The screen size in the ½ inch Kenics Mixer system is 4½" X 2".

that provided a four times reduction of the original taping. This process assured accurate probe positioning and uniform thickness and width. The foil side of the circuit board was covered with a thin (approximately 1/32 inch) layer of epoxy to insulate it from the fluid. Then the top edge of the board was lightly sanded so that only the tips of the foils were exposed. Wires were then soldered to the other ends of the foils and to a 14 pin connector. The circuit board and connector were then sealed into a Plexiglas housing; with the circuit board oriented so that the ten exposed foil tips, or probes, were on the leading edge of the fin formed by the circuit board. Table III-3 shows the spacing of the probes for the various mixing systems. The same probe array was used for both of the Ross mixers.

The probe design is similar in principle to the design discussed in reference (16). Basically the probes measure the electrical conductivity of a small volume of fluid surrounding the tip of the probe. A simplified discussion of the principles involved in the conductivity probes follows:

There are two electrodes in the system, one large screen electrode at the bottom of the column and a small point probe some distance above it. In the actual system used, there are ten point

TABLE III-3. SPACING OF PROBE TIP CENTERS, MEASURED IN INCHES FROM INSIDE TUBE WALL WHERE THE PROBE LEADS EXIT THE SYSTEM.

MIXER DIAMETER	PROBE WIDTH	POSITION									
		1	2	3	4	5	6	7	8	9	10
1"	.0125	.0250	.0750	.1250	.1750	.2250	.2625	.3125	.3625	.4125	.4625
3/4"	.0250	.0625	.1375	.2125	.2875	.3625	.4125	.4875	.5625	.6375	.7125
1"	.0250	.1000	.2000	.3000	.4000	.5000	.5500	.6500	.7500	.8500	.9500

probes, but each is independent and all are identical in operation so this discussion will only analyze the operation of one probe.

An a.c. voltage source is connected to the large screen electrode. This will set up an electric field in the electrolyte surrounding the screen electrode. The current between the two electrodes is a function of the resistance of the electrolyte between the two. This resistance can be described by the relation

$$R = \int \frac{dx}{\sigma A} \quad \text{III-3}$$

where dx is a differential element of length between the two electrodes, A is the cross sectional area normal to the flow of current and σ is the conductivity of the electrolyte (dimensions of mhos/length). Because the probe geometry is such that the two electrodes are separated by a relatively large distance and the point electrode has a much smaller exposed surface than the large electrode, the contribution to the resistance integral is much, much greater near the smaller probe because the area term becomes so small. Hence, the current into the probe is related to the conductivity of the fluid immediately surrounding the probe. Also, because the current density near the smaller electrode is so high relative to the current density in other regions, even large variations in the resistance of regions of an inhomogeneous electrolyte far from the smaller electrode have little effect on the total impedance.

When the tips of the probes are placed in a nonhomogenous electrolyte, the changing conductivity of the electrolyte immediately surrounding the probes will change the impedance of the probes. This will cause variations in the amplitude of the input carrier wave. Hence, the signal from the probes is an amplitude modulated sine wave. The electronics which process this signal must perform three functions. These are:

1. The input impedance of the electronics must be low enough to load the probes enough to insure that a significant current flows through them.
2. The input signal must be amplified and the gain must be adjustable to provide a d.c. output voltage from 0 to 1 V.
3. The signal must be demodulated by rectifying it and passing it through a low pass filter. This removes the carrier frequency and all the high frequency components of the concentration fluctuations. For this study it was desired to look only at frequency components lower than 10 Hz, hence this was chosen as the -3 dB corner frequency of the low pass filter.

Figure III-4 shows a block diagram of the signal processing components and a typical signal at each point.

A discussion of the electronics used to process the signal is given in Appendix A.

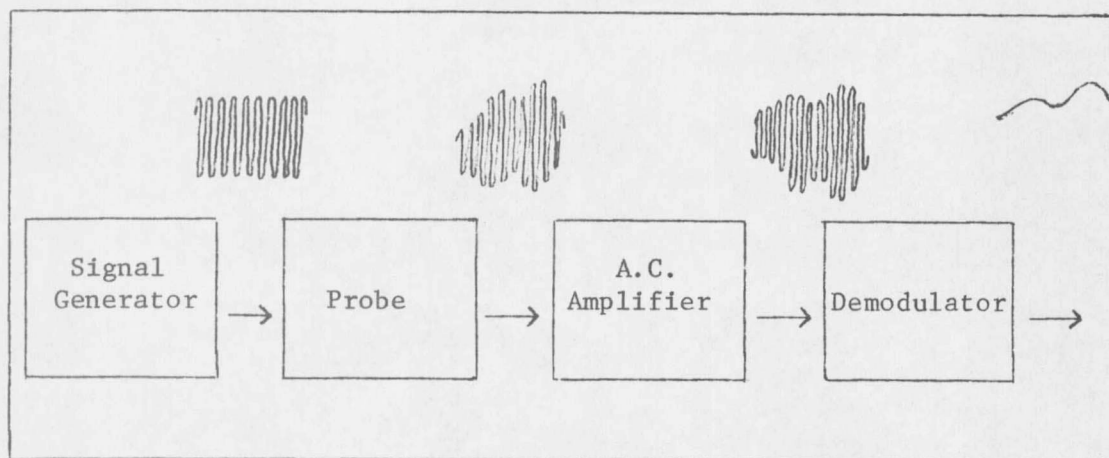


FIGURE III-4. SIGNAL PROCESSING BLOCK DIAGRAM.

At the output of the processing electronics, each signal consists of a voltage, the d.c. value of which is proportional to the electrical conductivity of the electrolyte immediately surrounding the tips of the probe. Since there are ten probes, there are ten signals, each of which is continuously available at the inputs of a Hewlett-Packard Model 5610A Analog to Digital Converter.

E. Digital Instrumentation

A digital data acquisition system was used to gather all of the conductivity data taken in this study. Although this system was developed in conjunction with this mixing study, the system is a general purpose, real-time system, and this study was its first application. The only portions of the system that will be discussed here are those applicable to this study.

The center of the system is a Hewlett Packard 2114B minicomputer donated to the chemical engineering department by E.I. DuPont de Nemours & Company. The computer is connected to several peripheral devices. For this study, these devices included a photoreader, a teleprinter, a flexible disc drive, an analog to digital converter, and a time base generator.

The communications between the computer and these devices were controlled by a program written for this study, working in conjunction with the acquisition system's operating system (18). The program written for the study is listed in Appendix B. Basically, the program samples the ten inputs to the A/D converter at time intervals specified by the user, and stores the samples on a flexible disc. It takes less than 200 microseconds to acquire and store the ten readings from the A/D converter. Because the conversions are so fast and because the interval of time between each group of samples is so much greater (at least 30 milliseconds), each group of samples can be thought of as an instantaneous voltage profile across the diameter of the tube. With the mass storage capabilities of the flexible disc it is possible to store well over 12,000 of these profiles for later analysis.

The time intervals between the profiles were measured with a crystal controlled time base generator. The major requirement of this time interval is that it must be such that the sampling frequency

(inverse of the sampling time interval) must be at least twice that of the highest frequency being measured. For this study, the highest frequency being measured was 10 Hz, as established by the low pass filter at the output of the amplifier. Hence, the sampling frequency had to be at least 20 Hz. That meant that the minimum interval between profiles had to be 50 milliseconds. The actual interval used during the runs was 45 milliseconds.

After the data were taken, they were transferred from the flexible disc to a moving head disc in a larger minicomputer system (around a Hewlett-Packard 2116B) for analysis. This computer had 16K of memory. Because of this, the largest data array that could fit into the machine, along with the analysis and system programs, without segmenting the data, was 6,000 words. Therefore, the number of profiles taken each run was limited to 600. Then the data were stored on magnetic tape so the flexible discs could be reused. This also provided a simple means of saving the original data so that, if desired, it can later be reanalyzed in some different manner.

F. Procedure of Data Acquisition

Data for the study were taken in groups of runs. Each group was designated as a runs series. Each run consisted of 600 voltage profiles taken at intervals of 45 milliseconds with constant CMC and water flow ratio in a single mixing unit. Each run was repeated at least three times to check for reproducibility of data. Each run

series consisted of sets of runs all taken in the same mixer and at the same CMC flow rate, but at five different water flow rates. The five water flow rates corresponded to rotameter readings of 20, 40, 60, 80, and 100. Hence, a run series consisted of at least 15 runs.

At least three run series were made for each CMC concentration in each mixer. Each was made at a different CMC flow rate. The CMC flow rates were the minimum and maximum obtainable with the Zenith pump, and one flow rate approximately midway between the minimum and maximum. Run series were made in each of the four mixers with water only, 1%, 2%, 3%, and 4% CMC solutions.

The procedure followed in making a runs series was:

1. Using the conductivity cell described in section III-B, the conductivity of the water was checked to make sure that it was between 1.5 and 2.0 millimhos/meter.
2. The water pump was started and the columns were emptied of air using the valve at the top of the column. Then with water only flowing through the system, the gain on each of the ten amplifiers was adjusted so that the output voltage of each channel was the same ± 1 mV. The water was then allowed to flow through the system for approximately ten minutes. After this period of time the outputs of each channel were again checked and, if necessary, the gains of

the appropriate channels were readjusted.

3. The CMC reservoir was pressurized to 20 psig. The water flow rate was adjusted to give a rotameter reading of 20, the CMC pump was started, and the valve in the CMC line was opened to allow CMC to flow into the mixing system. Then the speed of the CMC pump was adjusted to whatever flow rate was desired for the run series.
4. The level of the CMC was noted and a stopwatch started.
5. All the digital equipment was powered and the disc used for data storage was initialized. Then the data acquisition program was loaded into the computer from the disc.
6. The input voltage was adjusted to as high a value as possible without having the voltage output from any channel exceed 1 volt. Then the input voltage was recorded.
7. After the CMC had been flowing for at least 5 minutes, the first run was started. When the run was completed, another run was taken at the same conditions. When the second run was completed a third run was taken at the same conditions.
8. During the last run at a given set of conditions the CMC level was noted and the stopwatch was stopped and the time recorded.
9. A listing of the data file was requested to make sure the data was stored. Then the water flow rate was raised enough

to increase the rotameter reading by 20. Then the CMC level noted, the stopwatch was reset and started, and the data acquisition program was reloaded into the computer.

10. After a period of time that ranged from 1 minute with the 1% solution to 5 minutes for the 4% CMC solution the input voltage was adjusted as in item 6 and the next run was started. Again, three runs were taken at the same conditions and sometime during the third run the CMC level was noted, the stopwatch stopped and the elapsed time recorded to obtain a CMC flow rate. The period of time allowed in order to reach steady state was determined by observing the voltage change at a given position. When the water flow was first increased the voltage would drop because of the reduced CMC concentration. When the voltage had settled to some steady value, the input voltage would be readjusted as in item 6 and the reading at some point would be observed for any upward or downward trend that would indicate that steady state had not been reached. If no trend was noted the data acquisition was started.
11. Item 9 and 10 were repeated until data were taken at a rotameter reading of 100. The run series was then

complete and the CMC pump was shut off and the valve in the CMC line was closed.

If another run series was going to be made, the outputs of the amplifiers were again checked and, if necessary, readjusted as in item 2 and the procedure was repeated except that since the CMC column was kept pressurized it did not require repressurization.

Occasionally a run series was made slightly differently than as described above in that the first run was made at the highest flow (rotameter reading of 100) and the rotameter reading was reduced by 20 before each set of runs at a different flow rate. Run series made in this way, which repeated runs made in the other direction (e.g. SK014 and LK009) yielded virtually identical information. Also, the run series made in this way which did not repeat runs resulted in the same trends noted with the series made by increasing the flow rate through the series. The major difference noted between the two methods was that it took a little longer to reach steady state when the flow rate was decreased during a run series.

TABLE III-4. CMC VISCOSITY PARAMETERS

CMC Conc. wt %	m $\frac{\text{dyne sec}^n}{\text{cm}^2}$	$n=n'$ Dimensionless	m' $\frac{\text{dyne sec}^{n'}}{\text{cm}^2}$	γ $\frac{\text{gm}}{\text{cm sec}^{2-n'}}$
1	53	.930	53.9	46.6
2	380	.882	391.2	306
3	3400	.807	3563	2385
4 * (extrapolated)	31500	.607	34500	15240

G. Viscosity Measurements

As discussed in the previous chapter, the CMC solutions used in the study could be described as power law fluids which follow the relation

$$\tau = m\dot{\gamma}^n \quad \text{II-31}$$

and that their viscosities could be described by a generalized viscosity coefficient, γ , given by equation II-35.

$$\gamma = gc m' \dot{\gamma}^{n'-1} \quad \text{II-35}$$

Values for the constants m and n , and also for m' and n' which are calculated with equations II-36 and II-37, were determined using a Brookfield RVT-200 Syncho-lectric viscometer. A cone and plate configuration was used for CMC solutions of 2.5% and lower. Two different cone angles, 0.8° and 1.565° , were used. For CMC solutions of 2.5% and greater, a concentric cylinder configuration was used.

The inner cylinder had a diameter of 3/8 inches and a length of 2 inches; the outer cylinder was a 250 ml beaker with a diameter of 2½ inches.

With the cone and plate configuration, the shear rate, $\dot{\gamma}$, is very nearly constant at all radial positions. The apparent viscosity, η_A , of a solution could be directly measured at a given shear rate after the instrument was calibrated with a solution of known viscosity to determine the viscosity associated with a full scale reading. From equation II-34, the apparent viscosity of the CMC solutions can be described by

$$\eta_A = m \dot{\gamma}^{n-1} \quad \text{II-34}$$

Taking the logarithm of both sides of equation II-34 gives

$$\ln \eta_A = \ln m + (n-1) \ln \dot{\gamma} \quad \text{III-4}$$

By measuring η_A at several values of $\dot{\gamma}$, and then performing a least squares fit, the values of m and n which gave the least error for the line described by equation III-4 were obtained.

With the concentric cylinder configuration the shear rate is a function of radial position so the method used with the cone and plate configuration did not apply. However, the torque on the rotating inner cylinder is a function of its angular velocity, ω , the dimensions of the cylinders, and the fluid properties m and n . The derivation of this relationship is given in Appendix C and is

described by the following equations:

$$\omega = nCT^{1/n} \quad \text{III-5}$$

where T is the torque on the inner cylinder and C is given by

$$C = \frac{1}{2} \left(\frac{1}{2\pi LR_m^2} \right)^{1/n} \left(\left(\frac{1}{k^2} \right)^{1/n} - 1 \right) \quad \text{III-6}$$

where k is the ratio of the inner cylinder radius to the outer cylinder radius, R . L is the length of the inner cylinder immersed in the solution.

By calibrating the viscometer with a solution of known viscosity the torque associated with a given scale reading on the instrument is known. Then, using the solution to be measured, the torque is determined at several angular velocities. Taking the logarithm of both sides of equation III-5 gives

$$\ln \omega = \ln (nC) + \frac{1}{n} \ln T \quad \text{III-7}$$

By plotting (or performing a least squares analysis) $\ln \omega$ versus $\ln T$, the quantities C and n can be determined. The value of m can then be determined by rearranging equation III-6 to give

$$m = \frac{1}{2\pi LR^2} \left[\frac{\left(\frac{1}{k^2} \right)^{1/n} - 1}{2C} \right]^n \quad \text{III-8}$$

One complication in using the concentric cylinder configuration is the effects of the stress on the bottom of the cylinders. This end effect will be constant if the distance between the bottoms

of the two cylinders is kept constant and it can be accounted for in the preceeding equations by using a value of L greater than the actual inner cylinder immersion depth. The amount to increase L by is determined by measuring the torque and angular velocity and several different immersion depths. Then by plotting T/ω versus immersion depth, as shown in Figure III-5, the length correction, l_0 , will be the difference between origin and the intercept of the plot with the depth axis (refer to part 3 of reference 30). Hence

$$L = L_{\text{actual}} + l_0 \quad \text{III-9}$$

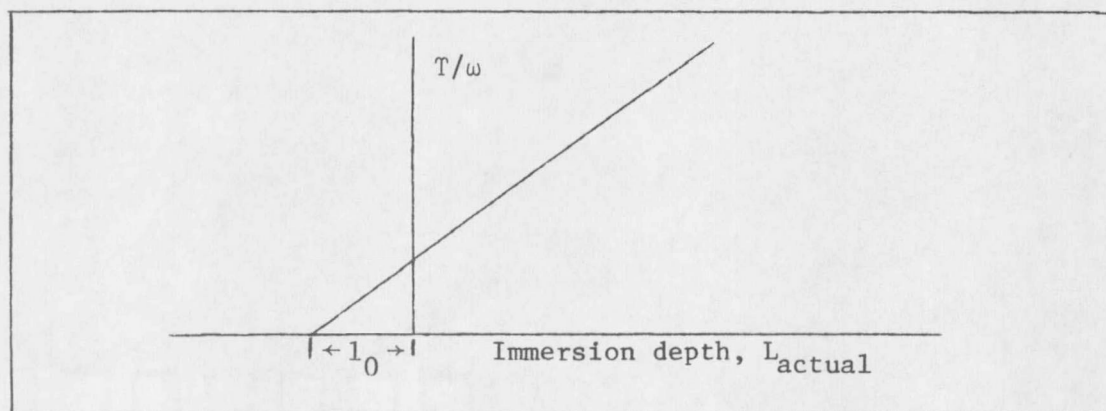


FIGURE III-5. DEPTH CORRECTION FOR CONCENTRIC CYLINDER CONFIGURATION

The values of m , n , and the viscosity coefficient γ , given by equation II-35, that were calculated from the viscometer measurements, are listed in Table III-4.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. The Data

As described in the previous chapter, the data were taken in groups of runs called run series. Each run was made at some CMC flow rate and some water flow rate, and in every case, more than one run was made at each CMC and water flow rate combination. Each run series was composed of the runs made at the same CMC flow rate but at several water flow rates, corresponding to rotameter readings of 20, 40, 60, 80 and 100. It was hoped that by using four different CMC concentrations the effect of viscosity ratio, λ , could be established. Similarly, by using three CMC flow rates and five different water flow rates, the effects of mix ratio and total flow rate could be investigated.

The raw data for each run consisted of 600 voltages, taken 45 milliseconds apart, at each of 10 positions across the diameter of the tube at the exit of the mixers. As described in Chapter II, each of these voltages is proportional to the instantaneous CMC concentration at that position. The raw data was then input to a FORTRAN IV program which calculated the average, standard deviation and coefficient of variation of the data for each position. The average and standard deviation of the voltages at each position are proportional to the average concentration, $\bar{C}$, and the root mean square concentration fluctuation, C'_{rms} , respectively. The coefficient of variation

is 100 times the ratio of the standard deviation to the average and hence is equal to the intensity of concentration turbulence, I_{CONC_k} , at that position as described by equation II-30.

Because well over 850 runs were made in the course of this study, the space required for the presentation of even this condensed data is prohibitive. Hence it was decided to present the average of the ten values of I_{CONC_k} , for each run and to designate that average as $\overline{I_{CONC}}$. Since each run was repeated typically three times, for each set of run conditions typically three values of $\overline{I_{CONC}}$ will be presented along with the average of the values of $\overline{I_{CONC}}$ and also the standard deviation. Figure IV-1 shows an example of the way the data will be presented in the tables. The water flow rates will be shown along the top of the table and the CMC flow rates will be presented along the left hand side of the table. Along with the CMC flow rate, the name of the run series in which the data for that CMC flow rate were taken will be listed. In the example shown, three runs were taken at a CMC flow rate of 5.4 ml/min and a water flow rate of 360 ml/min. The individual values of $\overline{I_{CONC}}$ for these three runs are 27.985, 28.006, and 27.845. Under the individual values of $\overline{I_{CONC}}$ a line is drawn and then the average of the individual values, 27.945, is listed followed by the standard deviation of the values, .088. In some cases more than three runs will have been taken at a set of conditions and in

a few instances only two; however, the individual values of $\overline{I}_{\text{CONC}}$ will always be separated from the average and standard deviation by a line. The values of $\overline{I}_{\text{CONC}}$ for all the mixing runs are presented as described previously, in Tables IV-2 through IV-17. Each table contains the values of $\overline{I}_{\text{CONC}}$ measured below a particular mixer with a particular inlet viscosity ratio (CMC concentration).

CMC Flow Rate ml/min	Water Flow Rate ml/min	
	360	775
5.4 Run Series SK011	27.985	29.597
	28.006	33.238
	<u>27.845</u>	<u>34.371</u>
	<u>27.945</u>	<u>32.402</u>
	.088	2.494

FIGURE IV-1. EXAMPLE OF DATA PRESENTATION

Table IV-1 presents the values of $\overline{I}_{\text{CONC}}$, measured with only water flowing through the systems. This data is presented in the same form as shown in Figure IV-1, except that instead of showing a CMC flow rate (which equals 0) on the left side of the table, the type of mixer is listed. The values of $\overline{I}_{\text{CONC}}$, listed in Table IV-1 are an indication of the magnitude of concentration fluctuations that are due to variations in the concentration of the inlet water and also to a lesser extent, apparent concentration fluctuations that are actually caused by instrumentation noise.

In all cases, the magnitude of I_{CONC} , with only water flowing through the mixers, were well under 2%.

By using $\overline{I_{\text{CONC}}}$, rather than the individual values of I_{CONC} , important information concerning the radial distribution of concentration turbulence is lost. For this reason each of the following sections of this chapter will contain a short discussion of the concentration and turbulence profiles typically found in the mixer under discussion in that section. Also, sketches of typical profiles will be presented.

The angular orientation of the probe array to the bottom of the mixer is of some importance in the analysis of the radial data. With the Kenics mixers this orientation was kept constant during all the data acquisition. This orientation is sketched in Figure IV-2. The last element in each Kenics mixer was a right helix. With the probe array setup used with the 1 inch (Ross) mixers, it was not possible to keep the orientation constant; however, there were trends that were apparent in all the runs.

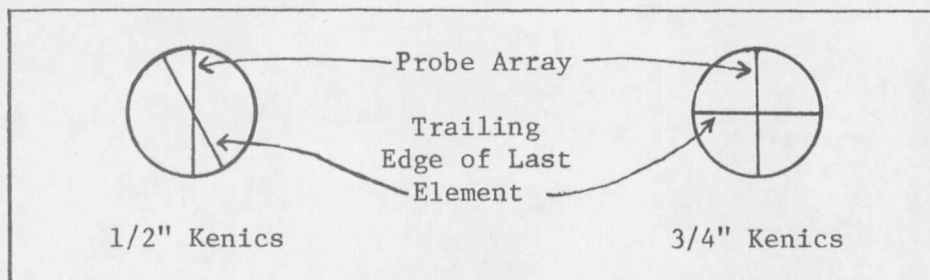


FIGURE IV-2. ORIENTATION OF PROBE ARRAY TO TRAILING EDGE OF LAST ELEMENT IN KENICS MIXERS (top view)

TABLE IV-1. AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I}_{CONC}$, WITH WATER ONLY PASSING THROUGH THE MIXING SYSTEMS

Mixer	Water Flow Rate min/ml				
	360	775	1205	1640	2080
1/2" Kenics	.892	.887	1.014	1.007	.924
	.892	.885	.979	.924	<u>.932</u>
	<u>.849</u>	<u>.870</u>	<u>.971</u>	<u>.927</u>	<u>.928</u>
	Run Series SK001	.878	.881	.988	.953
		.025	.009	.023	.047
3/4" Kenics	1.435	1.425	1.224	1.269	1.166
	1.461	1.448	1.193	1.177	1.169
	<u>1.473</u>	<u>1.412</u>	<u>1.155</u>	<u>1.138</u>	<u>1.196</u>
	Run Series LK001	1.456	1.428	1.191	1.195
		.019	.018	.035	.067
Ross LPD	.795	.825	.810	.771	.783
	.802	.822	.810	.788	.773
	<u>.798</u>	<u>.808</u>	<u>.795</u>	<u>.804</u>	<u>.780</u>
	Run Series LPD001	.798	.818	.805	.788
		.004	.009	.009	.017
Ross ISG	.825	.831	.809	.815	.811
	.825	.814	.823	.815	.810
	<u>.825</u>	<u>.820</u>	<u>.813</u>	<u>.806</u>	<u>.817</u>
	Run Series ISG001	.825	.822	.815	.812
			.009	.007	.005

TABLE IV-2. AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I}_{CONC}$, IN $\frac{1}{2}$ " KENICS MIXER WITH 1% CMC SOLUTION

Water Flow Rate ml/min CMC Flow Rate ml/min	360	775	1205	1640	2080
5.0	1.622	1.435	1.579	1.742	
	1.454	1.351	1.496	1.711	
	1.326	1.314	1.748	1.722	
Run Series SK002	1.467	1.367	1.608	1.725	
	.148	.062	.128	.016	
5.1	1.933	4.597	3.483	2.035	1.930
	1.594	5.548	2.843	1.832	1.879
	2.170	2.756	3.296	2.468	1.884
Run Series SK006	1.899	4.300	3.207	2.112	1.898
	.290	1.419	.329	.325	.028
8.9	2.874	5.124	4.934	4.086	1.674
	1.849	4.822	5.363	3.910	3.562
	2.032	5.139	4.517	3.292	1.596
Run Series SK003	2.525	5.028	4.938	3.763	2.277
	.547	.179	.423	.416	1.113
15.9	1.077	.9188	1.894	3.353	2.618
	1.187	.8353	2.461	3.663	2.260
	.950	.8710	2.812	3.173	2.102
Run Series SK004	1.071	.8750	2.389	3.396	2.327
	.119	.042	.463	.248	.264

TABLE IV-2 (con'd)

CMC Flow Rate ml/min	Water Flow Rate ml/min				
	360	775	1205	1640	2080
15.8 Run Series SK005	1.144	.776	2.778		
	1.089	.999	2.937		
	<u>.860</u>	<u>.911</u>	<u>3.732</u>		
	1.031	.844	3.149		
	.151	.095	.511		
15.0 Run Series SK007	1.657	.857	2.164	2.538	2.545
	<u>1.657</u>	1.418	2.107	2.773	2.273
	<u>1.657</u>	<u>.949</u>	<u>4.663</u>	<u>3.074</u>	<u>2.419</u>
	—	1.075	2.918	2.795	2.412
		.301	1.460	.269	.136

TABLE IV-3. AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I}_{CONC}$, IN $\frac{1}{2}$ " KENICS MIXER WITH 2% CMC SOLUTION

Water Flow Rate ml/min CMC Flow Rate ml/min	360	775	1205	1640	2080
5.4 Run Series SK011	27.985	29.597	36.676	31.185	19.435
	28.006	33.238	38.515	35.848	25.177
	<u>27.845</u>	<u>34.371</u>	<u>37.347</u>	<u>29.638</u>	<u>19.813</u>
	<u>27.945</u>	<u>32.402</u>	<u>37.513</u>	<u>32.224</u>	<u>21.475</u>
	.088	2.494	.931	3.233	3.211
9.4 Run Series SK012	21.520	31.487	32.826	34.054	23.704
	20.479	30.867	32.117	34.241	19.762
	<u>17.781</u>	<u>28.719</u>	<u>31.583</u>	<u>30.202</u>	<u>22.019</u>
	<u>19.927</u>	<u>30.358</u>	<u>32.175</u>	<u>32.166</u>	<u>21.828</u>
	1.930	1.453	.624	2.022	1.978
16.4 Run Series SK013	15.040	23.878	26.815	28.775	22.664
	14.350	23.898	26.020	29.204	22.654
	<u>17.128</u>	<u>26.398</u>	<u>24.552</u>	<u>27.661</u>	<u>23.771</u>
	<u>17.296</u>	<u>24.725</u>	<u>25.796</u>	<u>28.547</u>	<u>23.030</u>
	<u>15.954</u>	1.449	1.148	.796	.642
	1.482				

TABLE IV-4. AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I}_{CONC}$, IN $\frac{1}{2}$ " KENICS MIXER WITH 3% CMC SOLUTION

CMC Flow Rate ml/min	Water Flow Rate ml/min				
	360	775	1205	1640	2080
5.4 Run Series SK008	23.468	39.511	43.679	52.205	49.770
	31.311	41.235	47.126	47.514	48.746
	25.793	41.671	53.104	56.933	53.989
	<u>23.530</u>	<u>40.806</u>	<u>47.970</u>	<u>52.217</u>	<u>50.835</u>
	26.026	1.142	4.769	4.710	2.779
	3.686				
7.7 Run Series SK009	24.541	30.003	41.757	48.885	48.286
	26.033	30.961	45.542	46.878	49.387
	22.498	36.367	42.994	51.293	48.208
	<u>30.128</u>	<u>32.444</u>	<u>43.431</u>	<u>49.019</u>	<u>48.627</u>
	25.800	3.431	1.930	2.211	.659
	3.229				
13.5 Run Series SK010	21.046	23.467	27.314	39.489	43.132
	20.608	24.899	25.527	39.642	44.449
	20.054	27.581	25.662	40.315	44.219
	<u>20.218</u>	<u>25.316</u>	<u>25.170</u>	<u>39.815</u>	<u>43.933</u>
	20.482	2.088	25.918	.439	.703
	.442		.953		

TABLE IV-5. AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I}_{\text{CONC}}$, IN $\frac{1}{2}$ " KENICS MIXER WITH 4% CMC SOLUTION

CMC Flow Rate ml/min	Water Flow Rate ml/min				
	360	775	1205	1640	2080
5.4 Run Series SK014	42.390	36.092	67.970	77.133	91.402
	36.244	12.592	79.172	79.152	77.592
	<u>47.837</u>	11.652	81.787	<u>73.469</u>	<u>87.384</u>
	42.157	15.668	<u>77.263</u>	<u>76.585</u>	<u>85.459</u>
	5.800	<u>10.575</u>	<u>76.548</u>	2.881	7.103
		<u>17.316</u>	6.012		
		10.666			
5.4 Run Series SK017	43.401	10.569	65.395	88.557	
	48.840	10.187	64.048	78.166	
	<u>41.875</u>	<u>15.703</u>	<u>73.648</u>	<u>73.968</u>	
	44.705	<u>12.153</u>	<u>67.697</u>	<u>80.224</u>	
	3.661	3.080	5.198	7.499	
9.1 Run Series SK015	19.635	38.475	70.271	64.099	69.383
	23.973	49.983	54.802	70.480	75.548
	<u>18.864</u>	<u>52.435</u>	<u>83.207</u>	<u>54.396</u>	85.569
	20.824	<u>46.964</u>	<u>69.427</u>	<u>62.992</u>	<u>69.109</u>
	2.754	7.453	14.221	8.099	<u>74.902</u>
					7.708
16.1 Run Series SK016	21.264	35.427	42.655	41.216	53.905
	19.645	32.300	<u>49.512</u>	45.844	48.532
	<u>19.061</u>	<u>36.252</u>	<u>46.084</u>	<u>49.126</u>	<u>47.474</u>
	19.990	<u>34.660</u>	4.849	<u>45.395</u>	<u>49.970</u>
	1.141	2.085		3.974	3.448

TABLE IV-6. AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I}_{CONC}$, IN 3/4" KENICS MIXER WITH 1% CMC SOLUTION

CMC Flow Rate ml/min	Water Flow Rate ml/min				
	360	775	1205	1640	2080
5.6 Run Series LK002	1.429	1.319	1.158	1.842	1.619
	3.643	1.280	1.183	2.820	1.405
	<u>2.223</u>	<u>1.055</u>	<u>1.166</u>	<u>1.691</u>	<u>1.601</u>
	2.432	1.218	1.169	2.118	1.542
	1.122	.143	.013	.613	.119
9.6 Run Series LK003	2.225	1.396	1.247	2.215	1.727
	2.229	1.371	1.576	1.850	1.994
	<u>1.864</u>	<u>1.230</u>	<u>1.339</u>	<u>1.659</u>	<u>1.963</u>
	2.106	1.332	1.387	1.908	1.895
	.210	.090	.170	.283	.146
16.2 Run Series LK004	1.815	1.843	1.537	1.375	2.009
	1.596	1.938	1.308	1.363	1.986
	<u>1.644</u>	<u>3.052</u>	<u>1.650</u>	<u>1.377</u>	<u>2.062</u>
	1.685	2.278	1.498	1.372	2.019
	.115	.672	.174	.008	.039

TABLE IV-7. AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I}_{CONC}$, IN 3/4" KENICS MIXER WITH 2% CMC SOLUTION

CMC Flow Rate ml/min	Water Flow Rate ml/min				
	360	775	1205	1640	2080
5.6 Run Series LK008	10.732	14.237	16.243	21.273	21.044
	12.692	21.246	18.420	25.541	20.049
	16.079	16.317	17.980	13.045	17.808
	13.168	17.267	17.548	19.953	19.634
	2.705	3.600	1.151	6.352	1.657
9.4 Run Series LK009	17.163		12.060	17.402	15.705
	10.988		13.348	15.695	15.989
	14.076		12.474	16.663	19.492
	4.366		12.627	16.587	17.062
			.658	.856	2.109
10.15 Run Series LK011	6.311	14.049	13.266	13.633	15.336
	7.040	11.445	9.042	11.334	18.942
	8.223	13.014	12.249	14.803	16.722
	7.191	12.836	11.519	13.257	17.000
	.965	1.311	2.206	1.765	1.819
15.8 Run Series LK010	9.913	12.030	10.263	15.271	12.175
	8.520	12.278	11.201	15.752	15.770
	8.376	14.052	10.753	15.535	15.770
	8.936	12.787	10.739	15.519	16.060
	.849	1.103	.469	.241	13.097
					15.148
					2.571

TABLE IV-8. AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I}_{CONC}$, IN 3/4" KENICS MIXER WITH 3% CMC SOLUTION

Water Flow Rate ml/min CMC Flow Rate ml/min	360	775	1205	1640	2080
5.5 Run Series LK005	14.470	23.631	34.228	33.528	36.121
	14.059	23.490	29.333	30.170	33.261
	14.558	25.695	27.579	30.537	33.691
	14.362	24.272	30.380	31.412	34.358
	.266	1.234	3.446	1.842	1.542
9.1 Run Series LK006	10.236	18.038	21.402	26.931	25.644
	12.149	22.375	20.933	26.083	27.313
	13.737	21.862	21.934	28.877	32.061
	12.041	15.359	21.423	27.297	28.339
	1.753	19.409	.501	1.433	3.329
		3.321			
16.3 Run Series LK007	9.561	14.972	17.080	20.232	22.508
	8.993	13.788	14.470	19.461	21.384
	10.629	14.921	15.885	17.953	22.342
	9.728	14.560	15.812	19.215	22.078
	.831	.669	1.307	1.159	.607

TABLE IV-9. AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I}_{CONC}$, IN 3/4" KENICS MIXER WITH 4% CMC SOLUTION

CMC Flow Rate ml/min	Water Flow Rate ml/min				
	360	775	1205	1640	2080
5.5 Run Series LK012	24.598	34.289	33.288	46.010	49.689
	20.870	28.059	50.777	37.557	38.425
	<u>21.894</u>	<u>25.358</u>	<u>52.630</u>	<u>46.214</u>	<u>46.526</u>
	<u>22.454</u>	<u>29.235</u>	<u>45.565</u>	<u>43.260</u>	<u>44.880</u>
	1.926	4.580	10.672	4.940	5.810
9.5 Run Series LK013	15.250	21.212	31.081	35.064	36.318
	18.318	30.008	32.613	33.855	35.986
	19.677	<u>30.145</u>	<u>37.125</u>	<u>33.448</u>	<u>38.062</u>
	17.022	<u>27.122</u>	<u>33.606</u>	<u>34.122</u>	<u>36.789</u>
	<u>17.564</u>	5.118	3.142	.841	1.115
	<u>17.566</u>				
	1.634				
15.0 Run Series LK014	15.606	19.009	21.457	27.203	24.187
	17.222	14.932	23.027	31.690	30.295
	<u>11.073</u>	<u>20.978</u>	<u>25.743</u>	<u>25.985</u>	<u>32.799</u>
	<u>14.634</u>	<u>18.306</u>	<u>23.409</u>	<u>28.293</u>	<u>29.094</u>
	3.188	3.084	2.168	3.005	4.430

TABLE IV-10. AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I}_{\text{CONC}}$, IN ROSS LPD MIXER WITH 1% CMC SOLUTION

Water Flow Rate ml/min CMC Flow Rate ml/min	360	775	1205	1640	2080
5.8 Run Series LPD002	9.909	1.281	1.300	1.130	1.155
	3.928	1.245	1.096	1.152	1.185
	<u>5.262</u>	<u>1.319</u>	<u>1.080</u>	<u>1.131</u>	<u>1.162</u>
	6.366	1.282	1.159	1.138	1.167
	3.140	.037	.123	.012	.016
10.3 Run Series LPD003	11.705	1.522	1.199	1.306	1.350
	9.832	1.092	1.259	1.294	1.363
	<u>7.717</u>	<u>1.386</u>	<u>1.195</u>	<u>1.302</u>	<u>1.362</u>
	9.751	1.333	1.218	1.301	1.358
	1.995	.220	.036	.006	.007
17.4 Run Series LPD004	7.632	3.150	1.235	1.306	1.241
	8.690	2.698	1.227	1.460	1.266
	<u>8.240</u>	<u>1.546</u>	<u>1.179</u>	<u>1.611</u>	1.414
	8.187	2.465	1.214	1.459	1.291
	.531	.827	.030	.153	1.324
				<u>1.306</u>	1.307
					.060

TABLE IV-11. AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I}_{CONC}$, IN ROSS LPD MIXER WITH 2% CMC SOLUTION

CMC Flow Rate ml/min	Water Flow Rate ml/min				
	360	775	1205	1640	2080
5.4 Run Series LPD008	8.177	34.813	33.404	22.907	22.802
	<u>12.972</u>	36.781	35.797	32.702	22.167
	<u>10.575</u>	<u>29.325</u>	<u>30.077</u>	<u>24.411</u>	<u>23.162</u>
	3.391	33.640	33.093	26.673	22.710
		3.864	2.873	5.275	.504
9.2 Run Series LPD009	6.095	24.190	27.540	30.035	25.521
	12.404	26.918	33.367	33.897	26.029
	<u>11.265</u>	<u>26.853</u>	<u>27.523</u>	<u>33.647</u>	<u>30.246</u>
	9.921	25.987	29.477	32.527	27.265
	3.362	1.557	3.369	2.161	2.594
15.6 Run Series LPD010	6.036	23.149	29.833	28.936	25.100
	9.252	25.700	25.674	30.503	29.140
	<u>7.706</u>	<u>28.573</u>	<u>30.052</u>	<u>26.635</u>	<u>29.353</u>
	7.665	25.807	28.520	28.691	27.864
	1.608	2.714	2.467	1.946	2.396

TABLE IV-12. AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I}_{CONC}$, IN ROSS LPD MIXER WITH 3% CMC SOLUTION

CMC Flow Rate ml/min	Water Flow Rate ml/min				
	360	775	1205	1640	2080
5.3 Run Series LPD005	26.351	25.973	34.361	36.598	32.441
	21.485	27.055	31.790	39.143	35.419
	42.118	24.907	37.045	36.622	30.420
	29.985	25.978	34.399	37.626	32.760
	10.786	1.074	2.628	37.497	2.515
				1.198	
9.1 Run Series LPD006	38.187	21.365	22.321	35.950	37.121
	29.406	28.539	19.842	30.342	36.281
	36.148	17.456	24.302	37.808	35.424
	18.674	22.453	22.155	34.700	36.275
	30.604	5.621	2.235	3.887	.849
	8.794				
14.0 Run Series LPD007	17.135	17.237	18.372	30.857	35.123
	22.936	21.416	21.552	32.635	33.252
	18.744	21.132	16.892	26.193	34.641
	19.605	19.928	18.939	29.895	34.339
	2.995	2.335	2.381	3.327	.971

TABLE IV-13. AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I_{CONC}}$, IN ROSS LPD MIXER WITH 4% CMC SOLUTION

Water Flow Rate ml/min CMC Flow Rate ml/min	360	775	1205	1640	2080
5.3 Run Series LPD011	48.257	29.064	36.795	33.950	92.260
	<u>40.423</u>	25.381	<u>24.037</u>	29.279	89.669
	<u>44.340</u>	<u>24.460</u>	<u>30.416</u>	<u>98.589</u>	<u>94.012</u>
	5.539	<u>26.302</u>	9.021	<u>53.939</u>	<u>91.980</u>
		2.436		38.738	2.185
9.3 Run Series LPD012	34.967	37.938	27.800	47.077	75.261
	37.380	42.651	47.302	62.784	73.406
	<u>39.301</u>	<u>18.772</u>	<u>32.638</u>	<u>62.078</u>	<u>80.153</u>
	<u>37.216</u>	<u>33.120</u>	<u>35.913</u>	<u>57.313</u>	<u>76.273</u>
	2.172	12.647	10.155	8.872	3.486
16.2 Run Series LPD013	32.147	34.322	37.841	47.771	27.794
	20.420	28.455	26.151	33.765	16.038
	<u>37.657</u>	<u>41.724</u>	<u>19.524</u>	<u>41.649</u>	<u>12.838</u>
	<u>30.075</u>	<u>34.834</u>	<u>27.839</u>	<u>41.062</u>	<u>18.890</u>
	8.803	6.649	9.274	7.021	7.875

TABLE IV-14. AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I}_{\text{CONC}}$, IN ROSS ISG MIXER WITH 1% CMC SOLUTION

Water Flow Rate ml/min CMC Flow Rate ml/min	360	775	1205	1640	2080
5.7 Run Series ISG004	2.121	2.351	2.313	2.294	2.636
	2.114	2.452	2.340	2.267	2.764
	<u>2.147</u>	<u>2.339</u>	<u>2.322</u>	<u>2.281</u>	<u>2.612</u>
	2.127	2.381	2.325	2.281	2.671
	.017	.062	.014	.014	.082
10.0 Run Series ISG003	2.199	2.373	2.564	2.439	2.988
	2.199	2.399	2.544	2.489	2.618
	<u>2.175</u>	<u>2.371</u>	<u>2.504</u>	<u>2.909</u>	<u>3.450</u>
	2.191	2.381	2.537	2.612	3.019
	.014	.016	.031	.258	.417
14.7 Run Series ISG002	2.713	2.872	2.556	2.499	3.027
	2.647	2.715	2.567	2.483	3.013
	<u>2.653</u>	<u>2.797</u>	<u>2.567</u>	<u>2.495</u>	<u>2.727</u>
	2.671	2.795	2.563	2.476	2.757
	.036	.079	.006	.024	<u>3.011</u>
					2.907
					.151

TABLE IV-15. AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I}_{CONC}$, IN ROSS ISG MIXER WITH 2% CMC SOLUTION

Water Flow Rate ml/min CMC Flow Rate ml/min	360	775	1205	1640	2080
5.2	15.275	25.277	21.207	10.875	3.292
	20.379	25.445	20.559	13.949	4.230
	17.647	24.149	22.471	15.501	3.531
Run Series ISG008	17.767	24.957	21.412	13.442	3.684
	2.554	.705	.972	2.354	.487
7.2	15.768	21.214			
	11.403	25.531			
	19.429	26.297			
Run Series ISG009	19.722	24.347			
	13.382	2.740			
	15.941				
	3.662				
8.7			26.553	22.761	10.141
			26.595	21.222	9.822
			27.916	19.563	9.723
Run Series ISG009			27.021	21.182	9.895
			.775	1.599	.218
16.0	11.328	19.672	24.684	21.026	12.730
	11.372	16.539	23.916	18.943	12.559
	12.010	17.240	24.330	20.541	12.768
Run Series ISG010	11.570	17.817	24.310	20.170	12.686
	.382	1.644	.384	1.090	.111

TABLE IV-16. AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I}_{CONC}$, IN ROSS ISG MIXER WITH 3% CMC SOLUTION

Water Flow Rate ml/min CMC Flow Rate ml/min	360	775	1205	1640	2080
5.2	20.006	46.975	39.956	28.732	39.178
	14.295	39.962	34.757	33.044	35.577
	18.552	39.176	40.441	30.294	33.197
Run Series ISG005	17.618	42.038	38.385	30.690	35.984
	2.968	4.294	3.151	2.183	3.011
8.8	16.331	14.805	37.620	35.388	29.638
	18.327	12.525	42.164	34.771	29.258
	9.205	14.035	38.618	35.116	30.659
Run Series ISG006	14.621	13.788	39.467	35.092	29.852
	4.795	1.160	2.388	.309	.725
16.8	12.203	24.130	32.122	36.816	33.078
	11.460	23.274	32.723	36.597	33.582
	10.595	25.554	35.349	36.950	32.727
Run Series ISG007	11.419	24.319	33.398	36.788	33.129
	.805	1.151	1.716	.178	.430

TABLE IV-17. AVERAGE INTENSITY OF CONCENTRATION TURBULENCE, $\overline{I}_{CONC}$, IN ROSS ISG MIXER WITH 4% CMC SOLUTION

Water Flow Rate ml/min CMC Flow Rate ml/min	360	775	1205	1640	2080
5.0 Run Series ISG013	34.362	44.307	27.768	13.732	12.148
	47.396	74.528	28.142	10.811	6.164
	<u>35.595</u>	<u>52.784</u>	<u>19.753</u>	<u>11.028</u>	<u>11.053</u>
	39.118	57.186	25.221	11.857	9.788
	7.196	15.597	4.739	1.627	3.186
8.8 Run Series ISG012	23.443	40.853	42.415	24.377	18.375
	21.620	44.760	44.361	20.148	16.281
	<u>27.606</u>	<u>29.115</u>	<u>55.592</u>	<u>21.568</u>	<u>18.058</u>
	24.223	38.243	47.456	22.031	17.571
	3.068	8.143	7.113	2.152	1.129
16.4 Run Series ISG011	7.660	52.200	61.942	41.003	37.852
	7.484	60.410	75.619	38.853	29.278
	<u>13.165</u>	<u>58.545</u>	<u>79.721</u>	<u>44.067</u>	<u>29.321</u>
	9.436	57.052	72.427	41.308	32.150
	3.230	4.304	9.309	2.620	4.938

B. Discussion of the Kenics Static Mixer

1. Visual Observations

The evaluation of the data for the Kenics Static Mixers was to some extent easier than with the other two mixers because, since the Kenics mixers were placed in clear plastic tubes rather than steel pipes, observations of the mixing action inside the mixer could be noted during the runs.

Basically three different phenomena were observed while making runs with the Kenics mixers. These phenomena will be called homogenation, blocking, and channeling. Homogenation is simply the breaking up of the injected CMC stream into smaller "chunks", or pieces. It was always initiated by the division of the polymer stream on the leading edge of a mixing element and is the result of the mixing actions described in Chapter 1. Blocking is the filling of one side of a element with polymer solution, temporarily forcing all flow through the other side of the element. Blocking causes two different actions: 1) the CMC stream that had been flowing into one side of an element was forced to flow into the other side often causing that side to be blocked just as flow resumed through the side originally blocked, 2) the blocked side was divided in half by the succeeding mixer element, thus initiating the homogenation phenomenon. When the polymer stream was injected into the water stream, it would usually travel through

at least one, and often several, elements in a single thread or stream before homogenation was initiated. This is the phenomenon that will be called channeling. The effect of channeling was that the elements through which the polymer stream was channeled would provide negligible mixing. Usually once homogenation was initiated by an element, channeling would cease past that point in the mixer.

Blocking occurred more frequently and was more complete with the $\frac{1}{2}$ inch mixer than with the $\frac{3}{4}$ inch mixer. In the $\frac{3}{4}$ inch mixer, the complete filling of one side of an element was never observed; however, one side would become blocked enough to force the rest of the water and CMC through the other side of the element. Blocking occurred only at the two lower water flow rates and was more frequent the higher the CMC flow rate and the higher the CMC concentration. Blocking usually occurred in the second to fifth element in the mixer and was always preceded by channeling, except when the 3% or 4% CMC solutions were injected at the highest CMC flow rate into the water at its lowest flow rate in the $\frac{1}{2}$ inch mixer. In these cases blocking occurred in the first element.

Channeling was also more prominent in the $\frac{1}{2}$ inch mixer than the $\frac{3}{4}$ inch mixer, in that the polymer stream would extend through a greater number of elements in the smaller mixer. This phenomenon is undoubtedly the primary reason that I_{CONC} is much higher in

the smaller mixer. Channeling occurred at all flow rates, but was more prominent at intermediate rates. At low rates blocking would occur which almost always ended the channeling, while at the high flow rates the polymer "string" became thinner and was more easily bent over the leading edges of the elements and broken.

At one flow combination in the smaller mixer the channeling was so severe that the polymer stream went through the entire mixer, past the probe array, to the screen electrode in one piece. This, of course, resulted in deceptively low values of $\overline{I}_{CONC}$ for the run. This occurred with a 4% CMC solution injected at its lowest rate (5.4 ml/min) into a water stream flowing at 775 ml/min. Because the fluctuations seemed to be low while the runs were being made, five runs were made instead of three. Figure IV-9 shows $\overline{I}_{CONC}$ versus total flow rate¹ for the runs made with the lowest CMC injection rate in the ½ inch Kenics mixer. It can be seen that a value of $\overline{I}_{CONC}$ expected for the 4% CMC solution at the 775 ml/min flow rate would be between 60% and 70%, however the value obtained was about 17%. In an effort to explain the seemingly low value, the run series was repeated a few days later with similar results (see Table IV-5)

¹The total flow rate can be considered as equal to the water flow rate because the water rate could only be accurately maintained to ± 1 rotameter reading, which corresponds approximately to ± 20 ml/min. Since the highest CMC flow rate was about 17 ml/min, it is always less than the error involved in measuring the water flow rate. Also the CMC flow rate is always less than 5% of the water flow rate.

and it was at this time that the channeling was observed. It was found that by rapidly increasing and decreasing the water flow, homogenization could be initiated and maintained for 45 to 60 seconds after the flow fluctuations were ceased. Data for one complete run were taken during this period of induced homogenization and the value of $\overline{I}_{\text{CONC}}$ for that run was 68%.

Karnis, Goldsmith, and Mason (32) found that when inertial forces were important ($Re > 1$), suspensions of deformable drops, fibers, and filaments migrated toward the axis with steady flow in a circular tube, provided that the viscosity ratio was not high enough to make the drops quasi-rigid. Hence the particles tended to migrate toward the radial position where the axial velocity, v_z , was highest and

where $\frac{\partial v_z}{\partial r} \approx 0$.

This phenomenon is possibly part of the cause of the channeling effect. The stream of CMC is probably simply following a path through the mixer where the change in velocity with respect to the change in position on the plane normal to the velocity is at a minimum. The stream probably follows this path until the flow pattern is disturbed by part of the polymer string contacting and "catching" the leading edge of an element and thus initiating either the blocking or homogenizing actions. Also, because the CMC solutions are viscoelastic, the molecules will tend to hold together so that once a stream of CMC has channeled through part of the mixer it

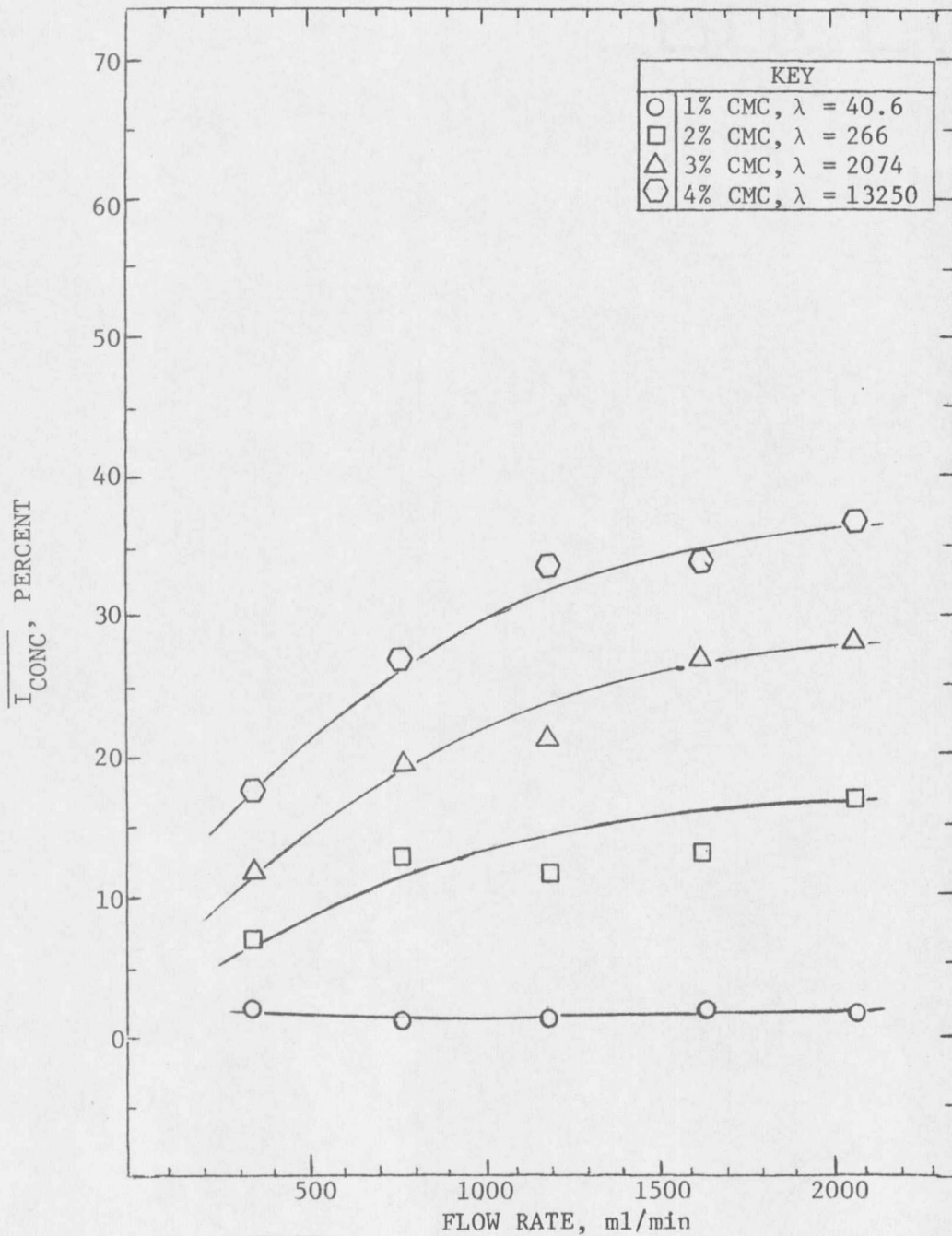


FIGURE IV-3. I_{CONC} VERSUS TOTAL FLOW RATE IN 3/4" KENICS STATIC MIXER AT LOW CMC INJECTION RATE (5.1 to 5.4 ml/min)

will continue to do so unless some part of the stream is subjected to enough force to cause it to break. Unlike the Ross mixers, the Kenics mixers have a constant cross-sectional area so the only time the fluids are subjected to "severe" accelerations is when passing from one element to the next, and most of the acceleration is in an angular or radial direction due to the alternate left and right hand element configurations. The fact that the trailing and leading edges of successive elements are oriented 90° apart will cause some axial accelerations due to the loss and gain of shear on the trailing and leading surfaces, respectively, of the elements in the transition between the two, but the magnitude of these forces is probably lower than the alternating angular and radial forces.

2. Averaged Intensity of Concentration Turbulence

Figure IV-3 shows the effect of viscosity ratio, λ , in the Kenics mixers for laminar flow. The shape of the curves is typical of all those taken in the 3/4 inch Kenics mixer and of those taken in the smaller Kenics mixer with a higher average viscosity. Figure IV-3 shows that the average intensity of concentration turbulence, $\overline{I}_{\text{CONC}}$, increases with increasing viscosity ratio indicating poorer mixing. It appears that $\overline{I}_{\text{CONC}}$ increases with flow rate, but this upward trend with flow rate is actually due to the lowering of the mix ratio (ratio of CMC flow rate to water flow rate) in moving from the

left to the right on the plot². This effect is better shown in Figure IV-4. This figure plots $\overline{I}_{CONC}$ versus flow rate for the three CMC injection rates. It shows that at each total flow rate $\overline{I}_{CONC}$ is higher, the lower the mix ratio. Also shown in Figure IV-4 are lines of constant mix ratio. It is important to note that these lines are nearly horizontal, indicating that, at a given viscosity ratio, $\overline{I}_{CONC}$ is dependent mainly on mix ratio rather than flow rate. Also the logarithmic spacing of the mix ratio lines indicates that $\overline{I}_{CONC}$ is proportional to $\ln(\text{mix ratio})$. This relationship is shown in Figure IV-5 which better shows the relationship between $\overline{I}_{CONC}$ and mix ratio. This figure shows that, over the range of flow velocities used in the 3/4 inch Kenics mixer, $\overline{I}_{CONC}$ is not related to flow rate but is directly related to viscosity ratio and mix ratio.

The runs in the 1/2 inch Kenics mixer were made at the same volumetric flow rates as in the larger mixer, hence the velocities in the 1/2 inch mixer were higher. It was found that at higher velocities the magnitude of $\overline{I}_{CONC}$ started to decrease. This effect is due to the onset of momentum turbulence in the mixer. By "onset of turbulence" it is meant that a velocity is reached at which the fluid in the mixer has sufficient kinetic energy so that disturbances in

²The reader is reminded that run series were made at a constant CMC injection rate with a varying flow rate. Hence at higher flow rates the mix ratio is lower.

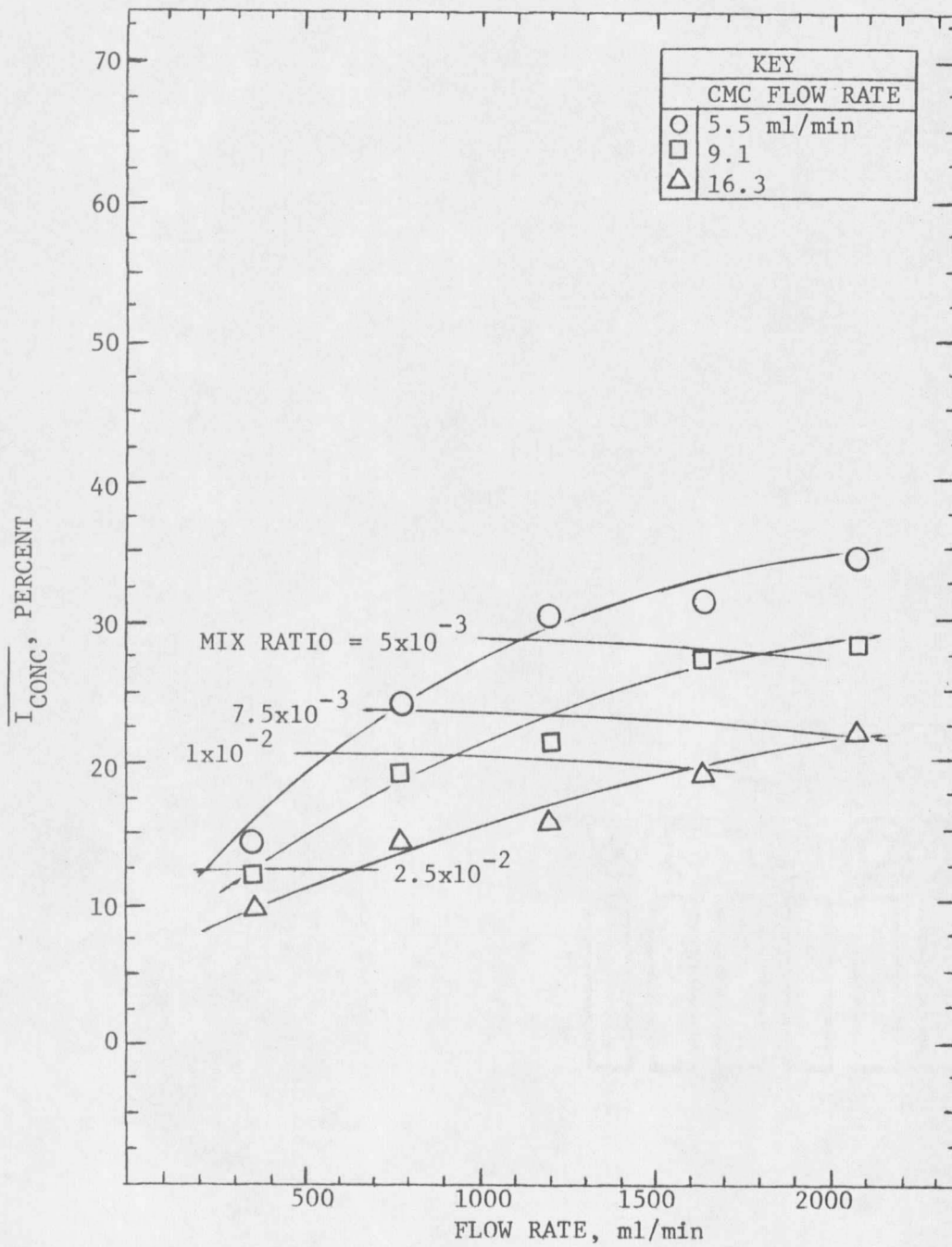


FIGURE IV- 4. $\overline{I_{CONC}}$ VERSUS TOTAL FLOW RATE IN 3/4" KENICS STATIC MIXER WHILE INJECTING 3% CMC SOLUTION ($\lambda = 2074$)

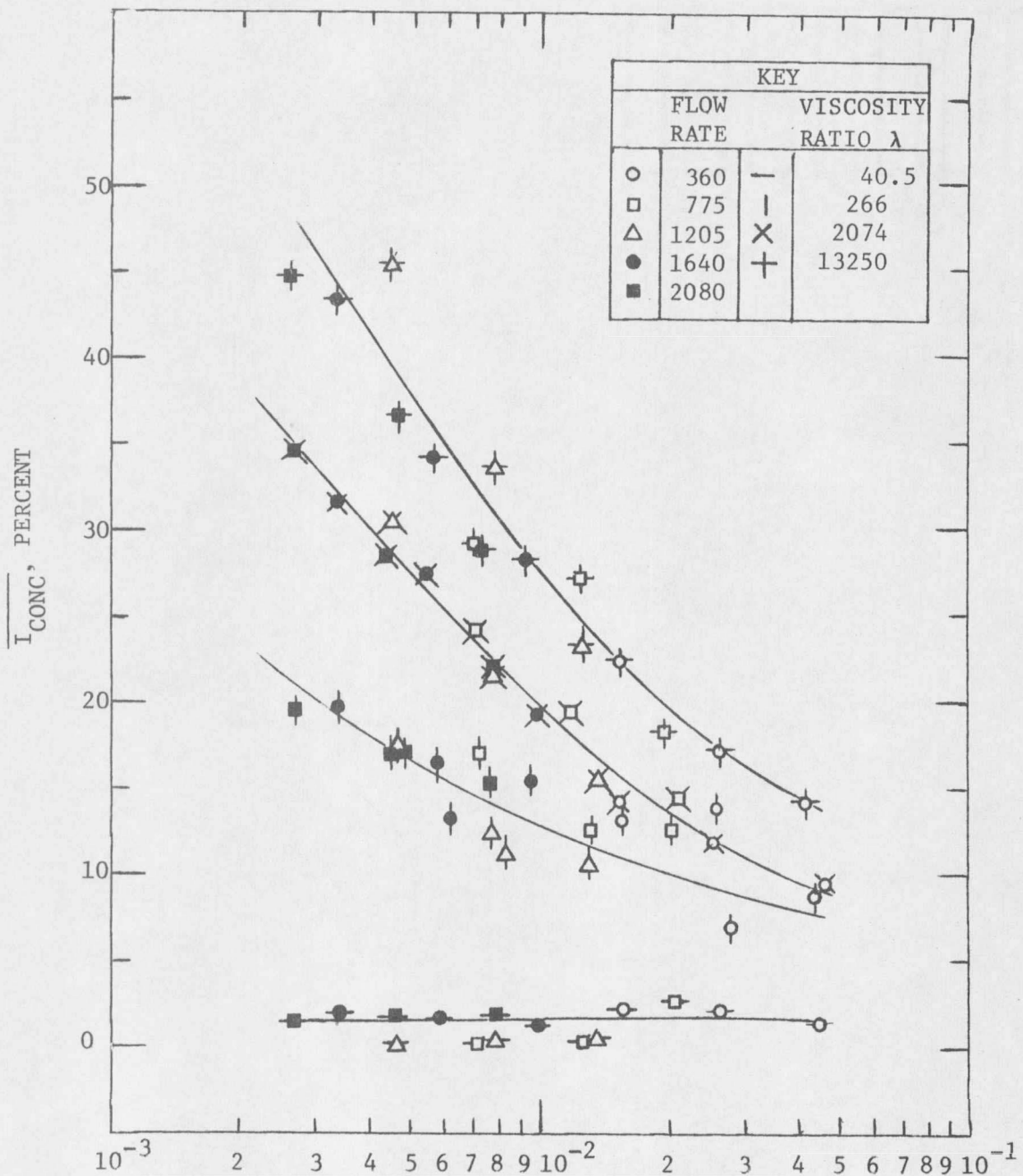


FIGURE IV-5. $\overline{I}_{CONC}$ VERSUS MIX RATIO FOR 3/4" KENICS STATIC MIXER.

the flow do not tend to diminish. Figure IV-6 is a plot of $\overline{I}_{CONC}$ versus mix ratio in the smaller Kenics mixer. This figure demonstrates the effect of momentum turbulence in decreasing the magnitude of concentration turbulence. It should be noted that no momentum turbulence is indicated while injecting the 4% solution and that the effect of momentum turbulence becomes more pronounced at lower average viscosities (lower mix ratios and viscosity ratios). Figures IV-7 and IV-8 further demonstrate this effect. Figure IV-7 presents the data taken while injecting a 3% CMC solution. It shows that the onset of momentum turbulence occurs at a lower flow rate with a lower CMC injection rate. This is probably because at the lower CMC injection rates the average viscosity of the fluid in the mixer is lower so that for a given total flow rate, the fluid streams with the lower mix ratio would also have a higher Reynolds number due to the lower viscosity. The effect is shown more dramatically with the 2% CMC solution as shown in Figure IV-8. This figure also shows that mix ratio is not as important after the onset of turbulence. Indeed, it is possible that once turbulence has developed, better mixing would be observed with a lower mix ratio simply because there would be less to mix.

Figure IV-9 summarizes the effect of viscosity ratio on the onset of turbulence. As discussed earlier, the low data point on the curve for the 4% CMC solution data was due to an almost complete lack of mixing because of the channeling effect.

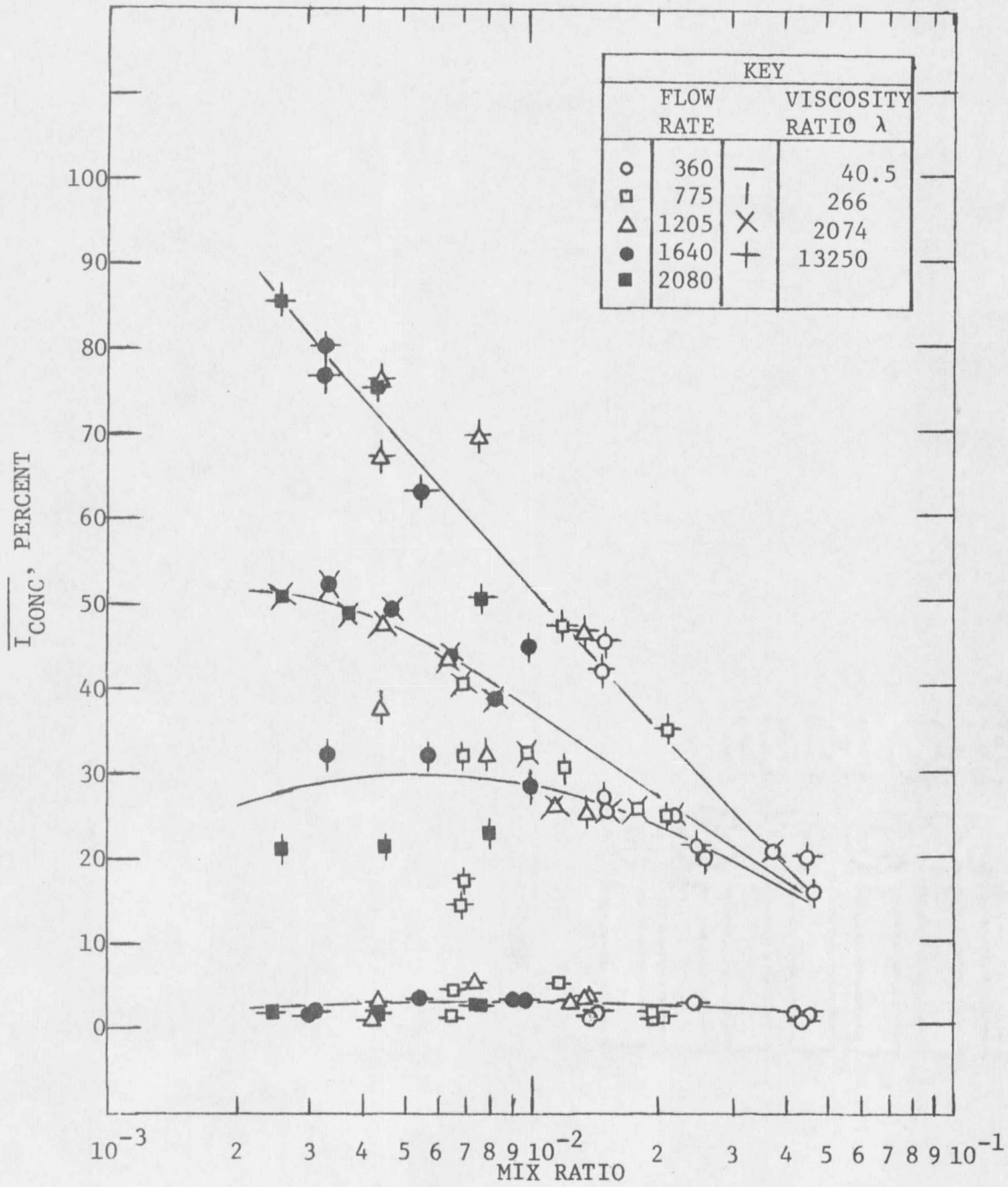


FIGURE IV-6. I_{CONC} VERSUS MIX RATIO FOR 1/2" KENICS STATIC MIXER

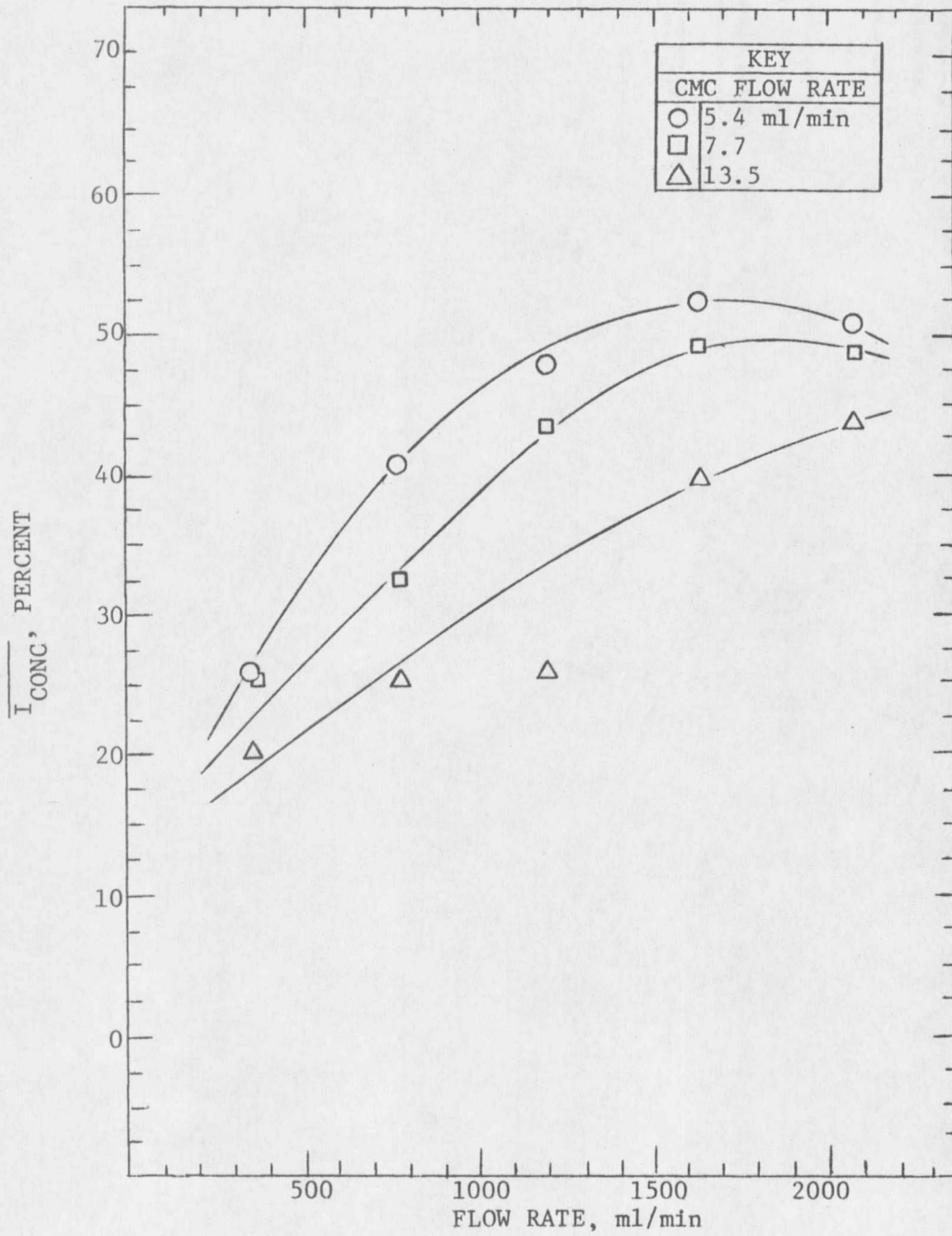


FIGURE IV-7. $\overline{I}_{CONC}$ VERSUS TOTAL FLOW RATE IN $\frac{1}{2}$ " KENICS STATIC MIXER WHILE INJECTING 3% CMC SOLUTION ($\lambda = 2074$)

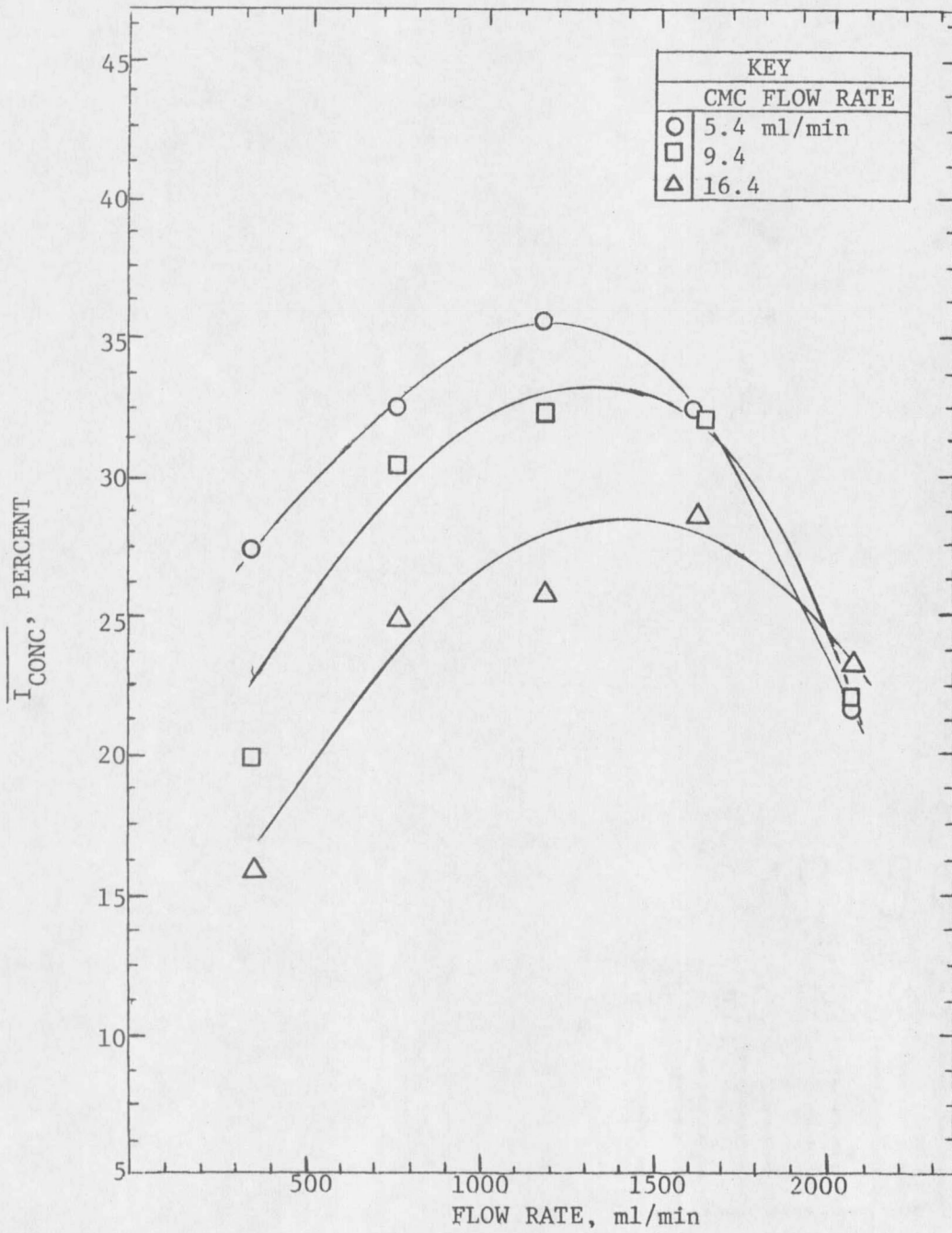


FIGURE IV-8. $\overline{I}_{CONC}$ VERSUS TOTAL FLOW RATE IN 1/2" KENICS STATIC MIXER WHILE INJECTING 2% CMC SOLUTION ($\lambda = 266$)

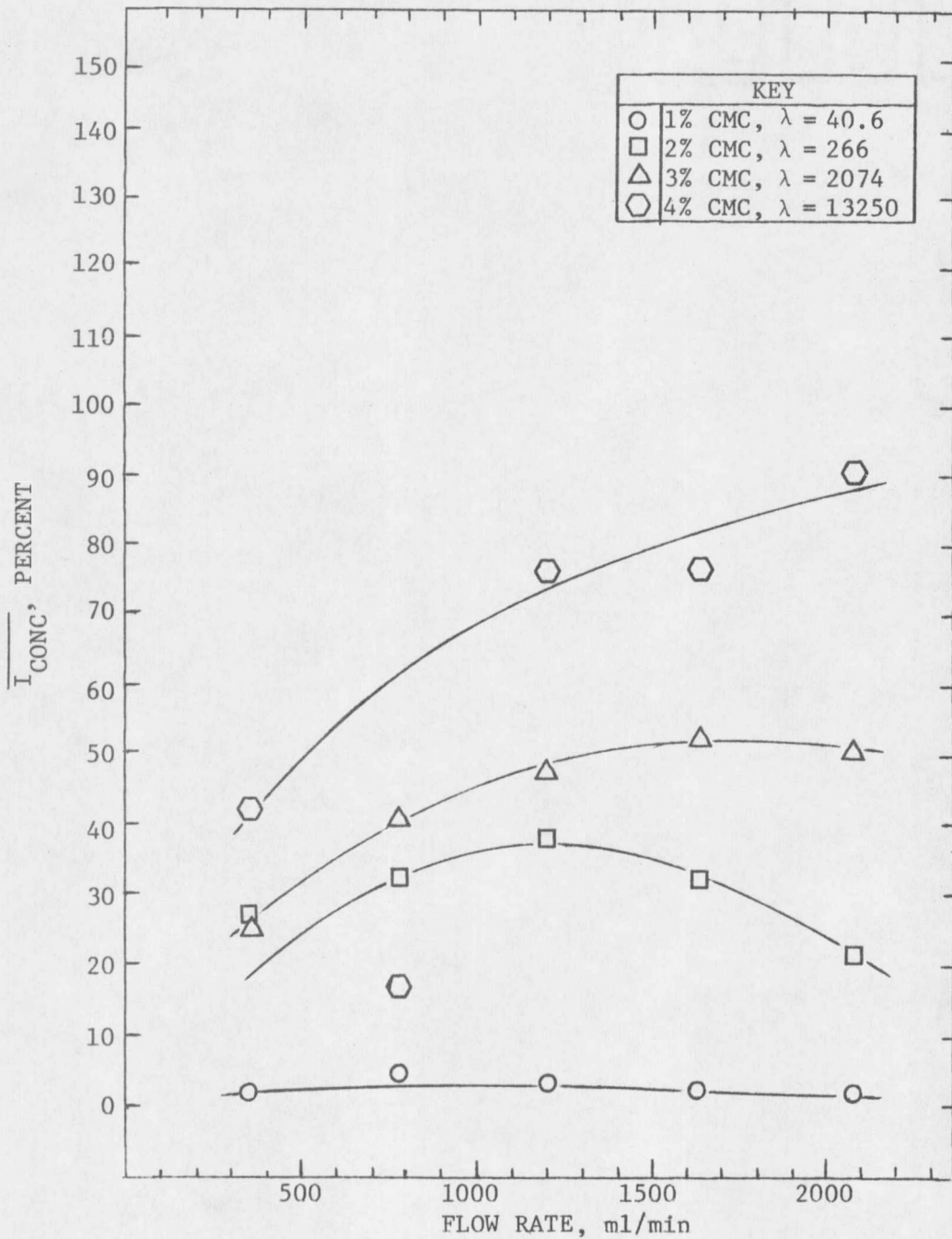


FIGURE IV-9. $\overline{I}_{CONC}$ VERSUS TOTAL FLOW RATE IN 1/2" KENICS STATIC MIXER AT LOW CMC INJECTION RATE (5.1 to 5.4 ml/min)

3. Radial Distributions

Figures IV-10 and IV-11 sketch typical intensity of concentration turbulence and concentration profiles, respectively, below the 3/4 inch Kenics mixer while injecting 3% and 4% CMC solutions. The curves became more exaggerated at higher flow rates (low mix ratios), but retained the same basic shape. The shape of the curve in Figure IV-10 is probably due to the effect of the CMC particles migrating to a position on each side of the elements at which the rate of change in axial velocity with respect to positions normal to that velocity ($\frac{\partial v}{\partial r}$ and $\frac{\partial v}{\partial \theta}$) is minimum. This would cause a higher concentration of CMC "pieces" at radial positions between the tube wall and the axis, and hence would cause a higher degree of concentration fluctuations at these positions. While injecting the lower concentration CMC solutions the basic shape of Figure IV-10 was retained but the curve was flatter indicating greater uniformity across the diameter. Also, with the lower concentration solutions the concentration profile was the same shape as the fluctuation profile, which is what would be expected with all the CMC solutions because of the migration of the higher concentration of CMC particles. The explanation for the higher center concentration with the higher viscosity solutions, as shown in Figure IV-11, is probably that some of the CMC gets caught on the last mixer element and gives the water passing over it a higher CMC concentration. Because of the

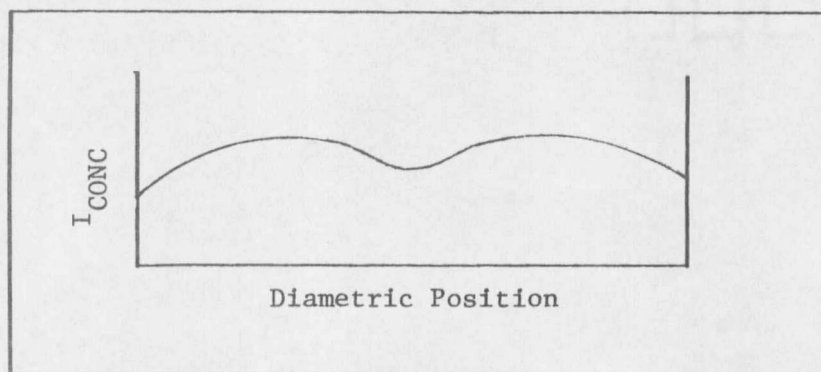


FIGURE IV-10. TYPICAL CONCENTRATION TURBULENCE PROFILE BELOW 3/4 INCH KENICS MIXER

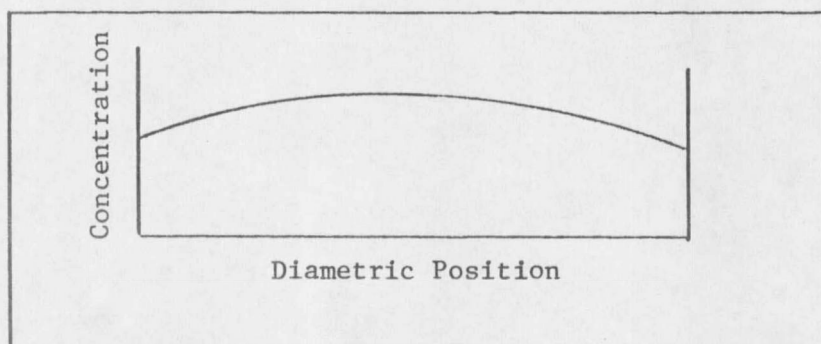


FIGURE IV-11. TYPICAL CONCENTRATION PROFILE BELOW 3/4 INCH KENICS MIXER WHILE INJECTING 3% AND 4% CMC SOLUTION

higher viscosity at the higher CMC concentrations these polymer solutions would be more likely to stick to the last element.

In the $\frac{1}{2}$ inch Kenics mixer, the profiles had a shape similar to the curve of Figure IV-11, except that, especially at lower flow rates, both the concentration and I_{CONC} were higher on one side than the other. This is probably a result of the channeling and blocking actions discussed in the beginning of this section. At the higher flow rates the profiles became flatter indicating more uniform CMC distribution. The flatter profiles are probably due to momentum turbulence at the higher flow rates.

C. Discussion of the Ross LPD Mixer

1. Averaged Intensity of Concentration Turbulence

Because the configurations of the Ross LPD are such that the cross-sectional area, as well as the direction of flow, is constantly changing, a fluid flowing through one of these mixers is subjected to a wider variety of accelerations, in three dimensions, than in the Kenics mixers. This resulted in greater promotion of momentum turbulence.

The behavior of the Ross LPD mixer while injecting a 2% CMC solution was similar to that of the small Kenics mixer. As shown in Figure IV-12, there is an increase in $\overline{I_{\text{CONC}}}$ as the flow rate starts to rise. This increase is probably due to the lowering of the mix ratio. Immediately after this increase, though, the

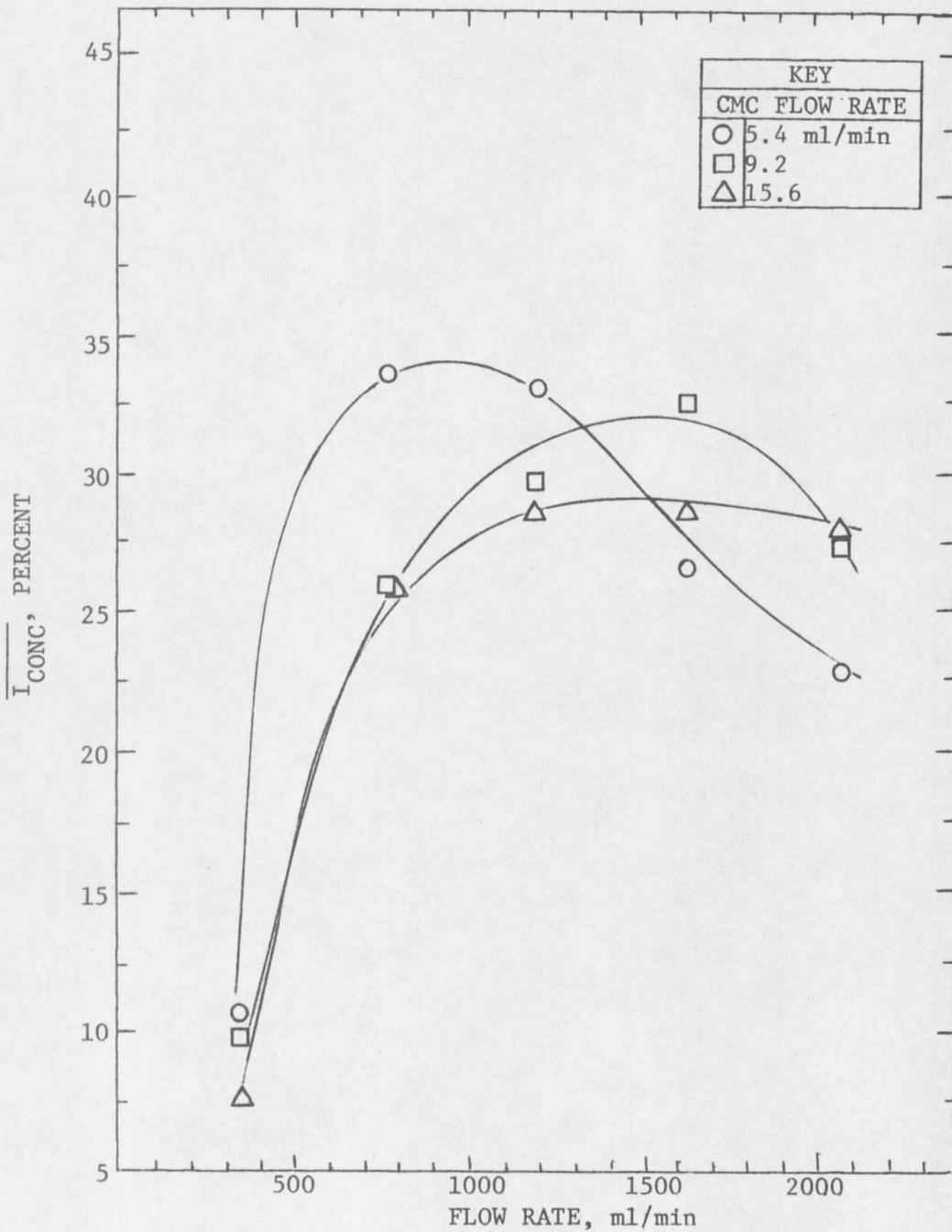


FIGURE IV-12. $\overline{I}_{CONC}$ VERSUS TOTAL FLOW RATE IN ROSS LPD MIXER WHILE INJECTING 2% CMC SOLUTION ($\lambda = 266$)

magnitude of $\overline{I}_{\text{CONC}}$ begins to drop due to the onset of momentum turbulence. As in the Kenics mixer, the momentum turbulence is observed at a lower flow rate at the lower mix ratios, probably because of the lower average viscosities of these streams.

The behavior of the Ross LPD mixer was not the same as with the Kenics mixer while injecting the 3% and 4% CMC solutions, in that rather than increasing with the lowering mix ratio at low flow rates, $\overline{I}_{\text{CONC}}$ decreased slightly and seemed independent of mix ratio. This is illustrated in Figure IV-13 by the downward slope of the curves at the lower flow rates. The curves take on a more expected shape at the highest flow rate, showing a relationship to mix ratio that might be expected before the onset of turbulence. Because Figure IV-13 shows data taken with the 4% CMC solution, it would be reasonable to assume that momentum turbulence would not be important at the flow rates studied (since turbulence was important with the much less viscous 2% solution). Hence the downward trend at the lower flow rates is due to some other effect. The trend may be due to a decrease in the apparent viscosity of the polymer at the higher shear rates present at the higher flow rates. At very low shear rates the apparent viscosity of a 4% CMC solution is very high, but because the flow behavior index is about 0.6, the apparent viscosity will drop rapidly with increasing shear as indicated by equation II-34.

Another possible explanation of the downward trend is that at

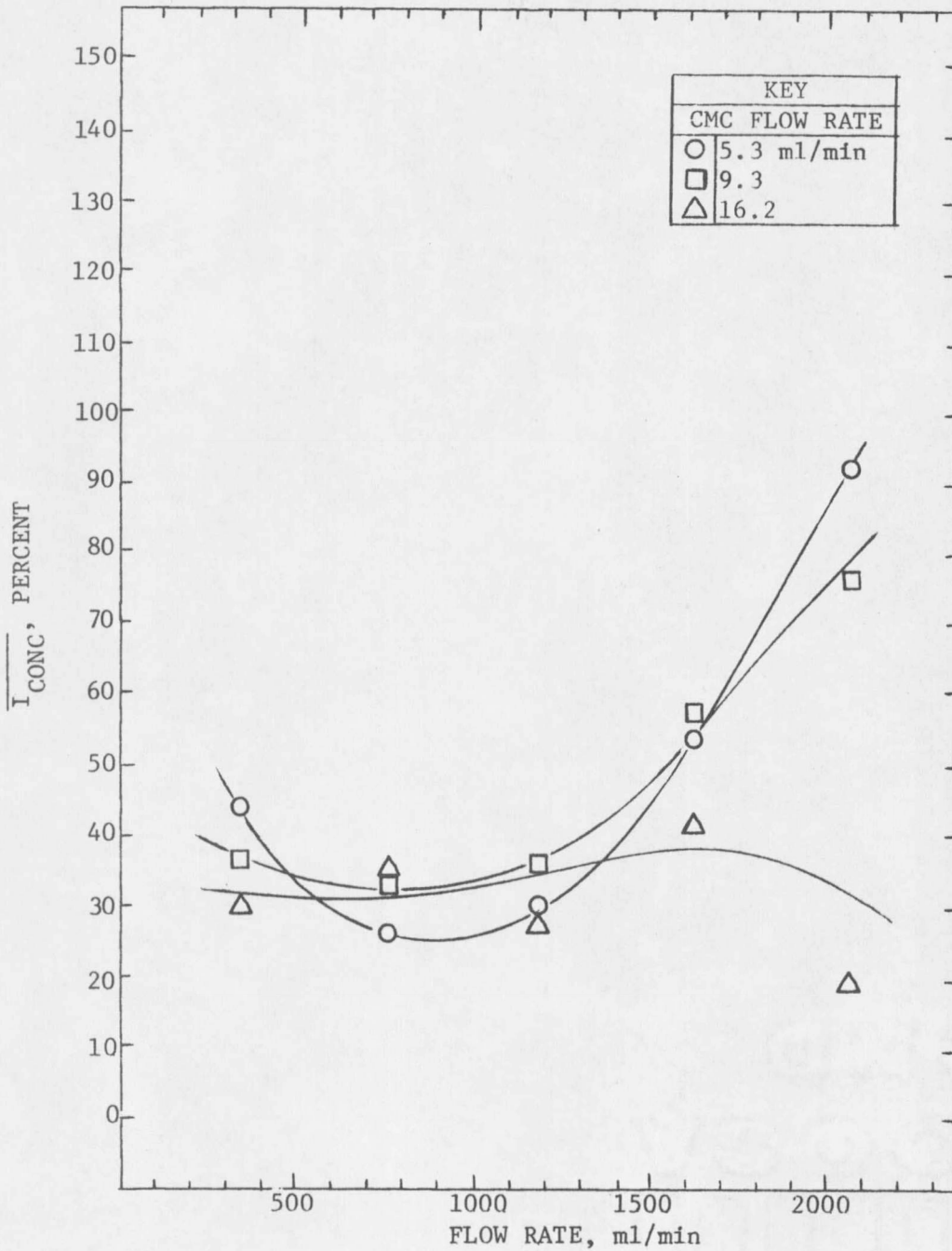


FIGURE IV-13. $\overline{I}_{CONC}$ VERSUS TOTAL FLOW RATE IN ROSS LPD MIXER WHILE INJECTING 4% CMC SOLUTION ($\lambda = 13250$)

low velocities through the mixer the acceleration forces on the fluid will be very small, so that the flow division characteristics of a mixer will be a major factor in the performance of a mixer at low flow rates. The Ross LPD mixer definitely does not have as strong a flow division action as the other two mixer designs, largely because of the relatively large distance between elements. The weaker flow division action could cause higher values of $\overline{I}_{CONC}$ at lower flow rates until the velocity gets high enough for the acceleration forces to contribute to the mixing action.

As a result of higher values of $\overline{I}_{CONC}$ at the lowest flow rates and the relatively early onset of momentum turbulence, the mixing performance of the Ross LPD mixer is not a strong function of mix ratio. As shown in Figure IV-14, there is much more scatter in $\overline{I}_{CONC}$ as related to mix ratio. Data for the 3% CMC solution were omitted from this figure because the additional points made the trends in the graph very hard to follow. However, a curve drawn through the 3% data would fall directly between the 2% and 4% curves ($\lambda = 266$ and 13250, respectively).

Figures IV-15 through IV-17 show the effect of viscosity ratio on $\overline{I}_{CONC}$ with increasing velocity with the 3% and 4% solutions at low flow rates that was previously discussed. The figure shows that there is little difference in the mixing performance with either the 2%, 3%, or 4% solutions over a short range of velocities.

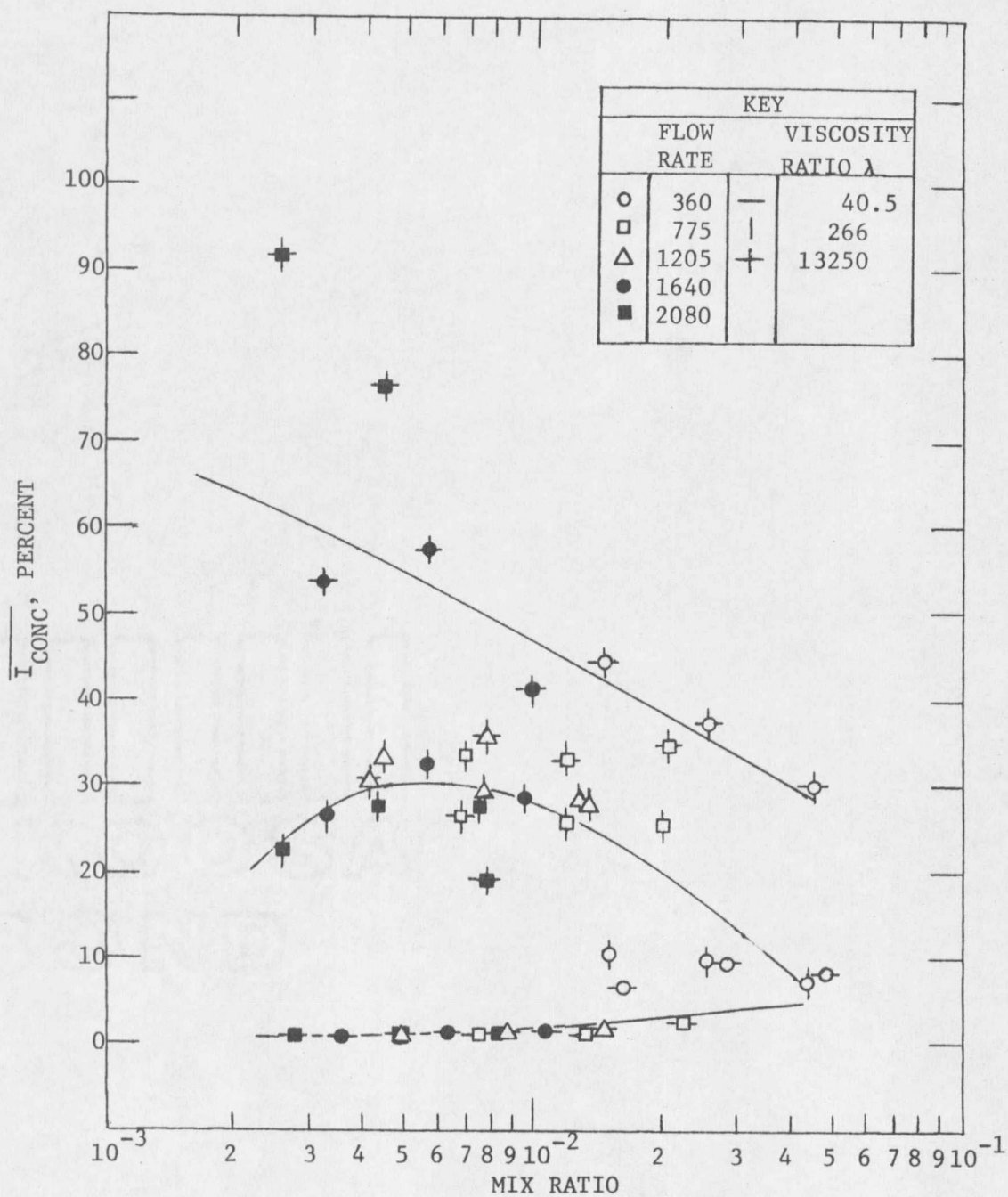


FIGURE IV-14. $\overline{I}_{CONC}$ VERSUS MIX RATIO FOR ROSS LPD MIXER

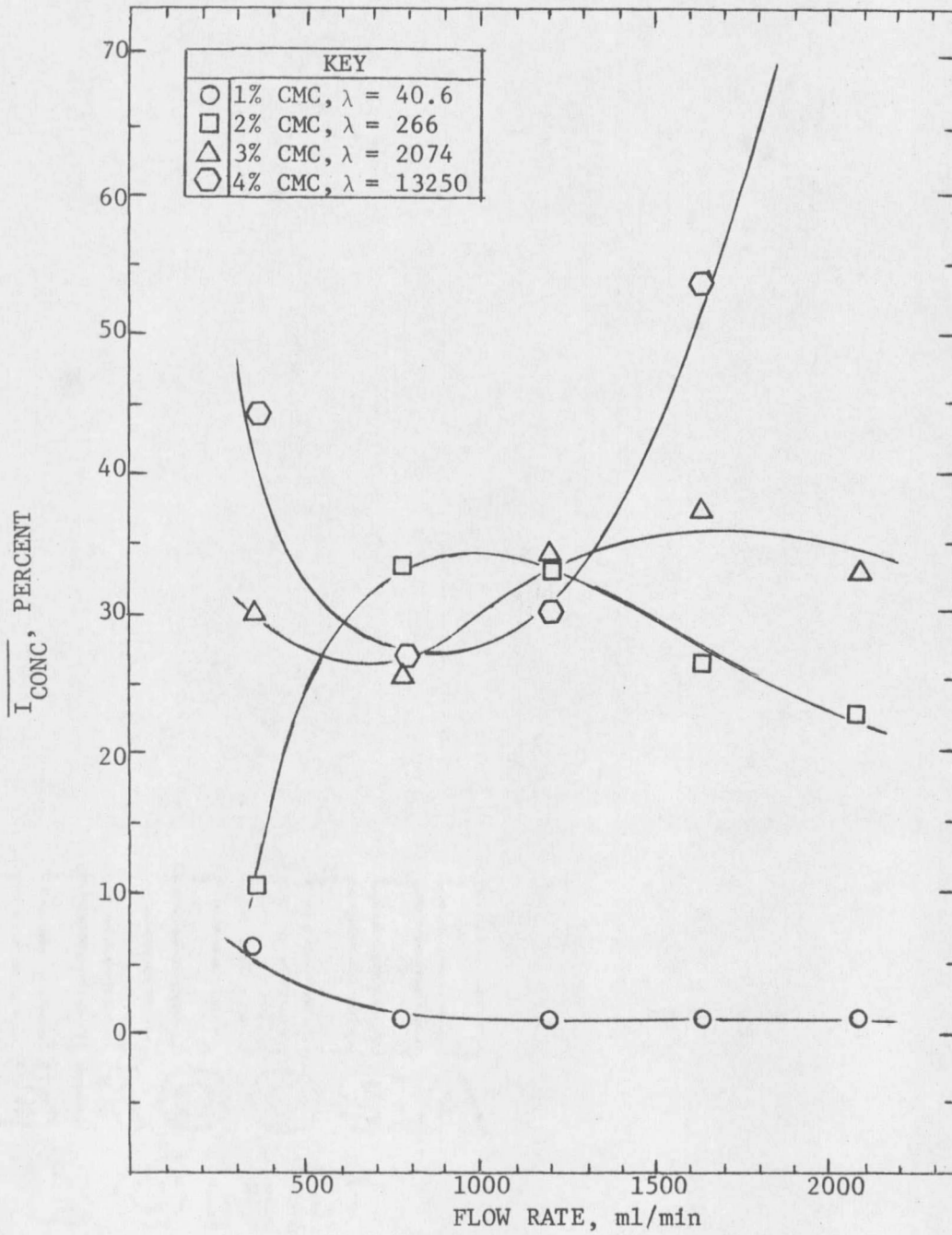


FIGURE IV-15. $\overline{I}_{CONC}$ VERSUS TOTAL FLOW RATE IN ROSS LPD MIXER AT LOW CMC INJECTION RATE (5.3 to 5.8 ml/min)

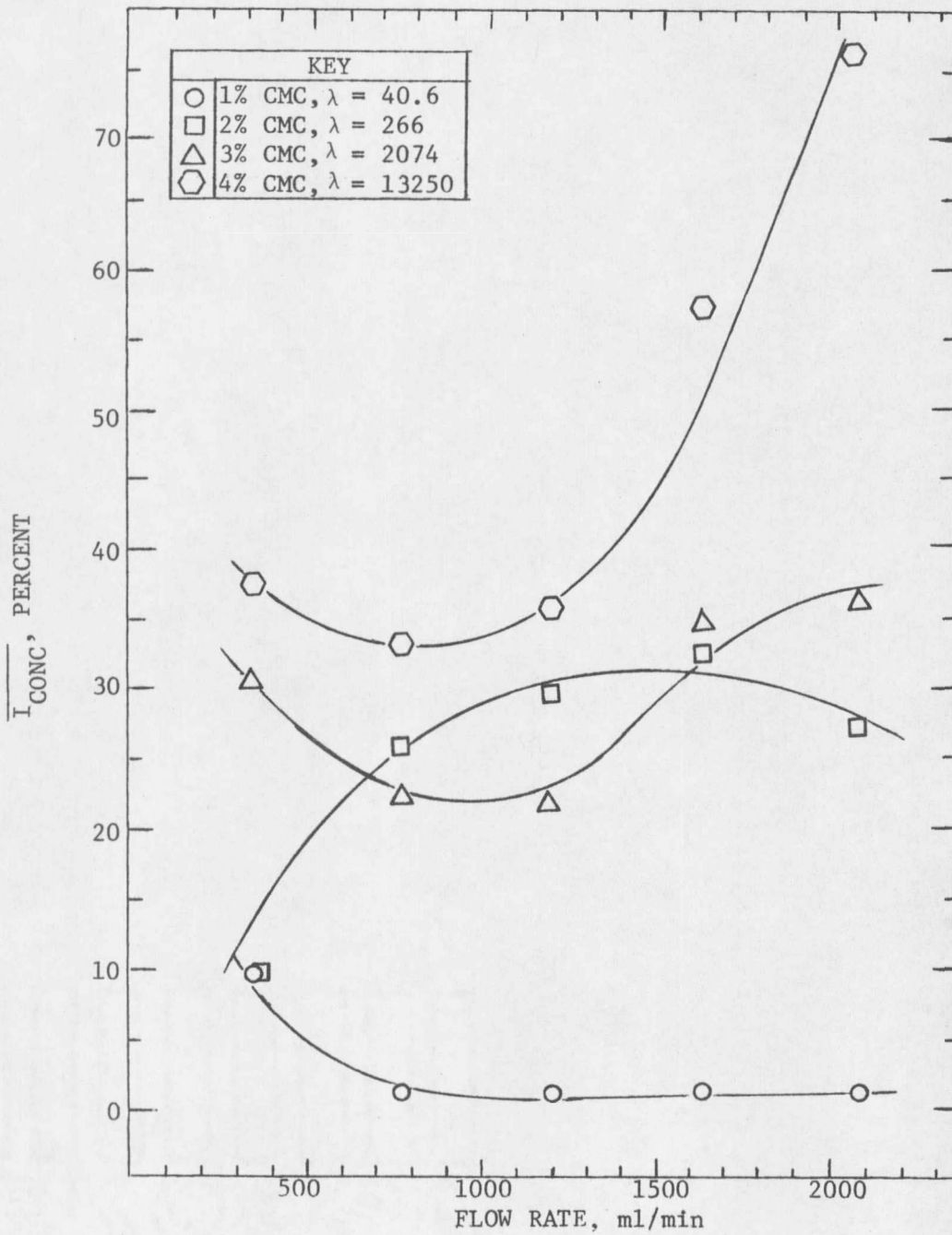


FIGURE IV-16. $\overline{I}_{CONC}$ VERSUS TOTAL FLOW RATE IN ROSS LPD MIXER AT MIDDLE CMC INJECTION RATE (9.1 to 10.3 ml/min)

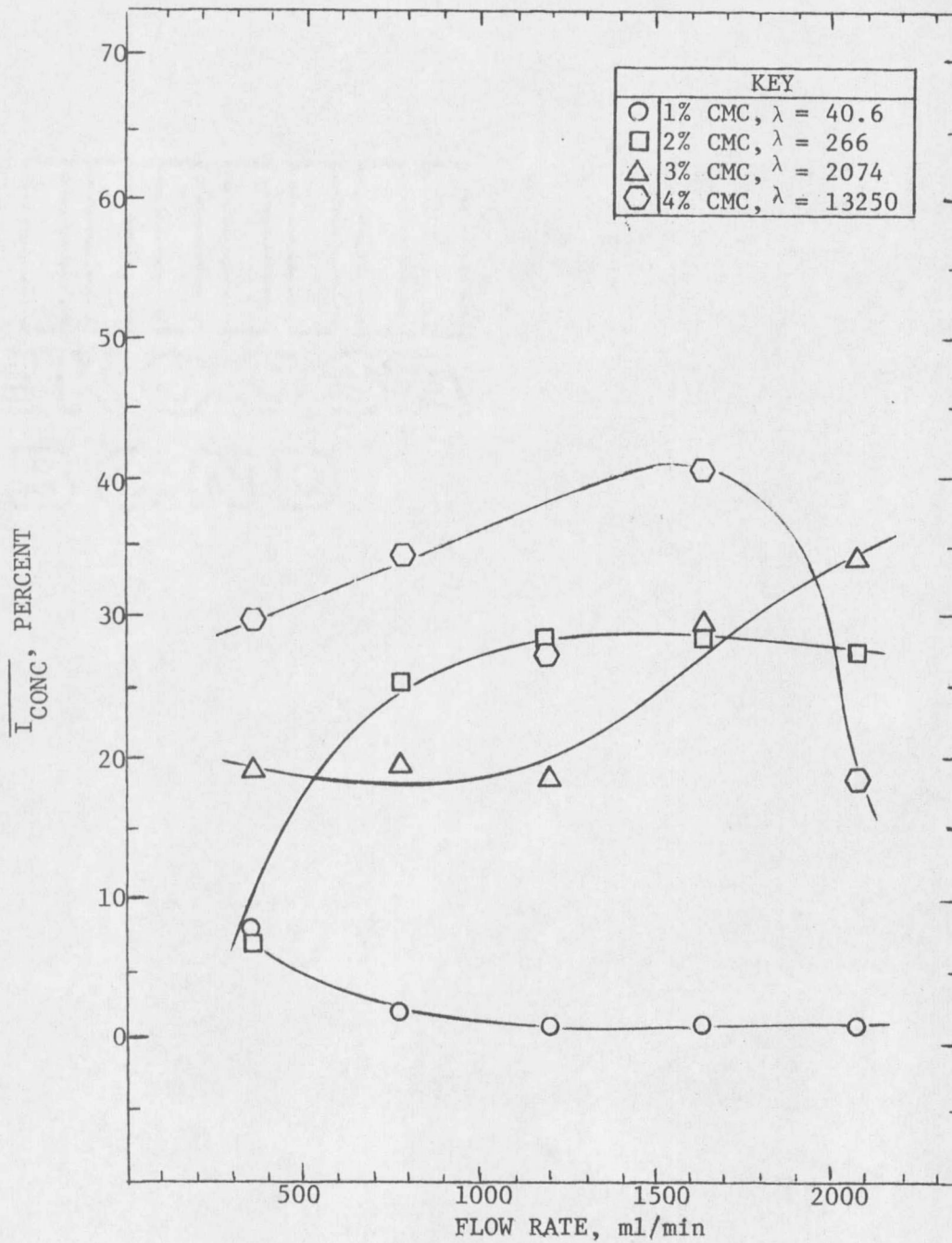


FIGURE IV-17. $\overline{I}_{CONC}$ VERSUS TOTAL FLOW RATE IN ROSS LPD MIXER AT HIGH CMC INJECTION RATE (14.0 to 17.4 ml/min)

This velocity range is at the onset of momentum turbulence with the 2% solution. The onset of turbulence occurs with the 3% solution at a little less than twice the velocity and with the 4% solution at a velocity higher than was made in the study. Figure IV-16 looks like an expansion of the left side of Figure IV-15 because the increased CMC injection rate increased the average viscosities of the mixer streams. Similarly, Figure IV-17 looks like an expansion of the left side of Figure IV-16, except for the sudden drop in $\overline{I}_{\text{CONC}}$ at the highest flow rate (also shown in Figure IV-13). The cause of this is not readily explainable, but the same phenomenon was observed with even more definition in the Ross ISG mixer, while injecting the 4% CMC solutions at higher flow rates. A possible explanation of the phenomenon will be presented with the discussion of that mixer.

It is interesting to note that while injecting a 1% CMC solution into the Ross LPD mixer, the intensity of concentration turbulence approached 10% at the lowest flow rate. At higher flow rates $\overline{I}_{\text{CONC}}$ was below 5%, as was true in all the other mixers at all flow rates investigated while injecting the 1% CMC solution. The high values of $\overline{I}_{\text{CONC}}$ at the lowest flow rate could be caused by the weaker flow division characteristics of the Ross LPD mixer.

2. Radial Distributions

Figures IV-18 and IV-19 show sketches of typical concentration and intensity of concentration turbulence profiles found below the

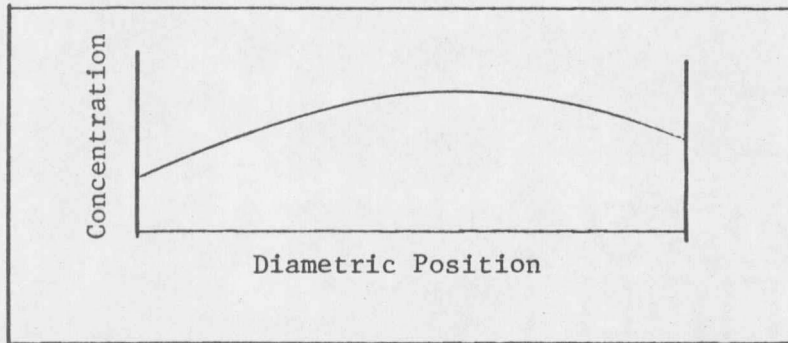


FIGURE IV-18. TYPICAL CONCENTRATION PROFILE BELOW THE ROSS LPD MIXER

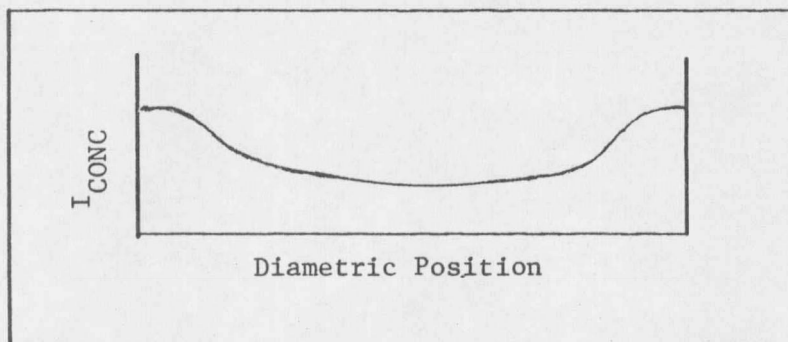


FIGURE IV-19. TYPICAL INTENSITY OF CONCENTRATION TURBULENCE PROFILE BELOW THE ROSS LPD MIXER

Ross LPD mixer, respectively. The concentration near the axis of the tube was always higher than at surrounding radial positions. The lowest average CMC concentrations were always at the tube wall. The higher CMC concentration near the axis is probably due to CMC clinging to the rod positioned down the axis of the mixer. This would provide a constant source of CMC enrichment near the center. The size of the concentration fluctuations were very nearly constant across the diameter, but because the average concentration was higher near the axis, a radial I_{CONC} distribution like the one sketched in Figure IV-19 resulted because I_{CONC} is the ratio of the fluctuations to the average value.

At the lowest flow rate the concentration profiles were fairly random, indicating that the runs were not long enough to measure low frequency effects due to pieces of CMC sticking to certain positions on the probe (resulting in high concentrations and low fluctuations at those positions). Overall, however, the magnitude of I_{CONC} was fairly constant across the diameter at low flow rates. As the flow rates increased the profiles shown in Figure IV-18 and IV-19 developed and became more pronounced the higher the flow rate became.

D. Discussion of the Ross ISG Mixer

1. Averaged Intensity of Concentration Turbulence

Figures IV-20 and IV-21 show the effect of mix ratio in the Ross

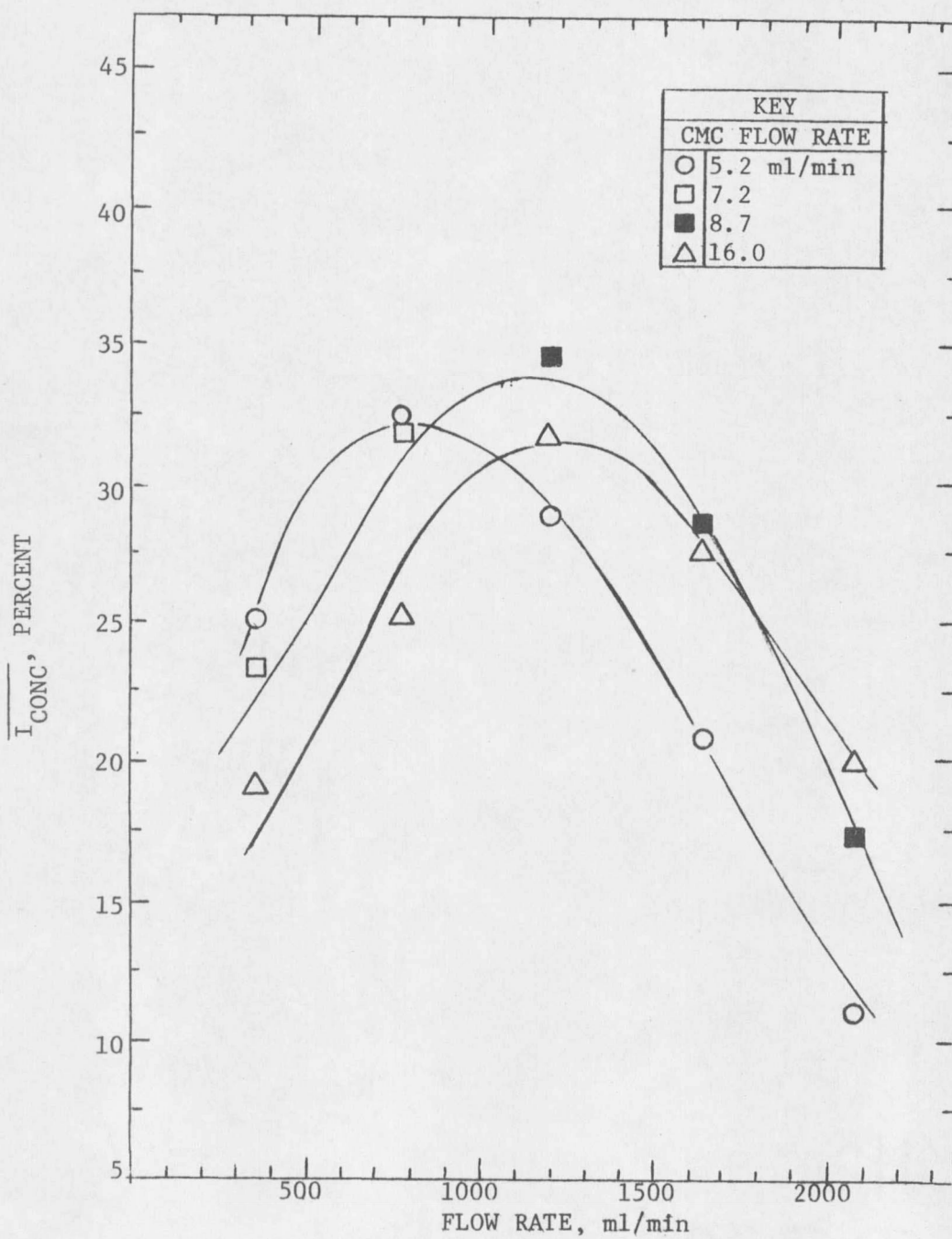


FIGURE IV-20. I_{CONC} VERSUS TOTAL FLOW RATE IN ROSS ISG MIXER WHILE INJECTING 2% CMC SOLUTION ($\lambda = 266$)

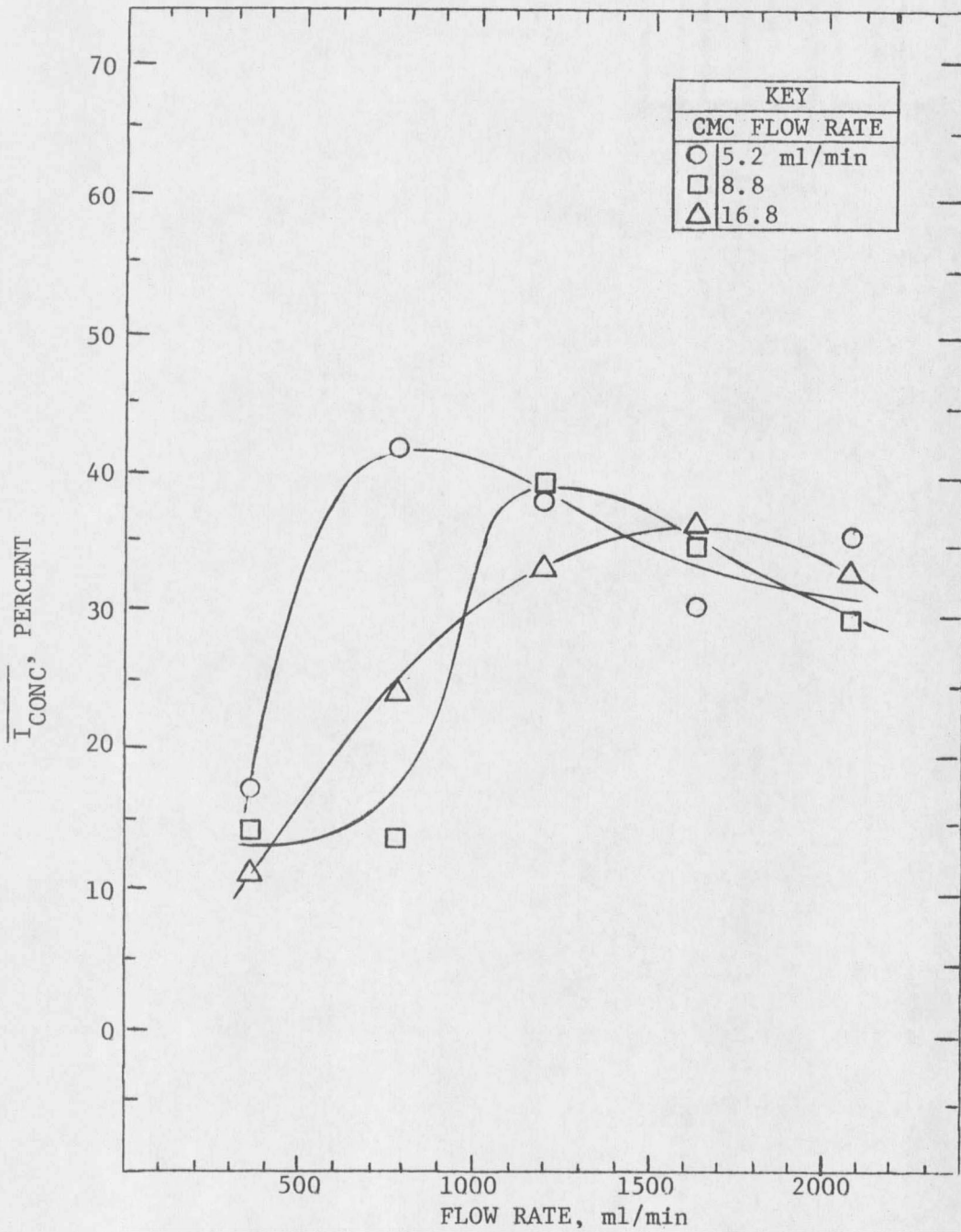


FIGURE IV-21. $\overline{I}_{CONC}$ VERSUS TOTAL FLOW RATE IN ROSS ISG MIXER WHILE INJECTING 3% CMC SOLUTION ($\lambda = 2074$)

ISG mixer while injecting 2% and 3% CMC solutions respectively. Both figures show an initial rise in $\overline{I}_{\text{CONC}}$ with flow rate followed by a decrease in $\overline{I}_{\text{CONC}}$. The shape of these curves is very similar to those for the $\frac{1}{2}$ inch Kenics Static mixer and can probably be explained in the same way; that is, the increase in $\overline{I}_{\text{CONC}}$ at lower flow rates is due to the lowering of mix ratio as more water was added to increase the flow, and the subsequent decrease in $\overline{I}_{\text{CONC}}$ is due to the onset of momentum turbulence. Again, the fact that $\overline{I}_{\text{CONC}}$ starts decreasing at a lower flow rate with a lower mix ratio supports the premise that the decline is due to the development of momentum turbulence, because the lower average viscosities at the lower mix ratios would result in higher Reynolds numbers of the same velocities. As with the Kenics mixer, once momentum turbulence has been initiated, mix ratio has little effect on mixing. If it has any effect it would appear to be an increase in mixing performance with decreasing mix ratio (opposite the laminar flow relationship) probably because there is less to mix.

Figure IV-22 shows the relationship between $\overline{I}_{\text{CONC}}$ and mix ratio in the Ross ISG mixer. The larger amount of scatter indicates that velocity is an important parameter affecting mixing performance in this mixer, especially with high viscosity ratios. It is interesting to note that for almost any given flow rate and viscosity ratio (especially the highest viscosity ratio), the relationship between $\overline{I}_{\text{CONC}}$ and $\ln(\text{mix ratio})$ is approximately linear. However the slope

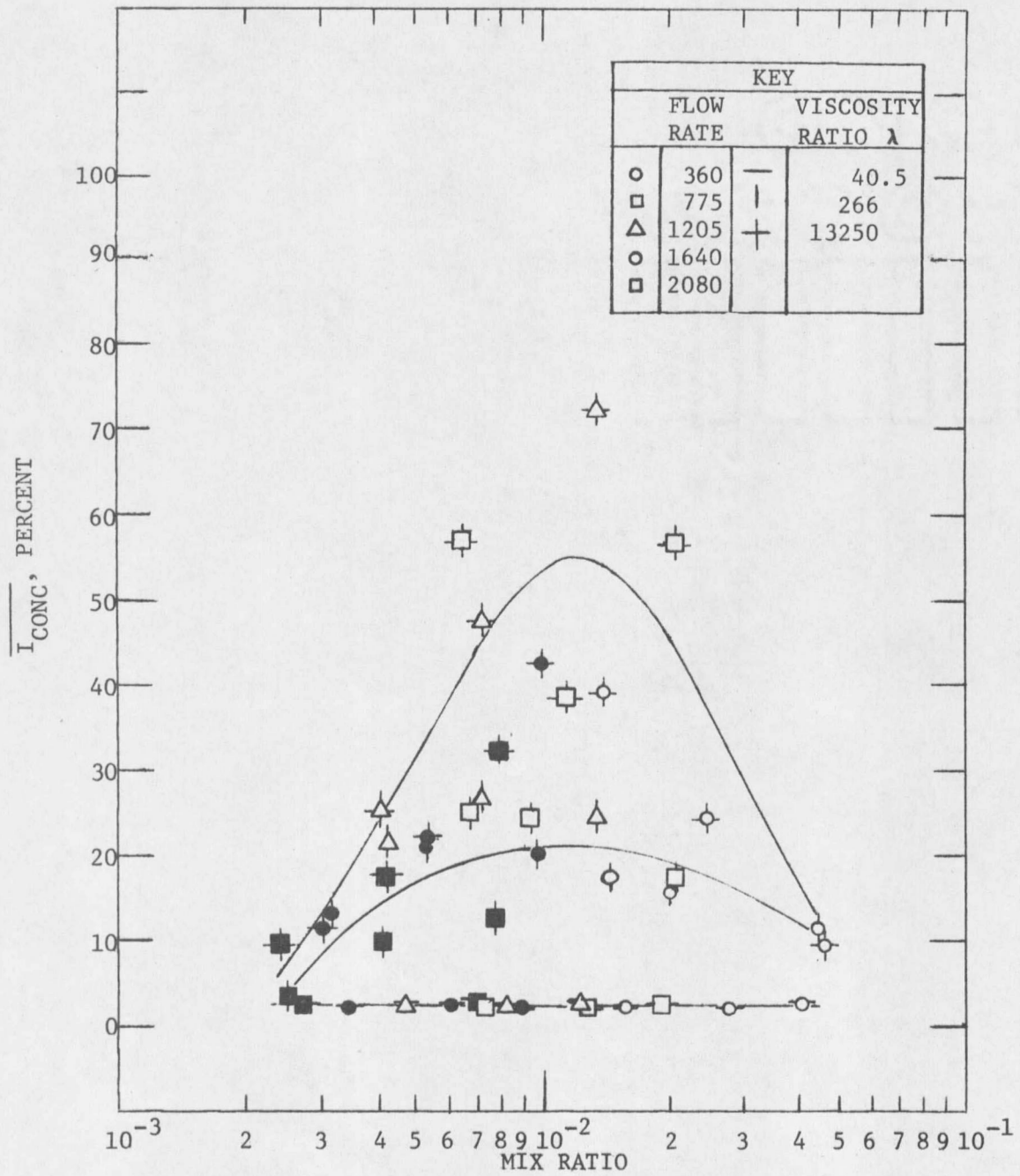


FIGURE IV-22. $\overline{I}_{CONC}$ VERSUS MIX RATIO FOR ROSS ISG MIXER

of the line is negative only at the lowest flow rates. As with the Kenics mixers, the mixing at low viscosity ratios (injecting 1% CMC) is independent of mix ratio and velocity.

An interesting phenomenon arose while injecting the 4% CMC solution into the Ross ISG: It appears there is a sudden development of momentum turbulence, occurring at about the same velocity as while injecting the 2% CMC solution, except of greater intensity; resulting in an extremely rapid decline in $\overline{I}_{CONC}$. This phenomenon is shown in Figures IV-23 through IV-25 and is possibly the same phenomenon that resulted in the sudden drop in $\overline{I}_{CONC}$ in the Ross LPD shown in Figures IV-13 and IV-17. Figures IV-23 through IV-25 show what would be considered normal curves for the 2% and 3% CMC solutions in that with the higher viscosity ratio there is higher intensity of concentration turbulence and momentum turbulence begins to develop at a higher flow rate.

The fact that the drop in $\overline{I}_{CONC}$ while injecting the 4% CMC solution occurs at a lower flow rate with a lower mix ratio, and that the drop in $\overline{I}_{CONC}$ is not as drastic as the CMC injection rate increases, would seem to support the idea that the drop in $\overline{I}_{CONC}$ was due to the development of momentum turbulence after reaching a critical Reynolds number. However why does the transition to turbulent flow occur at a lower velocity than with the less viscous 3% CMC solution and why does $\overline{I}_{CONC}$ drop so rapidly and reach a value that, at the low CMC injection rate, is below $\overline{I}_{CONC}$ while injecting the 2% CMC solution? One

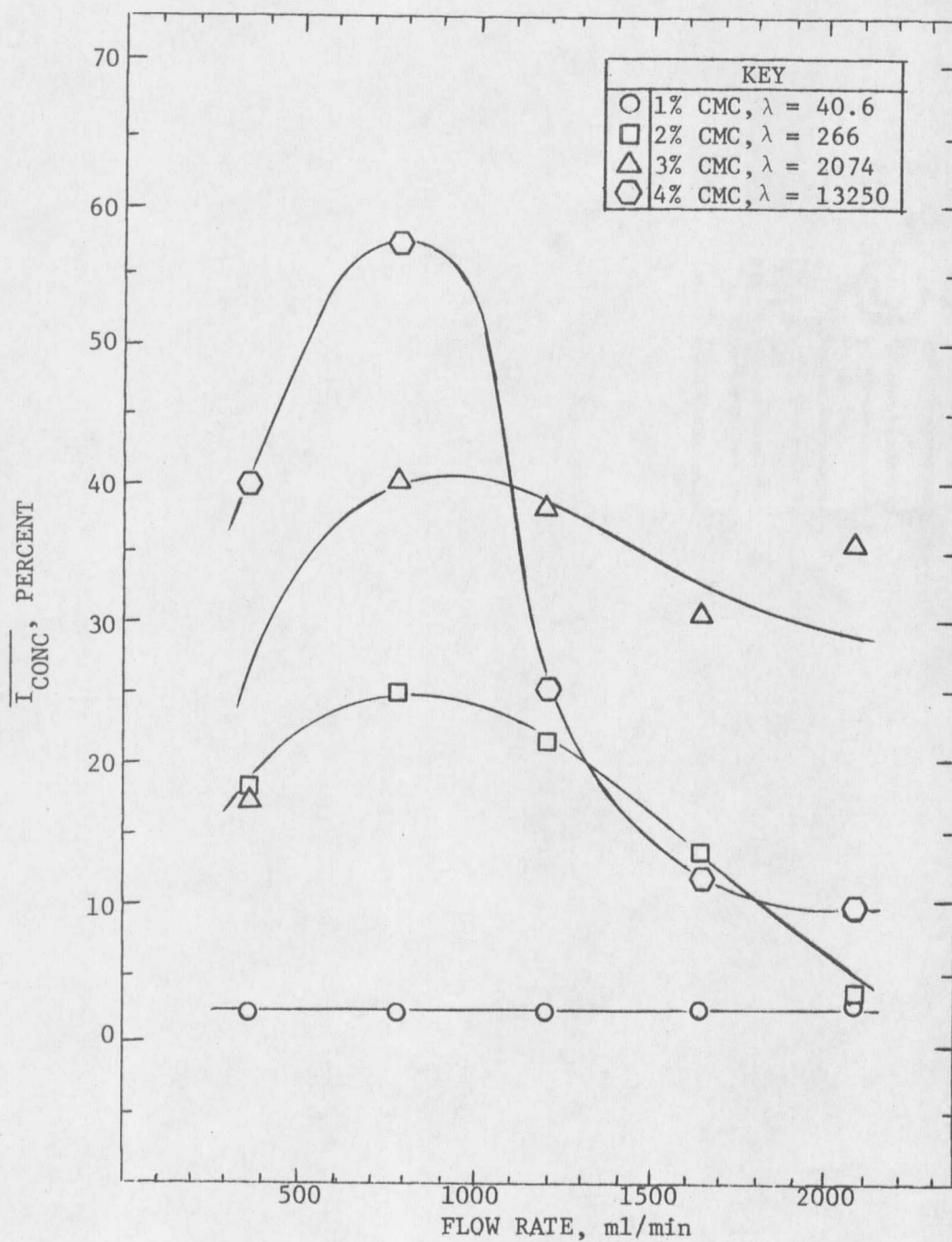


FIGURE IV-23. $\overline{I}_{CONC}$ VERSUS TOTAL FLOW RATE IN ROSS ISG MIXER AT LOW CMC INJECTION RATE (5.0 to 5.7 ml/min)

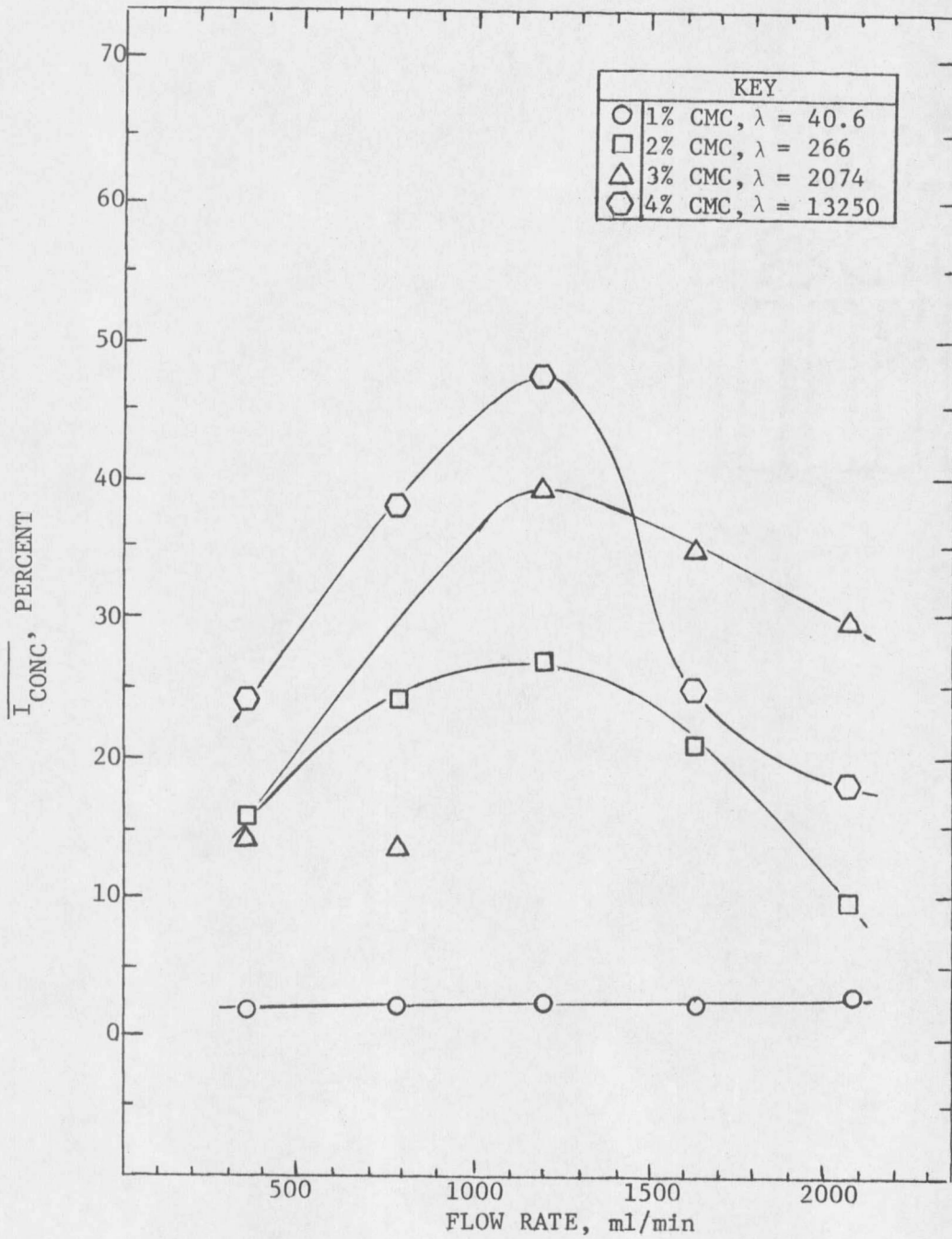


FIGURE IV-24. $\overline{I}_{\text{CONC}}$ VERSUS TOTAL FLOW RATE IN ROSS ISG MIXER AT MIDDLE CMC INJECTION RATE (7.2 to 10.0 ml/min)

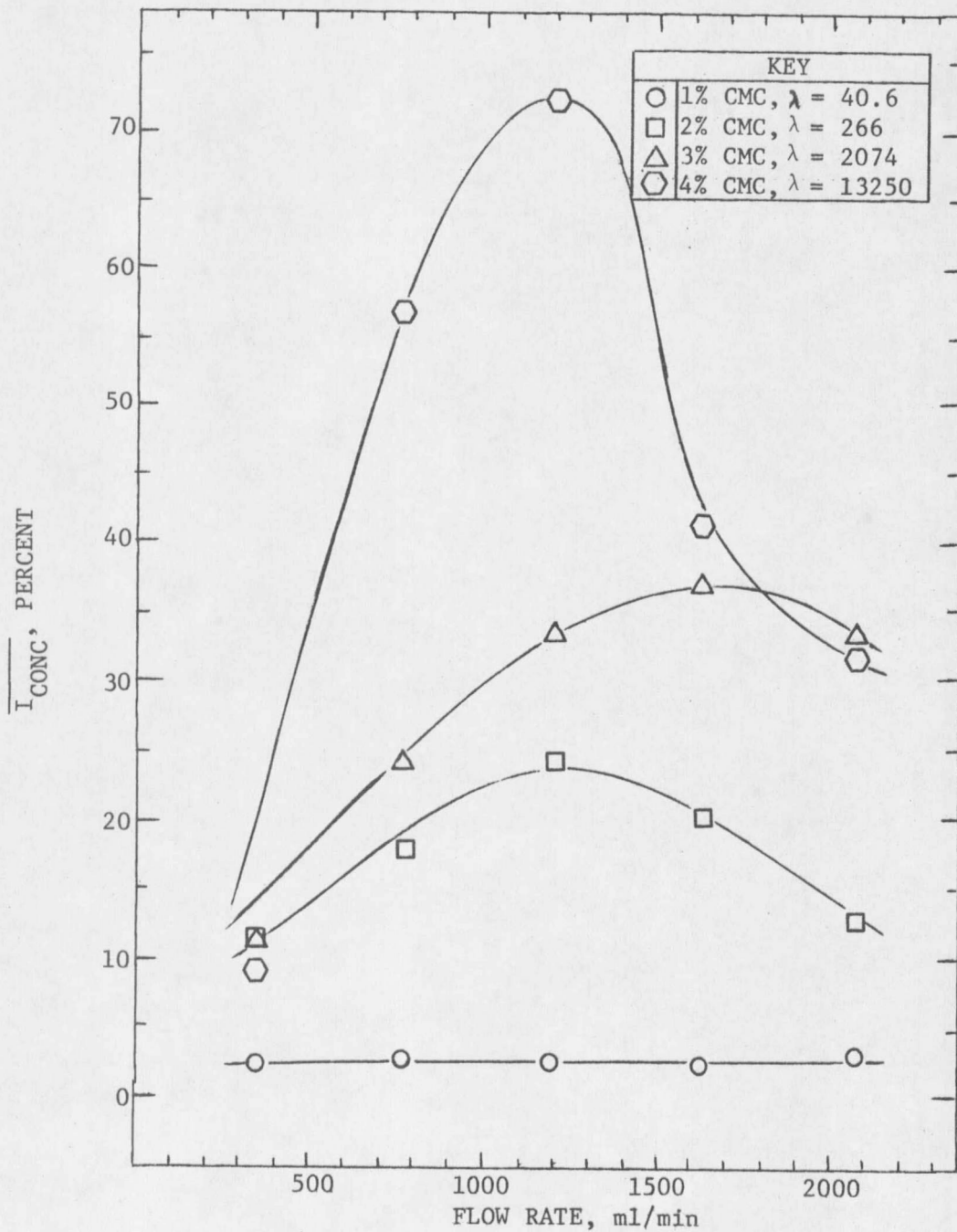


FIGURE IV-25. I_{CONC} VERSUS TOTAL FLOW RATE IN ROSS ISG MIXER AT HIGH CMC INJECTION RATE (14.7 to 16.8 ml/min)

possibility might be that the 4% CMC solution partially fills the chambers between the mixer elements thus causing much higher velocities, in constantly changing directions, in the less viscous water stream because of the reduced area of flow as compared to the mixer with the 2% or 3% solutions injected into it. This could lead to two different effects. The surfaces of the "chunks" of CMC partially blocking the chambers would be subjected to very high and erratic shearing forces which would greatly lower their apparent viscosity (the apparent viscosity of the 4% solution at a shear rate of 5000 sec^{-1} is about the same as the 3% solution at a shear rate of 450 sec^{-1}) and allow mixing as if the actual viscosity ratio were lower. A more probable effect might be that when subjected to very high and erratic shearing forces, the extremely viscoelastic 4% CMC solution reaches some critical deformation and then simply comes apart.

Whatever the cause of the phenomenon, it is very real and can be repeated. Each of the points shown in Figures IV-23 through IV-25 for the 4% solutions is the average of data taken for three runs, spanning a time period of about four minutes; and five minutes was allowed to pass before the first run as each flow rate was initiated (see Table IV-17 for the values of $\overline{I}_{\text{CONC}}$ for each run and the standard deviation in $\overline{I}_{\text{CONC}}$ for the three runs at each flow rate and CMC injection rate). Also, during run series ISG011 (the high 4% CMC injection rate series) the following comment was noted concerning the appearance of the mixers

exit stream at the 1205 ml/min water flow rate: "Pretty chunky - mixing looks poor". At the next higher flow rate the following comment was noted: "Much smaller chunks, better mixing". These observations were noted during the runs, several hours before the data were analyzed to calculate $\overline{I}_{\text{CONC}}$ values of 72.43 and 41.31 for the runs at the 1205 and 1640 ml/min flow rates, respectively.

2. Radial Distributions

No typical profiles for concentration or $\overline{I}_{\text{CONC}}$ can be sketched for the Ross ISG mixer because these profiles changed with flow rate and viscosity ratio. The concentration profile always got reasonably flat at higher flow rates. While injecting the 2% CMC solution there were always slightly higher concentrations and fluctuations near the tube walls. The same trend was noted with the 3% CMC solution at high flow rates, but at the lower flow rates the fluctuations were higher near the axis of the tube. With the 4% solution at higher flows the concentration profile was completely flat, while positions with higher concentration fluctuations occurred randomly across the diameter from run to run. Generally, at low flow rates there would be some points with higher concentrations and some points with higher fluctuations (not necessarily the same positions, but sometimes) during a run. But the position would change from run to run at the same conditions. This would indicate that there are concentration fluctuations of a lower frequency than could be measured with the 27 second runs.

V. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

1. The average of the intensity of concentration turbulence, I_{CONC} , at several positions in the outlet stream of a mixing system, $\overline{I_{CONC}}$, is a measure of the performance of that mixing system. I_{CONC} is defined as the ratio of the average magnitude of concentration fluctuations to the average concentration at a point. The lower $\overline{I_{CONC}}$, the better the mixing.

2. The frequency components of the concentration versus time waveform, as determined by Fourier analysis, will depend on the fluid velocities and the degree of mixing. Better mixing and higher velocities will give components of higher frequency. Also, as the fluids become better mixed the amplitudes of the frequency components become smaller.

3. An accurate measure of the magnitude of concentration fluctuations can be obtained only if a large fraction of the spectral (frequency) energy, as determined by a Fourier analysis of the concentration waveform, is included in the frequency range of the equipment measuring the concentration fluctuations. In most cases, the abundance of low frequency components (below 10 Hz) in the concentration waveform will preclude the use of analog equipment in measuring the concentration fluctuations, necessitating the use of some digital sampling scheme.

4. In general, mixing performance decreases with increasing

viscosity ratio.

5. The development of momentum turbulence greatly improves the mixing performance in all three mixers.

6. Momentum turbulence is promoted at lower flow rates in the Ross mixers than in the Kenics mixers and is more important to their performance. Flow division is important to the performance of motionless mixers at low flow rates and the lack of good flow division properties is most probably the reason that the Ross LPD mixer does not perform as well as the Ross ISG and Kenics mixers at low flow rates.

7. For laminar flow in the Kenics Static mixers, the mixing performance is independent of flow rate. $\overline{I}_{CONC}$ is linearly related to the logarithm of the mix ratio, where mix ratio is the ratio of the flow rate of the injected stream to the flow rate of the main stream. The mixing performance improved ($\overline{I}_{CONC}$ decreased) as the mix ratio increased. The slope of the line relating $\overline{I}_{CONC}$ to $\ln$ (mix ratio) depended on the viscosity ratio.

8. At high viscosity ratios in the Ross ISG mixer, $\overline{I}_{CONC}$ was logarithmically related to the mix ratio at any given total flow rate whether the flow was laminar or turbulent (though probably not in the transition region). In the laminar region $\overline{I}_{CONC}$ increases with decreasing mix ratio; in the turbulent region $\overline{I}_{CONC}$ decreases with decreasing mix ratio.

9. Care must be taken in choosing the size of a Kenics mixer when

injecting high viscosity streams into a lower viscosity main stream because of the tendency for the high viscosity stream to "channel" through the mixer. This channeling phenomenon is probably dependent on flow rate, fluid properties such as elasticity and tensile strength, and the relative diameter of the injected stream to the diameter open for flow. Channeling ceased with the onset of momentum turbulence. Also, once the channeling stream was broken at some point in the mixer (usually by contacting the leading edge of an element), from that point on the channeling was ceased.

B. Recommendations

1. Before attempting to measure the magnitude of concentration fluctuations, to measure mixing performance, it should be determined over what frequency range these fluctuations occur. The energy content of the frequency spectrum should be examined over as wide a range as possible, probably from 0.001 Hz to 100 Hz, to determine the frequency range that should be investigated for the particular fluids and velocities being studied. This would require filtering the signal to remove frequency components higher than 100 Hz, then taking at least 200 samples per second (and preferably more) for approximately 20 minutes at a given point. The data could then be processed with a Fast Fourier Transform to determine the magnitude of the frequency components in this range. Once the frequency range that should be examined has been determined, the proper signal filtering can be selected and

and the optimum sampling rate and number of samples can be determined.

2. The use of copper probes was adequate for the short runs used in this study. However, if longer runs are to be made, the exposed portion of the probes should be made of a less reactive metal such as gold or platinum, because oxidation or corrosion effects on the probe tips slowly change the effective impedance of the probe and hence would result in false low frequency changes. Also, if the tips of the probes could be made to extend from the leading edge of the fin it would reduce the length of time of getting an extended high concentration reading because of "chunks" of higher concentration material clinging to the fin and covering the tip of the probe and the flow at the point of measurement would be less disturbed by the presence of the probe array fin.

3. Further studies of the mixing mechanism in motionless mixers should be carried out, but with only one mixer at a time. This would greatly facilitate the presentation of the results and would allow much more work to be done on each mixer so that the mechanisms of each mixer could be better understood. Not only should more detailed studies be performed over the range of mix ratios, viscosity ratios, and flow rates covered by the present work, but also at very low flow rates where inertial effects are limited and over a wider range of turbulent flows.

4. The data for these studies would be much easier to correlate

if a Reynolds number could be calculated for each flow studied. Because of the extremely non-Newtonian behavior of the CMC solutions and the wildly varying shearing forces in the mixers, it was not possible in the present study to calculate Reynolds numbers. If a more Newtonian viscous fluid could be used, then perhaps with the use of pressure drop measurements, appropriate equivalent diameters could be determined and Reynolds numbers calculated.

NOMENCLATURE

a_0	Constant term in Fourier series
a_k	Coefficient of k^{th} cosine term in Fourier series
A	Ampere
A	Area, L^2
b_k	Coefficient of k^{th} sine term in Fourier series
C	Concentric cylinder viscometric constant, $L^{-1/n} F^{-1/n} t^{-1}$
C_i	Concentration of species i, M/L^3
$\bar{C}_i$	Average concentration of species i, M/L^3
C'_i	Concentration fluctuations of species i ($C_i - \bar{C}_i$), M/L^3
dB	Decibel
D	Molecular diffusivity, L^2/t
g	Acceleration of gravity, L/t^2
g_c	Ratio of mass times acceleration to force, ML/Ft^2
G	Electrical conductance, $\mathcal{U}$
I	Electrical current, A
I_{CONC_k}	Intensity of concentration turbulence at point k, dimensionless
$\overline{I_{\text{CONC}}}$	Average of the intensity of concentration turbulence at all points, dimensionless
k	Ratio of inner to outer cylinder radius in concentric cylinder viscometer, dimensionless
k	Integer constant used to indicate term in Fourier series, dimensionless

l_0	End effect depth correction length for concentric cylinder viscometer, L
L	Length, L
m	Number of corrugations per element in the KOCH Static Mixing System
m	Power law fluid consistency index Ft^n/L^2
m'	Consistency index used to calculate generalized viscosity coefficient, γ , $Ft^{n'}/L^2$
n	Integer constant used to indicate term in series, dimensionless
n	Number of mixer elements
n	Power law fluid flow behavior index, dimensionless
n'	Power law fluid flow behavior index, dimensionless
p	Pressure, F/L^2
q	Number of terms to be evaluated in Fourier series
r	Radial position or cylindrical coordinate, L
rms	Root mean square
R	Radius, L
R	Electrical resistance, Ω
S	Number of flow divisions
t	Time, t
T	Period of periodic function, t
v_k	Velocity in direction k, L/t

$\bar{v}_k$	Average velocity in direction k, L/t
$\hat{v}_k$	Velocity fluctuations in direction k ($v_k - \bar{v}_k$), L/t
V	Volts
V_k	Voltage at point k, V
$\bar{V}_k$	Average voltage at point k, V
$\hat{V}_k$	Voltage fluctuations at point k ($V_k - \bar{V}_k$), V
x	Rectangular coordinate, L
X_C	Capacitive reactance, Ω
y	Rectangular coordinate, L
z	Rectangular or cylindrical coordinate, L
γ	Generalized viscosity coefficient, $M/Lt^{2-n'}$
$\dot{\gamma}$	Shear rate, t^{-1}
Δ	Rate of deformation tensor (shear rate tensor), t^{-1}
η	Viscosity, M/Lt
η_A	Apparent viscosity, M/Lt
θ	Cylindrical coordinate, radians
λ	Viscosity ratio (γ/η), sec^{n-1}
ρ	Density, M/L^3
σ	Electrical conductivity, $\mathcal{U}/L$
τ	Shear stress, F/L^2
$\bar{\tau}$	Time-smoothed momentum flux tensor, F/L^2
$\overline{\tau}^t$	Time-smoothed turbulent momentum flux tensor, F/L^2

$\bar{\tau}_{ij}$	Components of $\bar{\tau}$, F/L^2
$\bar{\tau}_{ij}^t$	Components of $\bar{\tau}^t$, F/L^2
T	Torque, FL
Ω	Ohm
$\mathcal{O}$	Mho
ω	Angular frequency, radians/t

APPENDICES

APPENDIX A

SIGNAL ELECTRONICS

The signal processing electronics used in this study consisted of an inverting a.c. amplifier and an active peak detector to amplify and demodulate the input signal, respectively. Both the amplifying and demodulation sections incorporated LM324 operational amplifiers. The LM324 was chosen because of its high density (four amplifiers to a package) and its ease of use. These op-amps were also used as voltage followers to provide the reference voltages required by the signal processing circuit.

With signals taken from ten separate probes, it was decided to have ten independent, identical signal processing circuits rather than multiplexing the ten signals through a single processing circuit. This allowed for faster sampling rates and, more important, it allowed for independently adjusting the gain on each signal so that differences in the ten probes from manufacture (e.g., slightly different surface areas), or from oxidation during use, can be cancelled out.

Figure A-1 shows the circuit for the amplifier and demodulator used for processing each of the ten input signals. Resistor R1 loads the probes to establish a current density near the tips of the probes that is significantly greater than the current density elsewhere in the mixing system. The value of R1 was chosen to give a linear input waveform without seriously attenuating the signals. The

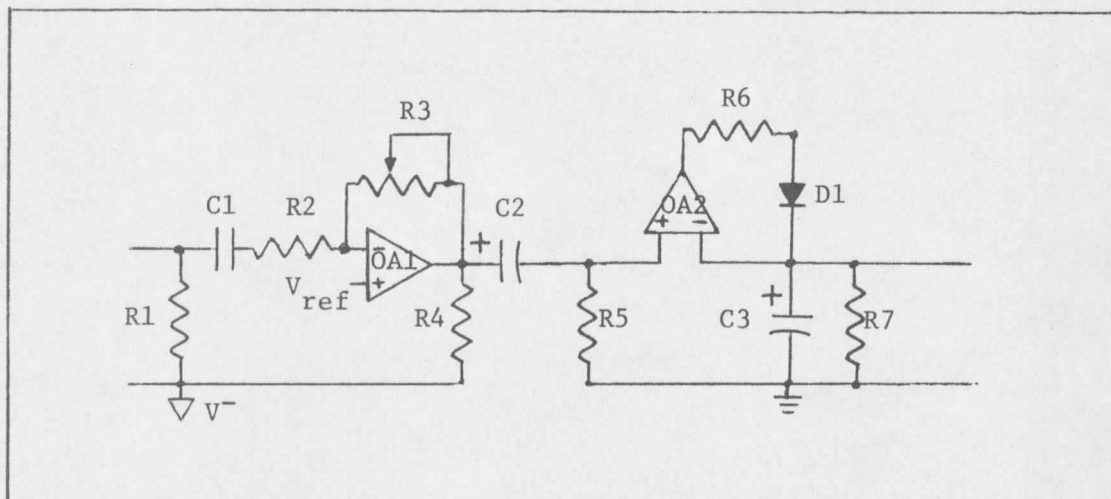


FIGURE A-1. TYPICAL SIGNAL AMPLIFIER AND DEMODULATOR

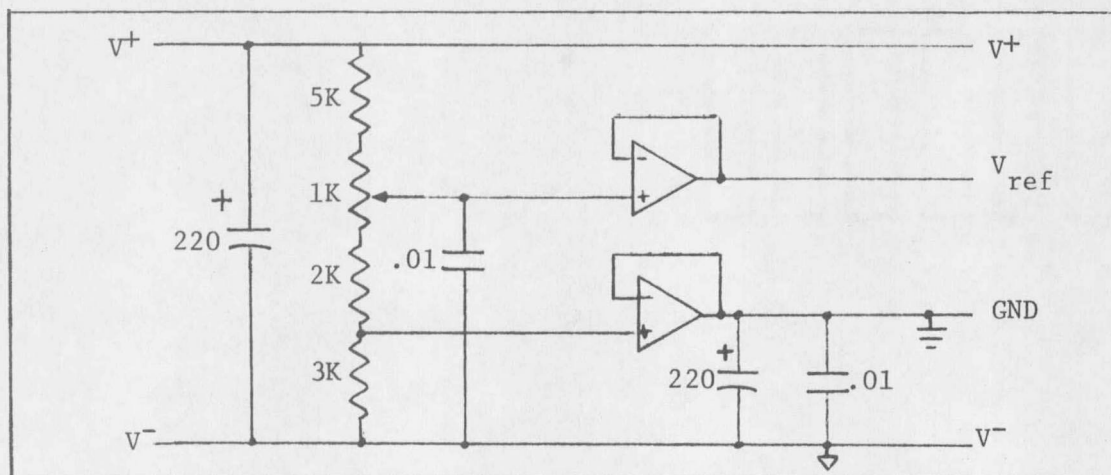


FIGURE A-2. CIRCUIT PROVIDING THE VARIOUS VOLTAGE LEVELS USED IN THE SIGNAL PROCESSING

signals were attenuated approximately one order of magnitude by the combined effects of the input impedance of the amplifier and the resistor R1.

The amplifying section was decoupled from the input load resistor by capacitor C1. This section is a standard inverting a.c. amplifier with a gain of $\frac{R3}{X_{C1} + R2}$, where X_{C1} is the reactance of capacitor C1 at the operating frequency. Because R3 was adjustable, the gain was adjustable. The reference voltage V_{ref} , was adjusted to be midway between the supply voltages for the op-amp (V^+ and V^-). Resistor R4 is used to bias the class A section of the LM324. It is necessary only because the output of the amplifier is capacitively coupled to its load by capacitor C2 (1).

The demodulating section consists of a rectifier and a low pass filter. Resistor R5 loads the output of the amplifier section and establishes a d.c. reference (ground) for the demodulating section. It was necessary for this reference voltage to be higher than the negative supply voltage of the op-amps so that the negative half cycles on the signal would not be more negative than is allowed with the LM324. This would have resulted in the clamping of the input signal that would have produced a non-linear relation between the d.c. voltage out of the demodulator and the a.c. voltage in. OA2 with the resistor R6 and diode D1 is used as an active rectifier. Because the output of this circuit is to be within the range from 0 to

1 V_{dc} , to be compatible with the analog to digital converter, the use of a standard diode detector was precluded because of the non-linearity of a diode in this voltage range.

The rectifier output was then filtered by capacitor C3. Bleeding resistor R7 allows the output voltage of the circuit to decrease when the signal voltage decreases (the A/D converter has high impedance FET inputs). The value of R7 was chosen so that the time constant on the filter (C3-R7) is 100 milliseconds. This value sets the corner frequency on this low pass filter at 10 Hz, so that the 5 kHz carrier frequency and all high frequency components of the concentration fluctuations will be filtered out. Figure A-3 shows the output voltage of the demodulating section as a function of input voltage.

Figure A-2 shows the origin of the supply and reference voltages used in the signal processing circuit. All of the op-amps are supplied by V^+ and V^- , which is input from an external regulated power supply. V_{ref} , which is used only as a reference voltage for the non-inverting inputs of the op-amps in the ten amplifying sections, is derived from a voltage follower whose input is taken from a trimmer in a voltage divider. The trimmer is adjusted so that

$$V_{ref} = \frac{V^+ - V^-}{2}$$

A-1

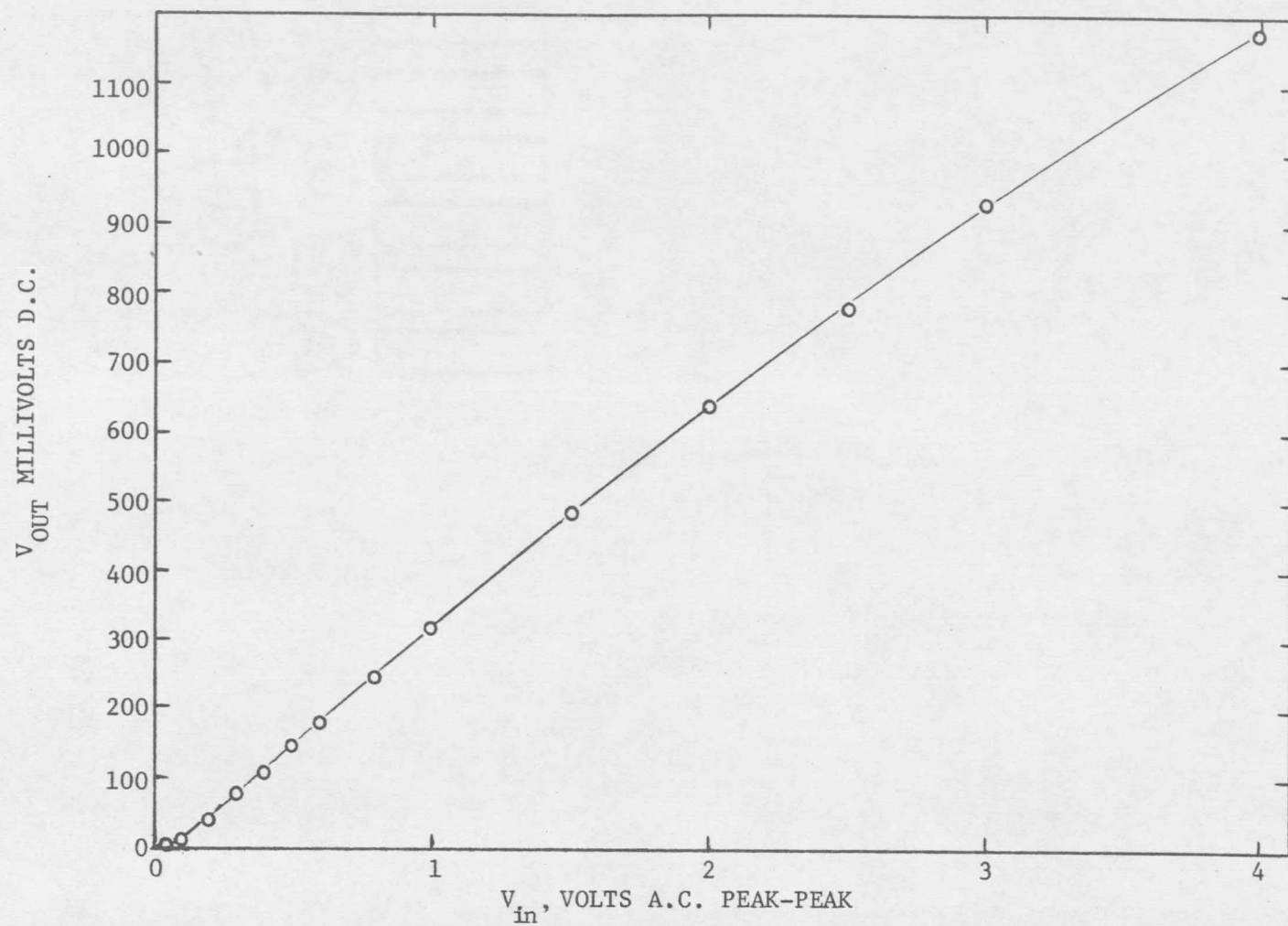


FIGURE A-3. PEAK DETECTOR TRANSFER FUNCTION

The input to the voltage follower has a disc capacitor to V^- to filter out any high frequency noise.

The other voltage derived from this circuit is the output reference voltage (GND). This voltage is of the same potential of the "ground" for the A/D converter (and all the digital equipment). It also is derived from a voltage divider through a voltage follower except that the output of the voltage follower is heavily filtered to eliminate noise in the reference to the A/D converter. The filtering is accomplished with an aluminum electrolytic capacitor and a ceramic disc capacitor to filter both high and low frequencies of noise.

Table A-1 lists the values of all the parts used in the schematic shown in Figure A-1.

TABLE A-1

AMPLIFIER COMPONENT VALUES

Part Label	Description
R1	Resistor 10 K Ω 5%
R2	Resistor 20 K Ω 5%
R3	Cermet type trimpot 1 M Ω
R4	Resistor 6.2 K Ω 5%
R5	Resistor 10 K Ω 5%
R6	Resistor 10 Ω 5%
R7	Resistor 10 K Ω 5%
C1	Capacitor - mylar .022 μ F @ 100 VDC
C2	Capacitor - tantalum electrolytic .47 μ F @ 35 VDC
C3	Capacitor - aluminum electrolytic 1 μ F @ 50 VDC
D1	Diode 1N4148
OA1	Operational amplifier $\frac{1}{4}$ LM324
OA2	Operational amplifier $\frac{1}{4}$ LM324

* PROGRAM TO ACQUIRE VOLTAGE PROFILES FROM THE A/D CONVERTER, THEN STORE
 * THEM ON THE FLOPPY DISC AND IF REQUESTED OUTPUT THE DATA TO A TTY

```

    ORG 128
    JSB TBGC,I    TIME BASE INTERRUPT
    JSB ADC.,I    A/D CONVERTER INTERRUPT
    ORG 2008
    DEF START
    ORG 3008
TBGC DEF TBG.C    LINK TO TIME BASE CONTINUATOR
ADC. DEF ADC.C    LINK FOR A/D CONVERTER INTERRUPT
    ORG 4008

```

** ROUTINE TO ASK FOR NECESSARY INPUT DATA **

```

START LDA D38      OUTPUT
      LDB TITLE    PROGRAM
      JSB OUTP.     TITLE
DNIN. LDA D21      ASK FOR
      LDB DN.IN     DISC & DATA
      JSB OUTP.     FILE NAMES
      JSB INPUT     GET NAMES
      LDB T.ADR     GET TTY INPUT ADDR
      LDA B,I       GET DISC NAME
      STA ONAME     STORE
      INB           INCR ADDRESS
      LDA B,I       GET FILE NAME
      STA FNAME     STORE
      CLA           ZERO RECORD
      STA R1        ENTRY
      STA R.KNT     INITIALIZE
      STA R.CNT     RUN COUNTERS
      STA BFLAG     INITIALIZE BUFFER FLAG
      STA I.RCD     INITIALIZE INPUT &
      STA O.RCD     OUTPUT RECORD NUMBER
      JSB DID,I     CHECK DISC ID
      JSB FID,I     DOES FILE
      SZB,RSS       ALREADY EXIST ?
      JMP DNIN.     YES TRY AGAIN
      JSB BUILD,I   CREATE THE FILE
      LDA B1ADR     INITIALIZE
      STA BADDR     BUFFER POINTER
      LDA D17       ASK FOR
      LDB NO.       THE NUMBER
      JSB OUTP.     OF PROFILES
      JSB INPUT     INPUT NUMBER
      LDA KOUNT     CONVERT
      CMA,INA       IT TO A
      LDB T.ADR     BINARY
      JSB ABC.,I    NUMBER
      STA BADDR,I   STORE IN BUFFER

```

COMPUTER PROGRAM LISTINGS

APPENDIX B

	CMA, INA	NEGATE, STORE
	STA P.KNT	INTO COUNTER
	ISZ BADDR	INCR BUFFER ADDRESS
	LDA D20	ASK
	LDB R.IN	FOR
	JSB OUTP.	SAMPLE RATE
	JSB INPUT	GET RATE
	LDA KOUNT	CONVERT
	CMA, INA	IT TO A
	LDB T.ADR	BINARY
	JSB ABC., I	NUMBER
	STA BADDR, I	STORE INTO BUFFER
	CMA, INA	NEGTE, THEN
	STA T.KNT	SAVE IN TIME COUNTER
	ISZ BADDR	INCR BUFFER POINTER
	LDA D12	ASK IF
	LDB TTY.O	TTY OUTPUT
	JSB OUTP.	IS DESIRED
	JSB INPUT	GET ANSWER
	LDB L.WRD	INITIALIZE TTY OUTPUT
	STB B.PTR	BUFFER POINTER
	LDA T.ADR, I	IS A TTY
	CLB, CCE	HARD COPY
	CPA YES	DESIRED ?
	ERB	YES
	DTB SWR	OUTPUT TO SWR
SWTCH	LIA SWR	WAIT UNTIL
	SLA, RSS	BIT 0 OF SWR
	JMP *-2	IS SET
	CMA	COMPLIMENT THE
	OTA SWR	SWITCH REGISTER
	LDB 03777	RESET FILE ENDING
	LDA D.PTR	ADDRESS TO
	ADA D2	MAKE ROOM FOR
	STB A, I	ADDITIONAL RUNS
	LDB D.RCD	PLACE THE DISC
	STB RCRD	HEAD IN THE PROPER
	STB L.REC	POSITION FOR THE
	JSB FWRT., I	WRITING OF THE DATA
	JSB WAIT	FOR THE NEXT RUN
	LDA P.KNT	INITIALIZE THE
	STA P.CNT	PROFILE COUNTER
	JSB TBG. I	START TIMER
SWRLP	LIA SWR	IS TTY OUTPUT
	SSA, RSS	DESIRED ?
	JMP T.OUT	YES
	LDA T.BZY	WAIT
	SZA	UNTIL

```

NEWRN JMP SWRLP      FINISHED
LIA SWR      IS ANOTHER
SLA,RSS     RUN DESIRED ?
JMP SWRLP   NO, NOT YET
XOR B15     YES, COMPLIMENT BIT 15
JMP SWTCH+3 START RUN

*
** ROUTINE TO OUTPUT READINGS TO TELETYPE **
T.OUT  LDB OM10      INITIALIZE
      STB L.KT      LOOP COUNTER
LOOP   LDB B.PTR     BUFFER
      CPB L.WRD     EMPTY ?
      JSB D.RD      YES
      INB          NO, INCR POINTER
      STB B.PTR     STORE BUFFER POINTER
      LDA 02        OUTPUT
      LDB BLNK.     TWO
      JSB OUTP.     BLANKS
      LDA B.PTR,I   GET DATA WORD
      CPA EOD       END OF DATA MARK ?
      JMP ODCNE     YES
      ALS          MULTIPLY BY 2
      JSB BAC.,I    CONVERT TO ASCII
      OCT 5         SIGNED W/LEADING BLANKS
      JSB OUTP.     OUTPUT TO TTY
      ISZ L.KT      FINISHED WITH PROFILE ?
      JMP LOOP      NO
      LDA 02        YES, OUTPUT
      LDB .CRLF     CARRIAGE RETURN
      JSB OUTP.     & LINE FEED
      JMP NEWRN     GO CHECK SWR
ODCNE  LDB L.WRD     REINITIALIZE
      STB B.PTR     BUFFER POINTER
      LDA 02        OUTPUT
      LDB .CRLF     CARRIAGE RETURN
      JSB OUTP.     & LINE FEED
      ISZ R.KNT     INCR. THE
      LDA R.KNT     RUN COUNTER
      CPA R.CNT     OUTPUT ALL RUNS ?
      JMP SWTCH     YES
      JMP T.OUT     NO, OUTPUT NEXT RUN

*
** SUBROUTINE TO INITIALIZE TTY AND WAIT FOR INPUT **
INPUT  NOP
      JSB T.INT,I   GET A CHAR.
      LDA BZFLG     STRING FROM TTY
      SZA          WAIT FOR
      JMP *-2       BUSY FLAG

```

```

JMP INPUT,I RETURN
** SUBROUTINE TO REFILL OUTPUT DATA BUFFER **
D.RO NOP ENTRY
ISZ D.RO INCR RETURN ADDRESS
LDA O.RCD DON'T READ FROM
CMA,INA THE DISC UNLESS THE
ADA I.RCD OUTPUT RECORD IS
SZA,RSS GREATER THAN
JMP D.RO+2 THE INPUT RECORD
LDB TBUF. GET OUTPUT BUFFER STARTING ADDR
JSB WAIT LET DISC FINISH BEFORE DISABLING
CLF OB DON'T LET THE TIME BASE IN
STB F.BUF UNTIL TRANSFER IS STARTED
LDA I.RCD GET INPUT RECORD NO.
ISZ I.RCD AND INCR.
STA RCRD SET UP BUFFER ADDRESS
STA L.REC AND RECORD NUMBERS
JSB FRD.,I GET A RECORD
LDB TBUF. RESET OUTPUT DATA
CLA,INA BUFFER POINTER
CPA I.RCD INCREMENTING BY 2
ADB D2 FOR FIRST RECORD
JSB WAIT WAIT UNTIL DONE
JMP D.RO,I RETURN

```

```

*
** SUBROUTINE TO EMPTY INPUT DATA BUFFERS **
D.BUF NOP
LDB BFLAG GET BUFFER INDICATOR
LDA B2ADR COMPARE BUFFER LOADING
CMA,INA ADDRESS TO STARTING
ADA BADDR ADDRESS OF SECOND BUFFER
SZB FIRST OR SECOND BUFFER ?
JHP BUF2 SECOND I
SSA FIRST BUFFER FULL ?
JMP D.BUF,I NO
LDA B1ADR YES,BUFFER ADDR IN A
XFER STA F.BUF TRANSFER
CMB BUFFER
STB BFLAG TO DISC
LDA D.BZY MAKE SURE
SZA THE DISC
JMP *-2 IS DONE
LDA O.RCD INCREMENT
ISZ O.RCD RECORD
STA RCRD COMPLIMENT
STA L.REC BUFFER
JSB FWRT.,I FLAG
JMP D.BUF,I RETURN

```

```

BUF2  SSA,RSS      SECOND BUFFER FULL ?
      JMP D.BUF,I  NO
      LDA B2ADR     YES,BUFFER ADDR IN A
      JMP XFER      GO TRANSFER
** TIME BASE GENERATOR INITIATOR **
TBG.I  NOP          ENTRY
      LDA T.KNT     INITIALIZE THE
      STA T.CNT     TIME COUNTERS
      CLA,INA       SET TIME BASE FOR
      OTA TBG       1 MILLISECOND INTERRUPTS
      STA T.BZY     SET BUSY FLAG
      STC TBG,C     ENABLE INTERRUPTS
      STF OB        BY TIME BASE
      JMP TBG.I,I   RETURN
*
*** TIME BASE GENERATOR CONTINUATOR & A/D CONVERTER INITIATOR ***
TBG.C  NOP
      STC TBG,C     REENABLE TIME BASE
      ISZ T.CNT     TIME TO SAMPLE ?
      JMP TBG.C,I   NO, RETURN
      STA ASAVE     YES, SAVE
      STB BSAVE     REGISTERS
      ERB
      STB ESAVE
      LDA TBG.C     SAVE THE
      STA TBG.R     RETURN ADDRESS
      LDA T.KNT     REINITIALIZE
      STA T.CNT     TIME COUNTER
      CLA           SET CONVERTER
      OTA ADC       TO CHANNEL 0
      LDA C.WRD     OUTPUT COMMAND
      OTA ADC       WORD TO CONVERTER
      LDA DM10      INITIALIZE
      STA ADKNT     COUNTER
      STC ADC,C     ENABLE A/D CONVERTER
      JSB D.BUF     SEE IF A BUFFER WAS FILLED
      ISZ P.CNT     GOT ALL DESIRED PROFILES ?
      JMP RSTOR     NO
      CLC TBG,C     YES,TURN OFF TIME BASE
      LDA ADKNT     WAIT FOR CONVERTER
      CLE,SZA       TO GET AN
      JMP *-2       ENTIRE PROFILE
      CLC ADC       TURN OFF CONVERTER
      JSB D.BUF     SEE IF A BUFFER WAS FILLED
      LDB EOD       MARK THE END OF
      STB BADDR,I   THIS DATA FILE
      ISZ R.CNT     INCR. RUN COUNTER
      LDB BFLAG     GET BUFFER FLAG

```

	LDA B2ADR	GET ADDRESS OF
	SZB	LAST WORD OF
	LDA LST.W	APPROPRIATE BUFFER
	CLB	ZERO
	SEZ,CCE,RSS	
	JMP **3	THE
	STB BADDR,I	REST
	ISZ BADDR	OF
	CPA BADDR	THE
	RSS	BUFFER
	JMP *-4	CLEAR BUSY FLAG
	STB T.BZY	CLEAR SWR,
	LIA SWR	EXCEPT KEEP
	ELA	BIT 15
	ERB	THE SAME
	QTB SWR	RESET THE
	LDB BFLAG	THE BUFFER
	LDA B1ADR	POINTER TO
	SZB,RSS	THE START OF
	LDA B2ADR	THE NEXT BUFFER
	STA BADDR	TRANSFER THE LAST BUFFER
	JSB D.BUF	END DATA FILE
	JSB EOF,I	RESTORE
RSTOR	LDA ASAVE	
	LDB ESAVE	
	ELB	
	LDB BSAVE	REGISTERS
	JMP TBG.R,I	RETURN

*** ANALOG TO DIGITAL CONVERTER DRIVER CONTINUATOR ***

ADC.C	NOP	ENTRY
	STA SAVEA	SAVE REGISTER A
	LIA ADC	GET READING
	AND 03777	MASK OFF ADDRESS
	ALF	IF THE DATA
	RAL,RAL	WORD IS NEGATIVE
	SSA	OR 1'S INTO THE
	IOR M77	UPPER BYTE TO
	ALF,ALF	MAKE THE READING
	RAL,RAL	A NEGATIVE NUMBER
	STA BADDR,I	STORE READING
	LDA BADDR	INCR BUFFER
	INA	POINTER (IF
	CPA LST.W	NECESSARY
	LDA B1ADR	SWITCH THE
	STA BADDR	INPUT BUFFERS)
	LDA SAVEA	RESTORE REGISTER A
	ISZ ADKNT	GOT ALL 10 READINGS ?

	STC	ADC,C	ENABLE A/D CONVERTER
	JMP	ADC.C,I	RETURN
* WAIT	BSS	1	WAIT
	LDA	D.BZY	FOR
	SZA		DISC
	JMP	*-2	TO
	JMP	WAIT,I	FINISH
A	EQU	0B	REGISTER A
B	EQU	1B	
SWR	EQU	1B	
TBG	EQU	12B	
ADC	EQU	13B	
T.INT	EQU	24B	LINK TO TTY INPUT INITIATOR
INIT	EQU	25B	LINK TO TTY OUTPUT INITIATOR
FRD.	EQU	31B	LINK TO F.RD
FWRT.	EQU	32B	LINK TO F.WRT
FID	EQU	33B	LINK TO F.ID
BAC.	EQU	35B	LINK TO BAC
ABC.	EQU	36B	LINK TO ABC
PROMT	EQU	41B	LINK TO PROMPT
T.ADR	EQU	42B	TTY INPUT BUFFER STARTING ADDR
BUILD	EQU	44B	LINK TO CREATE SUBR.
EOF.	EQU	45B	LINK TO EOF
D.BZY	EQU	73B	DISC BUSY FLAG
F.BUF	EQU	74B	DMA BUFFER START ADDR
OUTP.	EQU	201B	TTY OUTPUT SUBROUTINE
DNAME	EQU	216B	
FNAME	EQU	217B	
R1	EQU	220B	
RCRD	EQU	224B	
L.REC	EQU	225B	
D.PTR	EQU	226B	DIRECTORY POINTER
BZFLG	EQU	227B	TTY BUSY FLAG
KOUNT	EQU	231B	INPUT CHAR COUNTER
D.ID	EQU	2135B	D.ID ADDRESS
DID	DEF	D.ID	
.CRLF	DEF	CRLF	
TBG.R	NOP		TBG RETURN ADDRESS
C.WRD	OCT	120	A/D CONVERTER COMMAND WORD
B1ADR	DEF	B1	FIRST BUFFER STARTING ADDRESS
B2ADR	DEF	B2	SECOND BUFFER STARTING ADDRESS
LST.W	DEF	E.BUF	ADDR OF 1ST WORD AFTER BUFFER
BADDR	NOP		BUFFER POINTER
BFLAG	NOP		ADC INPUT BUFFER INDICATOR
TBUF.	DEF	*+1	
	BSS	64	OUTPUT DATA BUFFER
L.WRD	DEF	*-1	

B.PTR	NOP		BUFFER POINTER
O.RCD	NOP		FILE OUTPUT RECORD NO.
I.RCD	NOP		FILE INPUT RECORD NO.
ADKNT	NOP		READING COUNTER
P.CNT	NOP		PROFILE
P.KNT	NOP		COUNTERS
M77	OCT	77	
O3777	OCT	3777	
EOD	OCT	105555	END OF DATA MARK
B15	OCT	100000	
R.CNT	NOP		RUN
R.KNT	NOP		COUNTERS
L.KT	NOP		COUNTER
SAVEA	NOP		REGISTER STORAGE
ASAVE	NOP		SAVED
ESAVE	NOP		
BSAVE	NOP		REGISTERS
T.KNT	NOP		TIME
T.CNT	NOP		COUNTERS
T.BZY	NOP		TIME BASE BUSY FLAG
DM1	DEC	-1	
DM10	DEC	-10	
O2	OCT	2	
D2	EQU	02	
D12	DEC	12	
D17	DEC	17	
D20	DEC	20	
D21	DEC	21	
D38	DEC	38	
TITLE	DEF	++1	
	ASC	17,VOLTAGE PROFILE ACQUISITION PROGRA	
	OCT	46412	
CRLF	OCT	6412	
DN.IN	DEF	++1	
	ASC	11,DISC/DATA FILE NAME ?	
NO..	DEF	++1	
	ASC	9,NO. OF PROFILES ?	
R.IN	DEF	++1	
	ASC	10,SAMPLE RATE (MSEC) ?	
TTY.O	DEF	++1	
	ASC	6,TTY OUTPUT ?	
YES	ASC	1,YE	
BLNK.	DEF	++1	
	OCT	6040	DOUBLE BLANK
B1	BSS	64	FIRST ADC INPUT BUFFER
B2	BSS	64	SECOND ADC INPUT BUFFER
E.BUF	EQU	*	END OF ADC INPUT BUFFER
	END		

PROGRAM ART

```

C
C PROGRAM TO READ DATA FROM FLOPPY OR MOVING HEAD DISC, THEN
C ANALYZE TO CALCULATE AVERAGE AND STANDARD DEVIATION AT EACH POINT
C
LOGICAL FLAG,ERFLAG,DFLAG
INTEGER FILE(3),IBUF(6003),DATA(10,600),FFNAM,FSECT(5)
INTEGER QWORDS,RError(10,5),PROFLS(5)
EQUIVALENCE (IBUF(3),DATA)
DIMENSION AVE(10),SUM(10),SUM2(10),STDEV(10),PDEV(10)
DIMENSION IIBUF(65)
DIMENSION RCOVAR(10)
EQUIVALENCE (IBUF,IIBUF(65)),(IIBUF,FSECT),(IIBUF(6),PROFLS)
EQUIVALENCE (IIBUF(11),RError),(IIBUF(61),QWORDS)
EQUIVALENCE (IIBUF(62),NWORDS),(IIBUF(63),NRUNS)
EQUIVALENCE (IIBUF(64),NPRFL)
EQUIVALENCE (RCOVAR,IBUF(4900)),(STDEV,IBUF(4920)),(PDEV,IBUF(494
10)),(AVE,IBUF(4960))
INTEGER AFFIRM,DNAME,OFLAG
COMMON FLAG,FFNAM,ERFLAG,DFLAG,DNAME
DATA AFFIRM,NEG/2HYES,2HNO/
DATA FILE(1),FILE(3)/2HFD,2H /
DATA NFFNAM/2H**/
IEOD=105555B
OFLAG=-10

C
C WILL OUTPUT DATA BE REQUESTED ?
10 WRITE(1,1)
1 FORMAT("OUTPUT DATA ?")
READ(1,22) IANSWR
IF(IANSWR.EQ.AFFIRM)OFLAG=10
IF(IANSWR.EQ.NEG)OFLAG=0
IF(IANSWR.LT.0)GO TO 10

C
C INPUT FROM FLOPPY OR MOVING HEAD ?
20 WRITE(1,2)
2 FORMAT("INPUT FROM FLOPPY ?")
READ(1,22)IANSR
IF(IANSR.EQ.AFFIRM)GO TO 100
IF(IANSR.NE.NEG)GO TO 20

C
C INPUT NAME OF MOVING HEAD DISC FILE
30 WRITE(1,3)
3 FORMAT("INPUT NAME OF DISC FILE.")
READ(1,23) FILE
23 FORMAT(3A2)

```

```

      IF(FILE.EQ.NFNAM) GO TO 999
      CALL EXEC(18,FILE,1)
      IF(1.NE.0)GO TO 50
      WRITE(1,12)
      GO TO 30
50    CALL EXEC(14,103B,IIBUF,128,FILE,0)
      WRITE(6,222)
      GO TO 325
100   WRITE(1,11)
C
C INPUT NAME OF FLOPPY DISC FILE
      READ(1,22) FFNAM
      IF(FFNAM.EQ.NFNAM) GO TO 999
      FILE(2)=FFNAM
      DO 110NRUNS=1,5
      DO 110M=1,10
110   ERROR(M,NRUNS)=0
      M=0
      ISECT=0
      NRUNS=1
      DFLAG=.FALSE.
      FLAG=.TRUE.
      CALL FREAD(IBUF)
      IF(.NOT.ERFLAG) GO TO 120
      WRITE(1,88)
      GO TO 100
120   IF(.NOT.DFLAG) GO TO 130
      WRITE(1,12)
      GO TO 100
130   NPRFL=IBUF(1)
      OWORDS=NPRFL*10+3
      NWORDS=OWORDS-2
      NFSCTR=(OWORDS-1)/64+1
      NSCTRS=1
      WRITE(6,222)
      WRITE(6,44)DNAME,FILE(2)
      GO TO 190
150   CALL FREAD(IBUF)
      NSCTRS=NSCTRS+1
      IF(ERFLAG) CALL ERROR(ERROR,M,NRUNS,NSCTRS)
180   IF(.NOT.FLAG) GO TO 250
190   DO 200I=65,128
200   IBUF(I)=0
      GO TO 300
250   IF(NSCTRS.EQ.NFSCTR) GO TO 190
      CALL FREAD(IBUF(65))
      NSCTRS=NSCTRS+1
      IF(ERFLAG) CALL ERROR(ERROR,M,NRUNS,NSCTRS)

```

```

300 CALL EXEC(15,103B,IBUF,128,FILE,ISECT)
    ISECT=ISECT+1
    IF(FLAG) GO TO 320
    IF(NSCTRS.NE.NFSCTR) GO TO 150
    PROFLS(NRUNS)=NPRFL-M*8
    IF(NRUNS.LE.5) GO TO 310
    WRITE(1,65)
    WRITE(6,65)
    GO TO 320
310 M=C
    NRUNS=NRUNS+1
    FSECT(NRUNS)=ISECT
    NSCTRS=0
    NFSCTR=(NWORDS-1)/64+1
    GO TO 150
320 PROFLS(NRUNS)=NPRFL-M*8
C PUT INFORMATION CONCERNING SECTORS OF BAD DATA INTO THE FIRST
C 64 WORDS OF THE DATA FILE
    CALL EXEC(14,103B,IBUF,64,FILE,0)
    CALL EXEC(15,103B,IIBUF,128,FILE,0)
325 I=0WORDS+64
C ALL DATA IS NOW STORED
C TIME NOW TO BRING DATA BACK INTO MACHINE, ONE RUN AT A TIME,
C TO PERFORM NECESSARY CALCULATIONS
    CALL EXEC(14,103B,IIBUF,I,FILE,0)
    WRITE(6,55)NPRFL,IBUF(2)
    WRITE(6,57)FILE,NRUNS
    NRUN=1
    GO TO 340
330 CALLEXEC(14,103B,DATA,NWORDS,FILE,FSECT(NRUN))
340 TSUM=0
    TSUM2=C
    TAVE=0
    M=1
    DO 350 I=1,10
        SUM(I)=0
        SUM2(I)=0
350 DO 450 J=1,NPRFL
        IF(ERROR(M,NRUN).NE.J) GO TO 400
        J=J+8
        M=M+1
400 DO 450 I=1,10
        SUM(I)=SUM(I)+DATA(I,J)
450 SUM2(I)=SUM2(I)+FLOAT(DATA(I,J))*2
        WRITE(6,233)
        WRITE(6,56) NRUN
        AVPOEV=0
        IF(OFLAG.EQ.0)GO TO 500

```

```

460  WRITE(1,1)
      READ(1,22) IANSWR
      IF(IANSWR.EQ.NEG) GO TO 500
      IF(IANSWR.NE.AFFIRM) GO TO 460
      IF(NRUN.NE.1) WRITE(6,222)
      N=1
      DO 470 J=1,NPRFL
        IF(ERROR(M,NRUN).EQ.J) WRITE(6,888)
        IF(ERROR(M+1,NRUN).EQ.J) M=M+1
        IF(ERROR(M,NRUN).EQ.0) GO TO 470
        IF(ERROR(M,NRUN).NE.J-8) GO TO 470
        M=M+1
      WRITE(6,888)
470  WRITE(6,77) J, (DATA(I,J), I=1,10)
500  IF(IEOD.EQ.DATA(1,NPRFL+1)) GO TO 510
      WRITE(6,66)
510  DO 550 I=1,10
      TSUM=TSUM+SUM(I)
      TSUM2=TSUM2+SUM2(I)
      AVE(I)=SUM(I)/PROFLS(NRUN)
      STDEV(I)=SQRT((SUM2(I)-(SUM(I)**2/PROFLS(NRUN)))/(PROFLS(NRUN)-1))
      RCOVAR(I)=0
      PDEV(I)=100*STDEV(I)/AVE(I)
      AVPDEV=AVPDEV+PDEV(I)
550  AVPDEV=AVPDEV/10
      TAVE=TSUM/(10*PROFLS(NRUN))
      TTDEV=SQRT((TSUM2-TAVE*TSUM)/(PROFLS(NRUN)*10-1))
      PTTDEV=100*TTDEV/TAVE
      DO 650 I=1,10
650  RCOVAR(I)=PDEV(I)/AVPDEV
      WRITE(6,99) PROFLS(NRUN)
      WRITE(6,111) TAVE
      WRITE(6,211) AVPDEV
      WRITE(6,112) TTDEV
      WRITE(6,113) PTTDEV
      WRITE(6,114)
      WRITE(6,115) (I, I=1,10)
      WRITE(6,116) AVE
      WRITE(6,117) STDEV
      WRITE(6,118) PDEV
      WRITE(6,119) RCOVAR
      IF((NRUN.GE.NRUNS).AND.(IANSR.EQ.AFFIRM)) GO TO 100
      IF((NRUN.GE.NRUNS).AND.(IANSR.EQ.NEG)) GO TO 30
      IF(IANSWR.EQ.AFFIRM) GO TO 670
      IF(NRUN.NE.3) GO TO 700
670  WRITE(6,222)
700  NRUN=NRUN+1
      IF(NRUN.GT.5) GO TO 100

```

```

GO TO 330
11  FORMAT("INPUT NAME OF FLOPPY DISC DATA FILE"/"?"")
12  FORMAT("NO SUCH FILE LISTED !")
22  FORMAT(A2)
44  FORMAT("THE FOLLOWING OUTPUT IS BASED ON DATA FROM THE FLOPPY DISC
1  FILE ",I4,".")
55  FORMAT("THIS DATA CONSISTS OF",I4," VOLTAGE PROFILES "
1  "WHICH WERE SAMPLED AT"/"INTERVALS OF",I4," MILLISECONDS.")
56  FORMAT("RUN NUMBER-",I2)
57  FORMAT("FILE ",I4,"CONTAINS DATA FROM",I2," RUNS.")
65  FORMAT("DATA FILE CONTAINS MORE THAN 5 RUNS. ONLY THE FIRST 5 RUNS
1  WILL BE ANALYZED.")
66  FORMAT("END OF DATA ERROR")
77  FORMAT(I4,I10)
88  FORMAT("ERROR IN READING DIRECTORY FROM FLOPPY DISC"/)
99  FORMAT(X,"NO. OF VALID PROFILES:",I4)
111  FORMAT("AVERAGE OF READINGS FOR THE RUN (TAVE):",F8.3)
112  FORMAT(X,"OVERALL STANDARD DEVIATION:",E10.4)
113  FORMAT(X,"OVERALL CO. OF VARIATION:",F11.4)
114  FORMAT(62X,"POSITION")
115  FORMAT(16X,I10)
116  FORMAT("AVERAGE",12X,10F10.3)
117  FORMAT("STD. DEV. (AVE)",6X,10E10.4)
118  FORMAT("STD. DEV. (AVE)",4X,10E10.4)
119  FORMAT("S/S(AVE)",8X,10F10.5)
211  FORMAT(X,"AVERAGE CO. OF VARIATION (AVE):",F11.4)
222  FORMAT("1")
233  FORMAT(4/)
888  FORMAT(3X,"????????????????????????????????????????????????????????
1  ?????????????????????????????????????????????????????????")
999  STOP
END
SUBROUTINE ERROR(ERROR,M,NRUNS,NSCTRS)
INTEGER RERROR(10,5)
IF(M.LT.10) GO TO 123
WRITE(1,88) NRUNS
WRITE(6,88) NRUNS
RETURN
123  M=M+1
WRITE(1,99) NRUNS
WRITE(6,99) NRUNS
IF(NRUNS.EQ.1) RERROR(M,NRUNS)=(NSCTRS*64-66)/10+1
IF(NRUNS.GT.1) RERROR(M,NRUNS)=(NSCTRS*64-64)/10+1
N=RERROR(M,NRUNS)+7
WRITE(6,77) RERROR(M,NRUNS),N
RETURN
77  FORMAT("DATA FOR PROFILES",I4," THROUGH",I4," WILL NOT BE ANALYZED
1  ")

```

```

88  FORMAT("OVER 10 READ ERRORS HAVE BEEN MADE IN RUN",I2,". RESULTS F
    10R THIS RUN ARE NOT VALID.")
99  FORMAT("READ ERROR IN RUN",I3," DATA")
    END

```

```

*
* SUBROUTINE TO READ RECORDS FROM THE FLOPPY DISC
* ON FIRST ENTRY DIRECTORY WILL BE READ TO LOCATE FILE, SUBSEQUENT
* ENTRIES WILL READ SUCCESSIVE RECORDS OF THE FILE
*

```

```

      NAM FREAD,7
      COM FLAG,FDNAM,M.FLG,DFLAG,DNAME
      EXT .ENTR
      ENT FREAD
      A EQU 0B      REGISTER A
      B EQU 1B      REGISTER B
      FD.CB EQU 23B  FLOPPY CONTROL BOARD
      FD.DB EQU 24B  FLOPPY DATA BOARD
      BUFF BSS 1
      FREAD NOP
      JSB .ENTR
      DEF BUFF
      LDA FLAG      IS THIS THE
                      FIRST ENTRY ?
      SSA,RSS       NO, GO CONTINUE READ
      JMP READ      YES, CLEAR
      CLB           FLAG
      STB FLAG      PUT HEAD
      LDA B15       BACK TO
      IOR FUR       TRACK 0
      OTA FD.CB     GO READ DIRECTORY
      JSB FD.RD     GET THE
      LDB BUFF,I    DISC NAME
      STB DNAME     INITIALIZE THE POINTER
      LDB BUFF      TO SCAN THE DIRECTORY
      ADB D2        FOR THE DATA FILE ENTRY
      STR PTR       GET AN ENTRY NAME
      LDA B,I       IS IT THE RIGHT ONE ?
      CPA FDNAM     YES
      JMP F.FND     NO, HAVE ALL ENTRIES BEEN CHECKE
      CPA EFILE     YES, IT'S NOT THERE
      JMP N.FLE     NO, CHECK THE
      ADB D3        NEXT ENTRY
      JMP D.LP      GET THE FIRST
      F.FND INB     TRACK & SECTOR OF
      LDA B,I       THE FILE & SAVE
      STA RCRD      GET THE LAST
      INB           TRACK & SECTOR OF
      LDA B,I       THE FILE & SAVE
      STA L.REC

```

READ	LDB RCRD	GET THE NEXT DISC ADDRESS
	JSB FD, RD	READ THE SECTOR
	LDB RCRD	IF THE SECTOR
	CLA	JUST READ IS THE
	CPB L, REC	LAST RECORD IN
	LDA B15	THE DATA FILE
	STA FLAG	SET FLAG
	ISZ RCRD	INCREMENT RECORD
	JMP FREAD, I	RETURN
N. FLE	LDA B15	SET DIRECTORY FLAG TO
	STA DFLAG	INDICATE NO SUCH FILE
	JMP FREAD, I	RETURN
FD. RD	NOP	
	CLF OB	INTERRUPTS OFF
	LDA BUFF	INITIALIZE
	STA PTR	POINTER
	LDA FOCW	GET READ CONTROL WORD
	IOR B	MERGE WITH TRACK & SECTOR
	STA FCW	SAVE COMPLETE CONTROL WORD
O. CH	OTA FD. CB	OUTPUT CONTROL WORD
	STC FD. CB, C	ENABLE CONTROL BOARD
	STC FD. DB, C	ENABLE DATA BOARD
	IOR B11	GET FCW READY FOR CHECK
	LDB DM64	INITIALIZE
	STB W. KT	WORD COUNTER
	SFS FD. DB	WAIT FOR THE DISC
	JMP *-1	CONTROL WORD TO BE READ
	LIB FD. DB, C	GET THE WORD
	XOR B	DO THE
	SZA	WORDS MATCH ?
	XOR FUR	NO, MAYBE FU WAS RESET
	SZA, RSS	MATCH NOW ?
	JMP W. LP	YES
	LDB M. FLG	HAS READ BEEN
	SSB, RSS	TRIED THRICE YET ?
	JMP TS. 00	NO, TRY READ AGAIN
W. LP	SFS FD. DB	WAIT FOR
	JMP *-1	DATA WORD
	LIA FD. DB, C	GET DATA WORD
	STA PTR, I	STORE INTO BUFFER
	ISZ PTR	INCR. BUFFER POINTER
	ISZ W. KT	GOT ALL 64 WORDS
	JMP W. LP	NO, GET ANOTHER
	CLC FD. DB	YES, TURN OFF DATA BOARD
	SFS FD. CB	WAIT FOR THE CONTROL
	JMP *-1	BOARD TO FINISH
	CLC FD. CB	TURN OFF CONTROL BOARD
	LIA FD. CB	GET ERROR WORD

	SZA		IS IT ZERO ?
	JMP	TS.00	NO, ERROR
	STA	M.FLG	YES, CLEAR MISREAD FLAG
RETRN	LDA	FCW	DEACTIVATE LOAD
	XOR	FDCW	HEAD & SEEK
	OTA	FD.CB	SIGNALS
	STF	OB	INTERRUPTS ON
	JMP	FD.RD,I	RETURN
TS.00	LDB	M.FLG	GET MISREAD FLAG
	SZB	RSS	FIRST MISREAD OF THIS SECTOR ?
	JHP	T.AGN	YES, TRY AGAIN
	SSB		THIRD MISREAD OF THIS SECTOR ?
	JMP	RETRN	RETURN WITH ERROR FLAG
	LDA	B15	NO, PUT DISC HEAD
	OTA	FD.CB	BACK TO T&S 00
T.AGN	LDB	DN4	WAIT
	ISZ	M.FLG	FOR
	JMP	*-1	A
	ISZ	B	FEW
	JMP	*-3	SECONDS
	STA	M.FLG	SET MISREAD FLAG
	LDA	FCW	GET CONTROL WORD
	JMP	Q.CW	TRY THE READ AGAIN
D2	DEC	2	
D3	DEC	3	
DN4	DEC	-4	
DN64	DEC	-64	
FDCW	OCT	30000	READ CONTROL WORD
B11	OCT	4000	BIT 11
B15	OCT	100000	BIT 15
FUR	OCT	40000	FILE UNSAFE RESET BIT
H.KT	NOP		WORD COUNTER
FCW	NOP		FLOPPY CONTROL WORD
PTR	NOP		BUFFER POINTER
EFILE	ASC	1,**	
RCRD	NOP		CURRENT FILE RECORD
L.REC	NOP		LAST RECORD OF FILE
	END		

APPENDIX C

DERIVATION OF CONCENTRIC CYLINDER VISCOMETRIC RELATIONSHIPS

The tensorial form of the Ostwald-deWaele (power law) Model is

$$\tau = - \left[m \left| \dot{\gamma} \right|^{n-1} \right] \dot{\gamma} \quad \text{C-1}$$

where the double dot product term of the shear rate tensors, in cylindrical coordinates, is given by

$$\begin{aligned} \dot{\gamma} : \dot{\gamma} = & 2 \left[\left(\frac{\partial v_r}{\partial r} \right)^2 + \left(\frac{1}{r} \frac{\partial v_\theta}{\partial \theta} + \frac{v_r}{r} \right)^2 + \left(\frac{\partial v_z}{\partial z} \right)^2 \right] + \\ & \left[r \frac{\partial}{\partial r} \left(\frac{v_\theta}{r} \right) + \frac{1}{r} \frac{\partial v_r}{\partial \theta} \right]^2 + \left[\frac{1}{r} \frac{\partial v_z}{\partial \theta} + \frac{\partial v_\theta}{\partial z} \right]^2 \\ & + \left[\frac{\partial v_r}{\partial z} + \frac{\partial v_z}{\partial r} \right]^2 \end{aligned} \quad \text{C-2}$$

Assuming that $v_r = v_z = 0$ for all r , z , and θ yields

$$\frac{\partial v_r}{\partial r} = \frac{\partial v_r}{\partial \theta} = \frac{\partial v_r}{\partial z} = \frac{\partial v_z}{\partial r} = \frac{\partial v_z}{\partial \theta} = \frac{\partial v_z}{\partial z} = 0 \quad \text{C-3}$$

Also, once the concentric cylinders and separating fluid have reached steady conditions all angular derivatives go to zero. Hence, equation C-2 reduces to

$$\dot{\gamma} : \dot{\gamma} = \left[r \frac{\partial}{\partial r} \left(\frac{v_\theta}{r} \right) \right]^2 + \left(\frac{\partial v_\theta}{\partial z} \right)^2 \quad \text{C-4}$$

Assuming end effects are negligible

$$\frac{\partial v_\theta}{\partial z} \approx 0 \quad \text{C-5}$$

Hence

$$\frac{1}{2}\Delta:\Delta = \left[r \frac{\partial}{\partial r} \left(\frac{v_{\theta}}{r} \right) \right]^2 \quad C-6$$

Taking into account equations C-3 and C-5, the shear rate tensor reduces to

$$\Delta = r \frac{\partial}{\partial r} \left(\frac{v_{\theta}}{r} \right) \quad C-7$$

Substituting equations C-6 and C-7 into equation C-1 gives

$$\tau = - \left[m \left| r \frac{\partial}{\partial r} \left(\frac{v_{\theta}}{r} \right) \right|^{n-1} \right] r \frac{\partial}{\partial r} \left(\frac{v_{\theta}}{r} \right) \quad C-8$$

Since τ is a function only of r

$$\tau = - \left[m \left| r \frac{d}{dr} \left(\frac{v_{\theta}}{r} \right) \right|^{n-1} \right] r \frac{d}{dr} \left(\frac{v_{\theta}}{r} \right) \quad C-9$$

If R is the radius of the revolving outer cylinder and kR is the radius of the stationary inner cylinder, then

$$v_{\theta} = 0 \text{ @ } r = R \quad C-10$$

and

$$v_{\theta} = \omega kR \text{ @ } r = kR \quad C-11$$

Since $k < 1$ and $v_{\theta}|_{kR} > v_{\theta}|_R$ C-12,13

$$\frac{dv_{\theta}}{dr} < 0 \quad C-14$$

therefore

$$r \frac{d}{dr} \left(\frac{v_{\theta}}{r} \right) < 0 \quad C-15$$

Hence equation C-9 becomes

$$\tau = -m \left| r \frac{d}{dr} \left(\frac{v_{\theta}}{r} \right) \right|^n \quad \text{C-16}$$

because τ must be less than zero to express the proper direction of the force on the inner cylinder.

Because v_{θ} is the only velocity component

$$\tau = \tau_{z\theta} + \tau_{r\theta} \quad \text{C-17}$$

Assuming that the shear on the end of the cylinder, $\tau_{z\theta}$, is much less than the shear on the cylindrical surface¹, $\tau_{r\theta}$,

$$\tau \approx \tau_{r\theta} = -\frac{T}{2\pi L r^2} \quad \text{C-18}$$

where T is the torque.

Combining equations C-16 and C-18

$$\frac{T}{2\pi L r^2} = m \left| r \frac{d}{dr} \left(\frac{v_{\theta}}{r} \right) \right|^n \quad \text{C-19}$$

Since $r > 0$, equation C-19 can be rearranged to give

$$\left| \frac{d}{dr} \left(\frac{v_{\theta}}{r} \right) \right| = \left(\frac{T}{2\pi L m} \right)^{1/n} r^{-(1 + 2/n)} \quad \text{C-20}$$

Since $\frac{v_{\theta}}{r}$ decreases as r increases

$$\frac{d}{dr} \left(\frac{v_{\theta}}{r} \right) < 0 \quad \text{C-21}$$

¹See Chapter III, Section G for a description of the method to include the effects of $\tau_{z\theta}$ into τ .

Therefore

$$\left| \frac{d}{dr} \left(\frac{v_\theta}{r} \right) \right| = - \frac{d}{dr} \left(\frac{v_\theta}{r} \right) \quad \text{C-22}$$

Hence equation C-23 becomes

$$- \frac{d}{dr} \left(\frac{v_\theta}{r} \right) = \left(\frac{T}{2\pi L m} \right)^{1/n} r^{-(1 + 2/n)} \quad \text{C-23}$$

Separating variables and integrating from the surface of the inner cylinder to the outer cylinder

$$- \int_{\omega}^0 d \left(\frac{v_\theta}{r} \right) = \int_{kR}^R \left(\frac{T}{2\pi L m} \right)^{1/n} r^{-(1 + 2/n)} dr \quad \text{C-24}$$

Assuming that m and n are not a function of shear rate, equation

C-24 becomes

$$\omega = \left(\frac{T}{2\pi L m} \right)^{1/n} \int_{kR}^R r^{-(1 + 2/n)} dr \quad \text{C-25}$$

Performing the indicated integration

$$\begin{aligned} \omega &= \left(\frac{T}{2\pi L m} \right)^{1/n} \left[- \frac{n}{2} \left(R^{2/n} - (kR)^{-2/n} \right) \right] \\ &= \left(\frac{T}{2\pi L m} \right)^{1/n} \frac{2}{n} \left[\left(\frac{1}{k^2} \right)^{1/n} - 1 \right] \\ &= \left(\frac{T}{2\pi L R^2 m} \right)^{1/n} \frac{n}{2} \left[\left(\frac{1}{k^2} \right)^{1/n} - 1 \right] \end{aligned} \quad \text{C-26}$$

Let

$$C = \frac{1}{2} \left(\frac{1}{2\pi L R^2 m} \right)^{1/n} \left[\left(\frac{1}{k^2} \right)^{1/n} - 1 \right] \quad \text{C-27}$$

Then C is a constant for any given power law fluid between any given pair of concentric cylinders. Substituting equation C-27 into equation C-26 gives

$$\omega = nC T^{1/n} \quad \text{C-28}$$

Taking the logarithm of both sides of equation C-28 yields

$$\ln \omega = \ln (nC) + \frac{1}{n} \ln T \quad \text{C-29}$$

Hence if one were to measure the torque on the inner cylinder at various rotational speeds and plot $\ln \omega$ versus $\ln T$ as shown in Figure C-1, the result should be a straight line of slope $\frac{1}{n}$ with an intercept on the $\ln \omega$ axis of $\ln (nC)$. This plot will yield values for C and n . Once C and n have been determined m can be calculated by rearranging equation C-27 to give

$$m = \frac{1}{2\pi LR^2} \left[\frac{\left(\frac{1}{k^2}\right)^{1/n} - 1}{2C} \right]^n \quad \text{C-30}$$

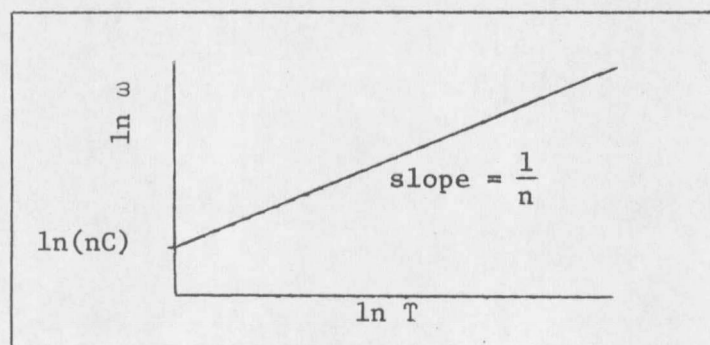


FIGURE C-1. PLOT USED TO DETERMINE PHYSICAL PARAMETERS OF A POWER LAW FLUID WITH A CONCENTRIC CYLINDER VISCOMETER

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