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ENTITLED

Design of a Low-Reynolds Number Static Mixer

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Chemical Engineering

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DESIGN OF A LOW-REYNOLDS NUMBER STATIC MIXER

BY

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THESIS

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1.1 ABSTRACT

A 12" long, 2" ID static mixer with a perforated helical inner geometry has been studied for use in the mixing of 2 fluids under low Reynolds number (Re < 1) flow conditions. Helices were constructed from perforated sheet metal, with hole diameters of 0.0625" and 0.033". Helix angles and cone angles ranged from 15 to 45 degrees. The two fluids utilized were dyed and clear corn syrup, whose viscosities ranged from 100 to 1000 centipoise (cp), depending on its water content. Linear velocities in the mixer ranged from 1.05 to 3.92 cm/min. Reynolds numbers based on the 2" ID plexiglass pipe ranged from 0.012 to 0.431.

The optimal design was found to be an internal geometry consisting of four 3" sections of alternatively upward and downward facing helices constructed from 0.033" hole diameter perforated metal with helix and cone angles of 35 degrees.

Using this configuration, water (1 cp) could effectively be mixed with 1000 cp fluids. This mixer was also able to effectively mix two 1000 cp fluids.

2.1 INTRODUCTION

The problem of mixing two or more fluids is prevalent in chemical engineering. High viscosities add further complications. The goal of this senior thesis project is to design a static mixer which will effectively mix high viscosity fluids at a low Reynolds number ($Re < 1$) flow.

Static mixers have 2 major advantages over conventional mixers. They have no internal moving parts, but rather depend on their internal geometry to cause mixing. In conventional mixers, internal moving parts are apt to become fouled. Seals around drive shafts may leak under the high pressures needed to move viscous fluids. Another problem may be degradation of sensitive materials by viscous heating effects caused by moving parts. A static mixer would eliminate or minimize all of these problems.

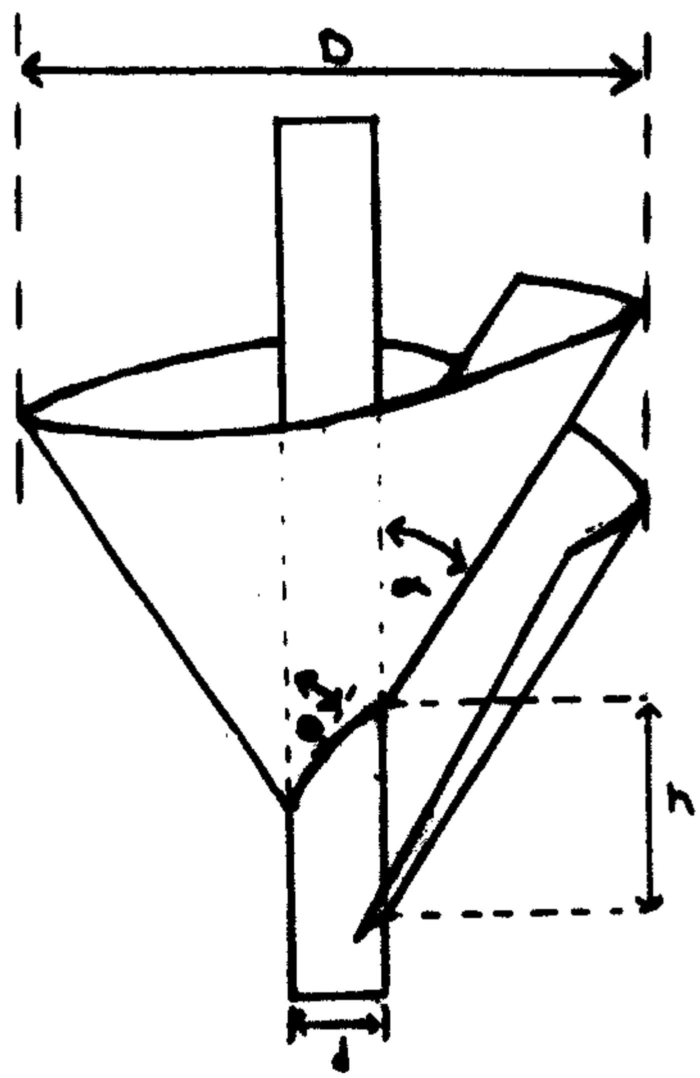
The second advantage of static mixing is that the only power required to run them is the pump head needed to move the fluid. Conventional mixers need power to move the fluid and to run the mixer motor.

Numerous static mixers exist, but most are designed for high Reynolds number flows. In these systems, turbulence is the primary mixing mechanism. Turbulence is non-existant in low Reynolds number flows. Instead, mixing is accomplished by laminar shear, elongational flow, and distribution. Laminar shear draws components out into progressively thinner layers.

Elongational flow stretches a fluid element out, thereby increasing its surface area. Distributive mixing uses flow division and recombination to create a mixing effect.

The approach taken in this project involves the use of a perforated helical inner geometry (Fig. 1). As the fluids spiral down the helix, they will be drawn out by shear as desribed above. Furthermore, axial flow through the perforations "pushes" one fluid element through the other in an elongational mechanism. Distributive mixing also occurs between the various stages of the mixer in a mechanism similar to that of a Kenics Mixer.

The quality of mixing obtained is determined by noting the striation thickness of the mixture as it flows through a 1/8' wide channel at the bottom of the column (the viewing plate). In the final designs, this thickness was on the order of one millimeter.



D = Tube Diameter
d = Support Rod Diameter
h = Height between helices
α = cone angle
θ = helix angle

Figure 1. Helix Parameters

3.1 SURVEY OF LITERATURE

3.1.1 INTRODUCTION

Mixing operations are encountered throughout the chemical industry. While mixing is commonly used, it is not well understood from a technical standpoint. The lack of knowledge in the mixing processes is often hidden by overdesign, which is undesireable from an economic standpoint

At this point it is instructive to review the background information on mixing that pertains to the problem of developing a low Reynolds number flow static mixer. The mixing of fluids under laminar flow conditions will be reviewed, followed by a literature survey of static mixers.

3.1.2 MIXING QUALITY

Mixing operations are used to reduce inhomogeneities in a mixture of fluids. It is therefore not suprising that the two commonly used measures of mixing quality in viscous flows, the scale and intensity of segregation (Fig. 2), are measures of the degree of inhomogeniety that exists between two components in a mixture.

The first measure of mixture quality is the scale of segregation. This is a measure of the size of the unmixed regions. In a static mixer, fluids undergo a series of divisions and reorientations. Ideally, however, the concentration at any point is either pure fluid A or pure fluid B.

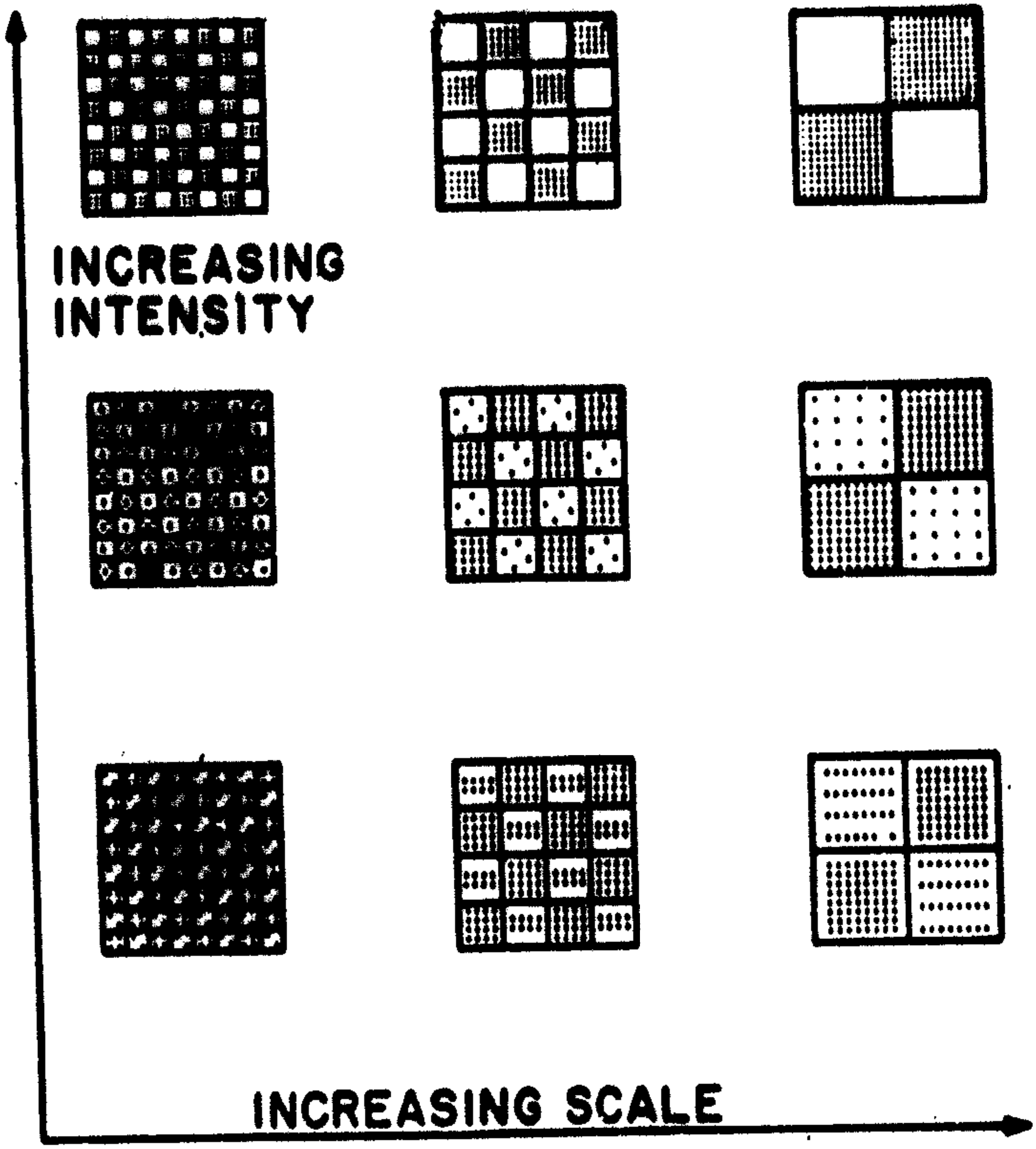


Figure 2. Scale and Intensity of Segregation
(Reproduced from Ind. Chem. Eng. 49, 1855 (1957))

Related to the scale of segregation is the striation thickness (Fig. 3). Striation thickness is defined as the distance between two like interfaces, and is a common measure of mixture quality in unidirectional viscous flows.

The second measure of mixture quality is the intensity of segregation. This is the measure of concentration differences between the undistributed portions and the desired mean composition. The intensity of segregation may be reduced by molecular diffusion. If there is no diffusion, the intensity of segregation remains constant. This mechanism may play a significant role in mixing only after the scale of segregation has been reduced to a small size.

3.2 LAMINAR MIXING

Many liquids are too viscous to be mixed by conventional agitated vessels. The power required to induce turbulence may be too great, and could lead to extremely high stresses in the machinery.

In other cases, laminar flow may be the desired. Examples of this are the processing of heat sensitive materials, in which excessive heat caused by an impeller may damage the fuids. Other examples include the mixing of biological materials, where excessive power inputs may damage micro-organisms.

Under laminar flow conditions, inertial forces are small,

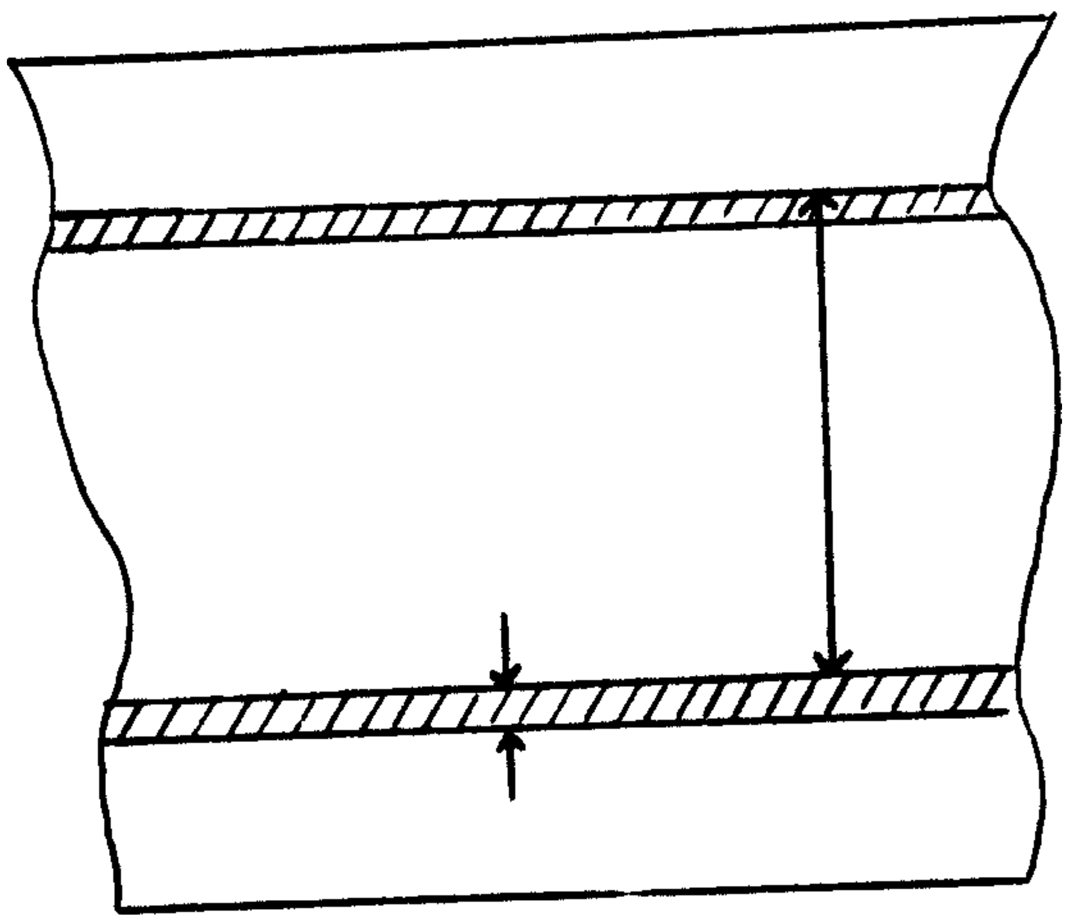


Figure 3. Striation Thickness

therefore turbulent mechanisms do not contribute to mixing. The basic mixing mechanisms for laminar flow are laminar shear, elongational or extensional flow, and distributive mixing.

3.2.1 LAMINAR SHEAR

In the laminar shear mixing mechanism, the relative motion of the fluid across its streamline introduces a deforming stress (Fig. 4) which draws out the components into progressively thinner layers. This increases the area between the two fluids and reduces the size of the regions occupied exclusively by one component, thereby reducing the striation thickness.

3.2.2 ELONGATIONAL OR EXTENSIONAL FLOW

Elongational flows are beneficial in that they increase the surface area that exists between two components (Fig. 5). This is important because it enhances the laminar shear mechanism.

3.2.3 DISTRIBUTIVE MIXING

Distributive mixing, a spatial redistribution, is illustrated best by a "slicing and rotating" mechanism (Fig. 6). This mechanism increases the interfacial area between two components, thereby reducing the scale of intensity.

The distributive mixing mechanism is enhanced by the shearing mechanism, and their combination is the basis for the design of most static mixers.

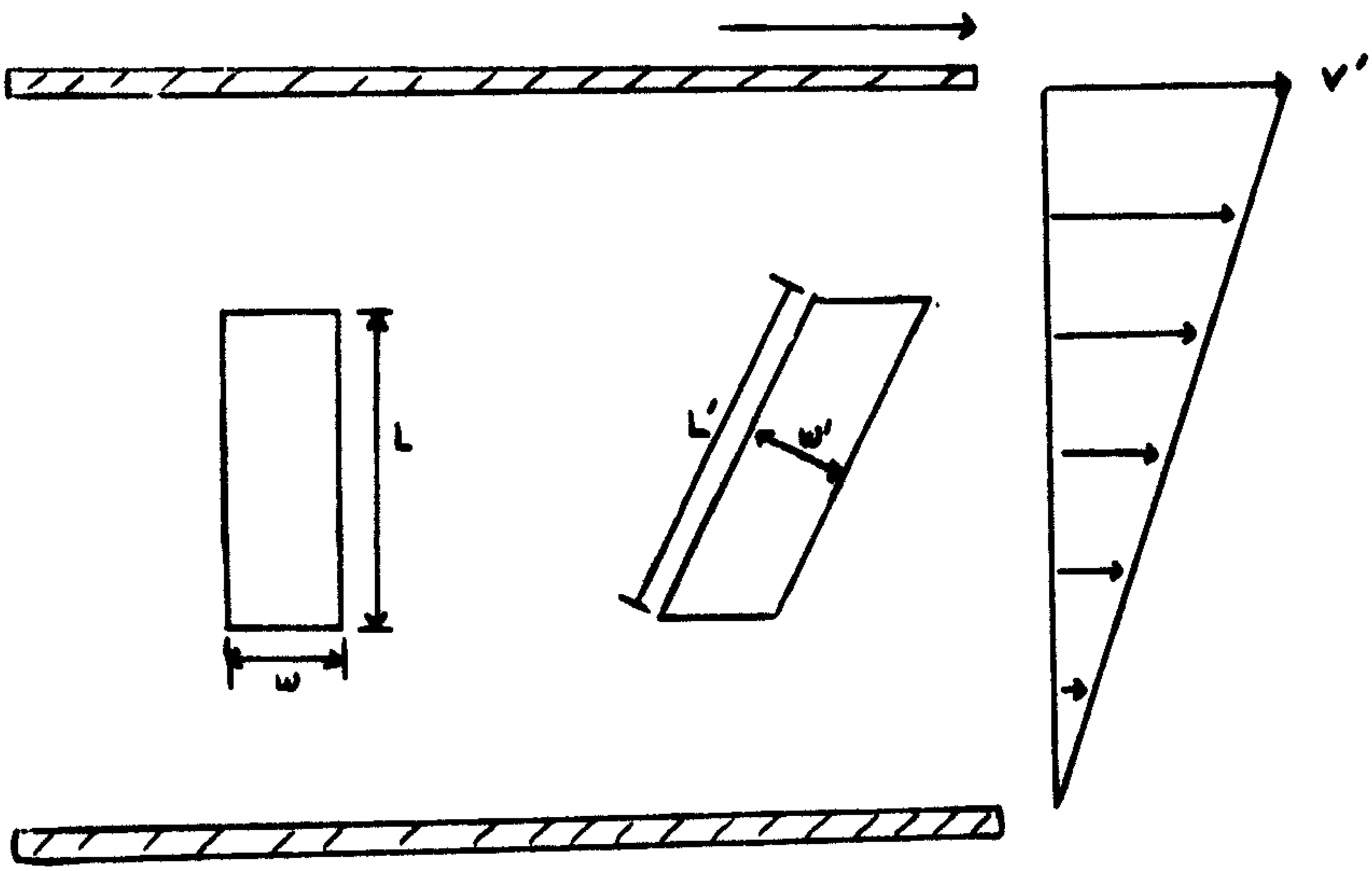


Figure 4. Laminar Shear

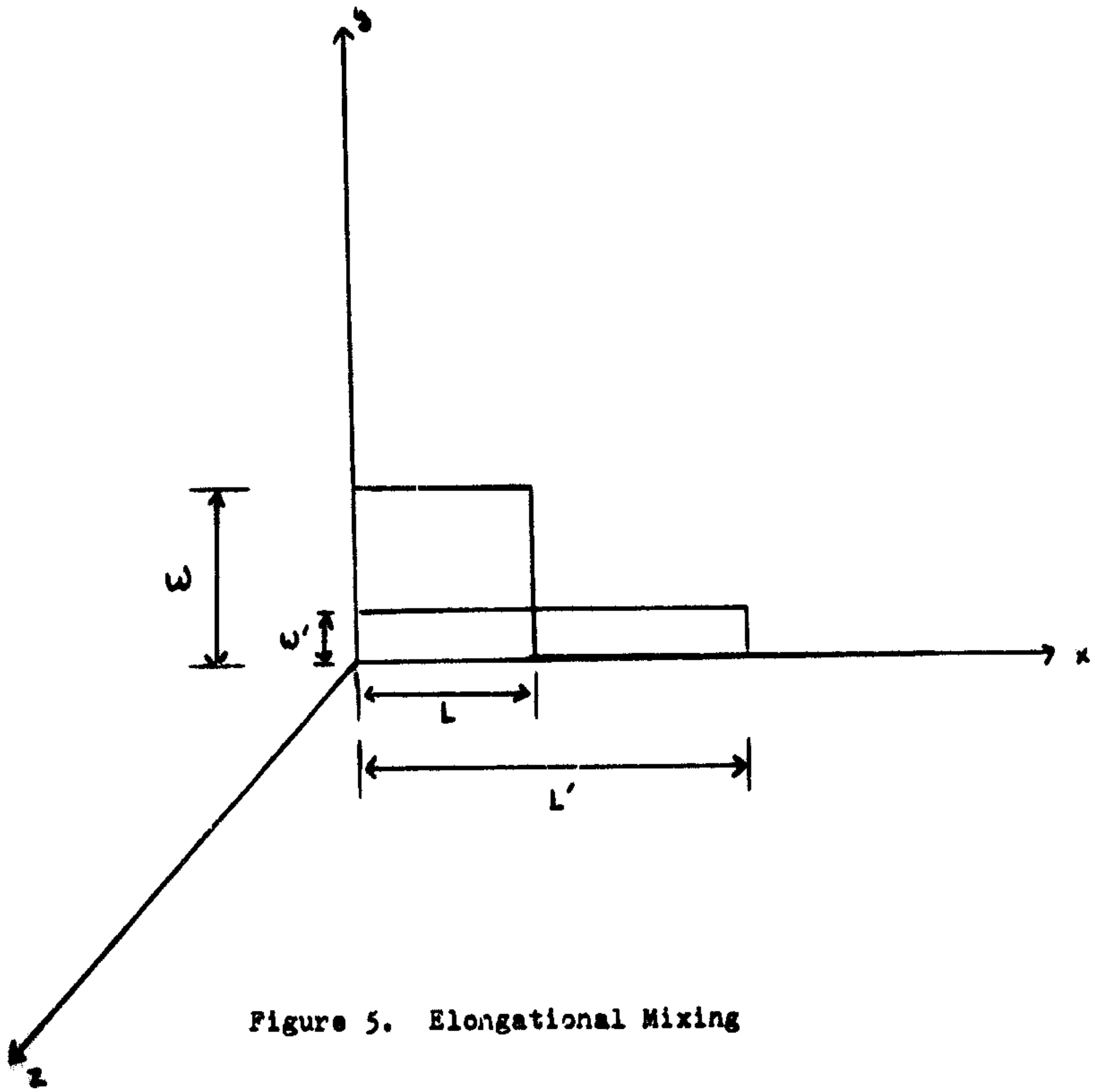


Figure 5. Elongational Mixing

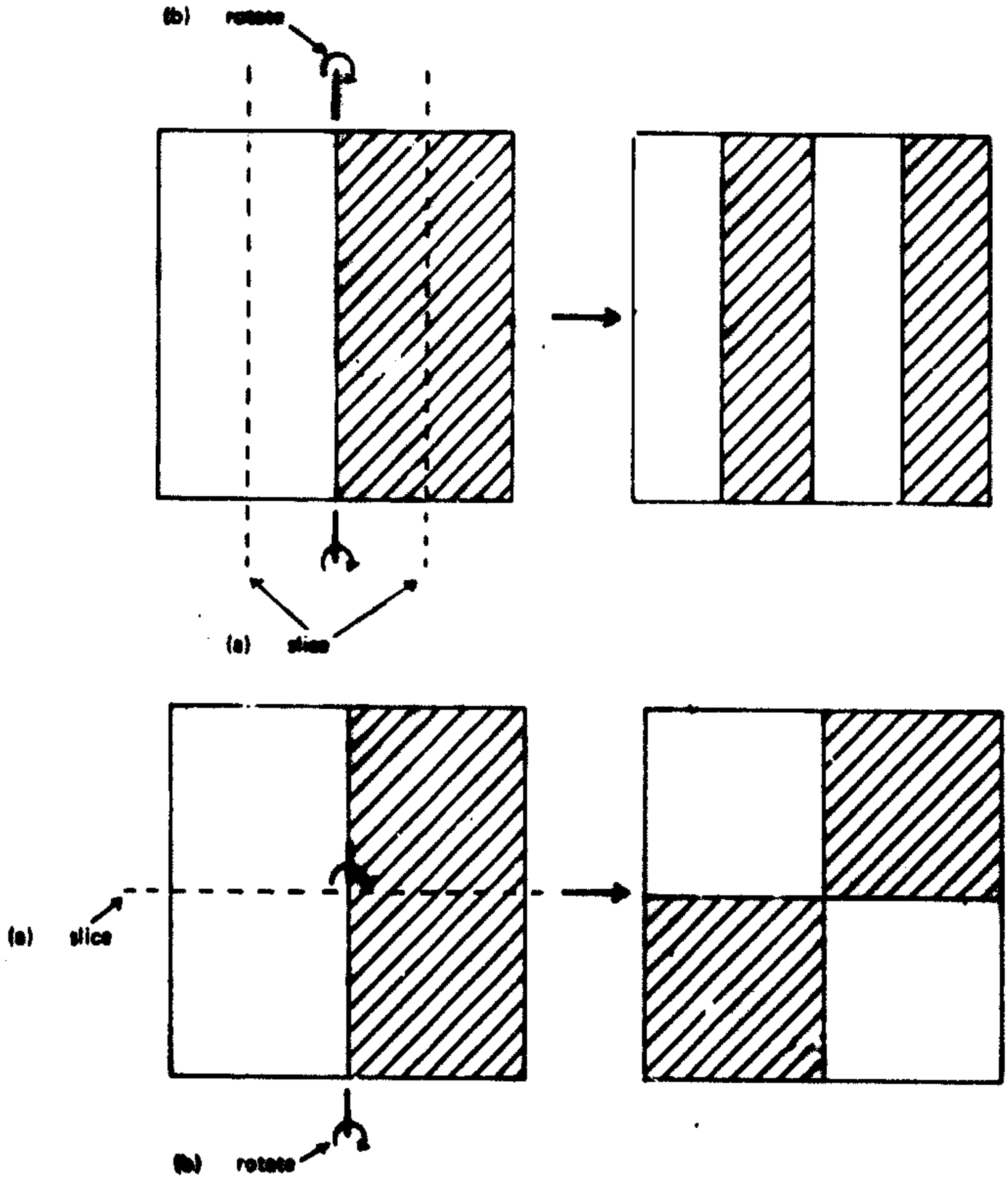


Figure 6. Distributive Mixing

(Reproduced from Harnby et.al., Mixing in the Process Industries, p. 216)

3.3 STATIC MIXERS

Static mixers are mixing devices which consist of a number of elements inserted into a length of pipe. The internal geometry of these elements brings about mixing, and causes an increase in the pressure drop compared to a straight pipe of the same diameter.

As mentioned earlier, static mixers rely on a process of flow division and re-orientation accompanied by shear to produce the mixing effect under laminar flow conditions.

Several static mixer designs currently exist, among them are the Kenics mixer (Fig. 7), the Etoflow mixer (Fig. 8), the Sulzer mixer (Fig. 9), the Ross mixer (Fig. 10) and the Lightnin mixer (Fig. 11).

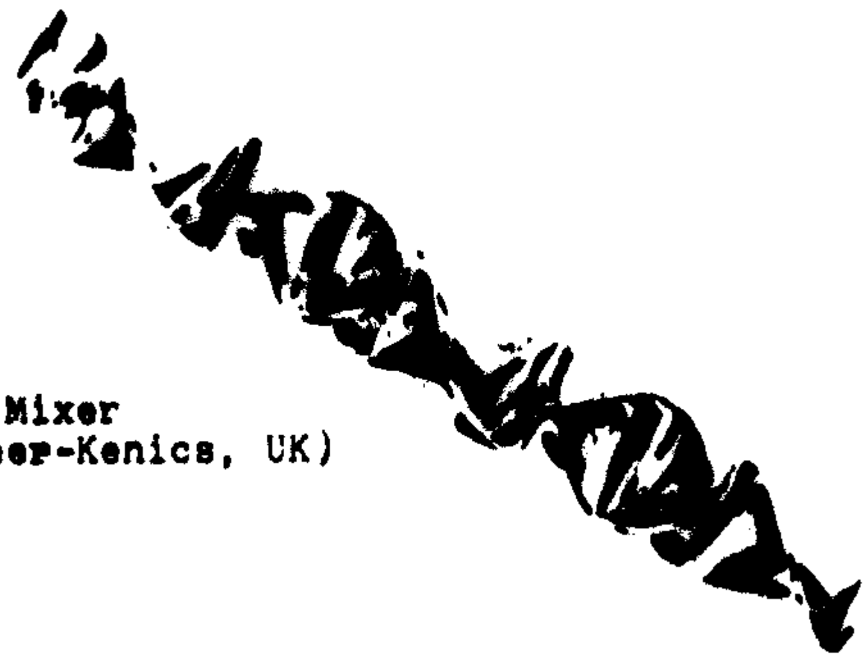


Figure 7. Kenics Mixer
(courtesy, Chemineer-Kenics, UK)

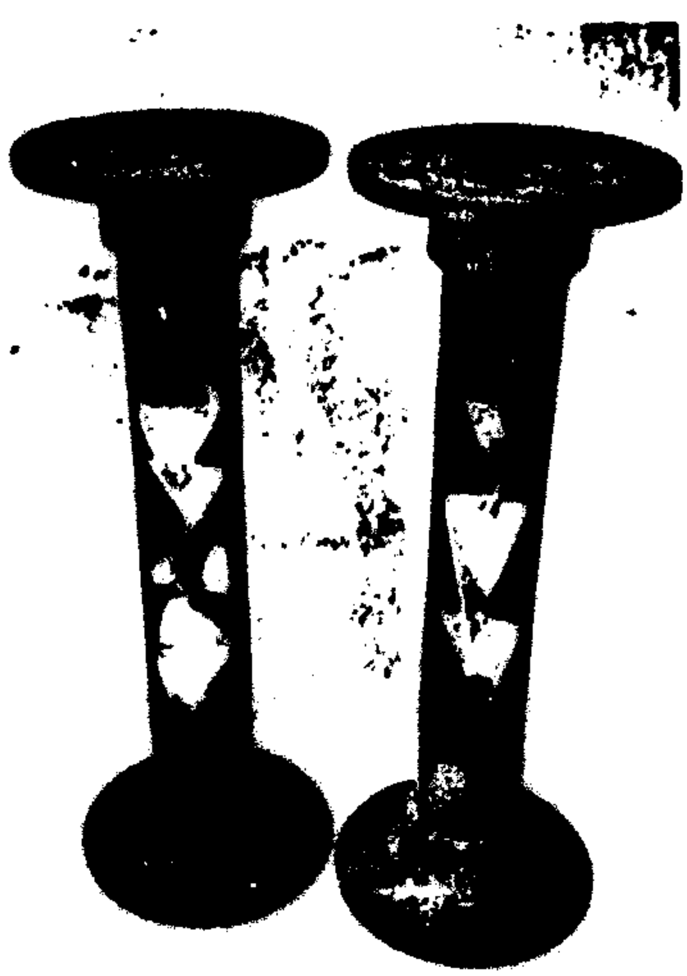


Figure 8. Etoflo Mixer
(courtesy, Wymbs Engineering Ltd)

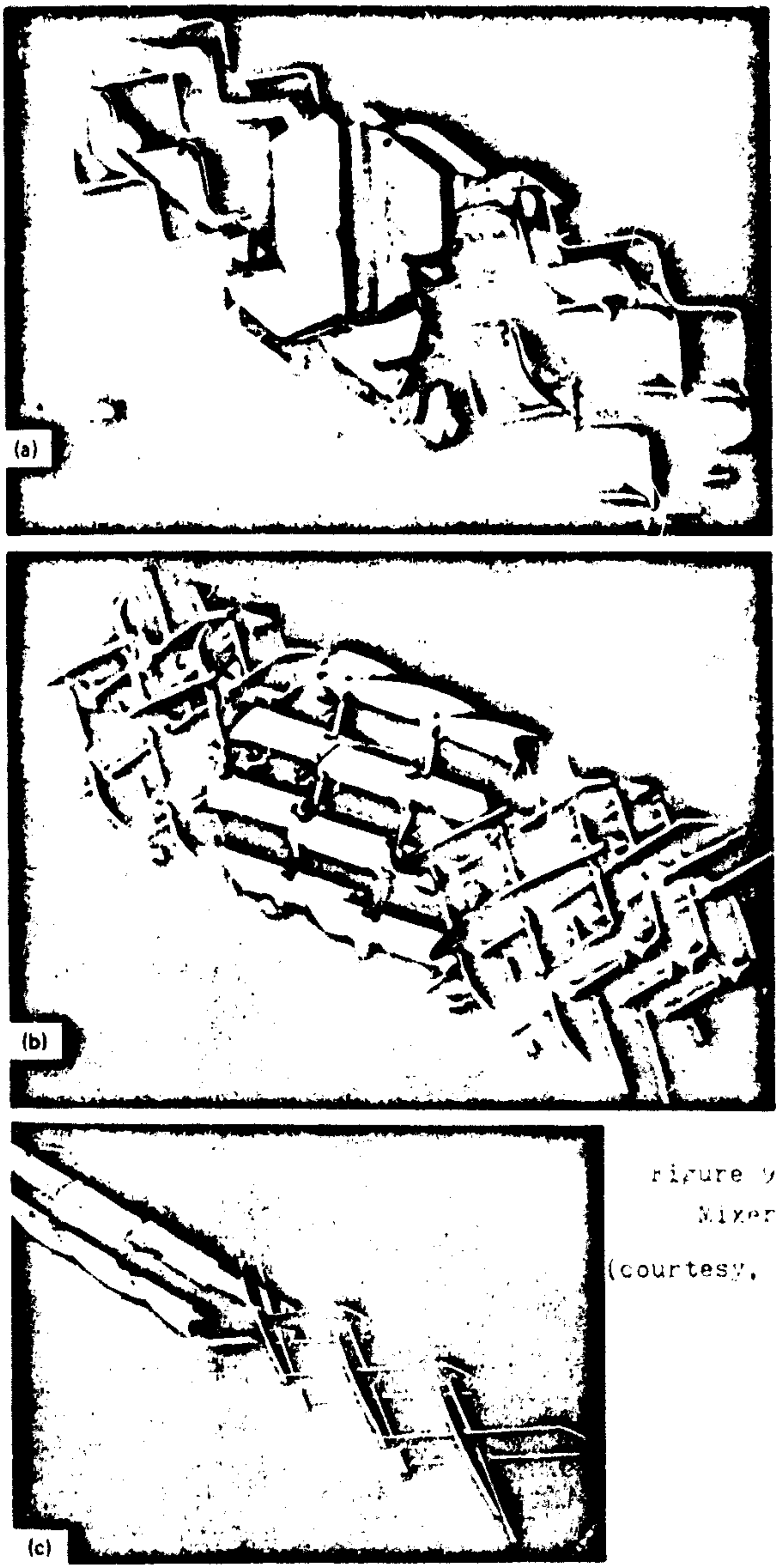
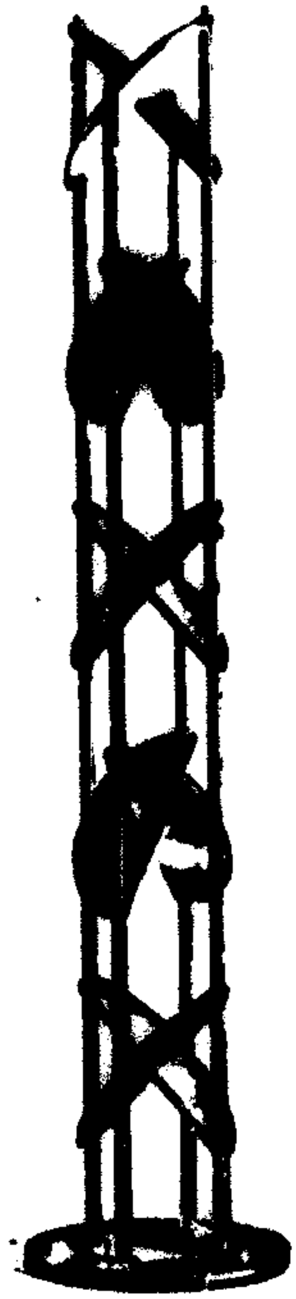


Figure 9. Sulzer Mixers
(courtesy, Sulzer, UK)



(a)

Figure 10. Ross Mixers
(courtesy, Transkem Plant)

Figure 11. Lightnin Mixer
(courtesy, Lightnin Mixers and Aerators)

4.1 APPARATUS

The apparatus used to investigate possible mixer designs is shown in Fig. 12. The mixer body consisted of a 2" ID, 12 inch long plexiglass cylinder, capped at both ends. The top cap of the mixer had two 1/4" inlets connected to a double headed peristaltic pump which was used to pump the fluids. The pump inlets were each connected to a 2 liter jar containing the fluids to be mixed.

The bottom of the cylinder was a 1/8" wide outlet slit across the diameter of the cylinder. This lead to a 4" wide X 5" long rectangular plexiglass channel, through which the final flow pattern could be observed. This was of particular use in the viewing of striation thickness, the basis used for assessing mixing quality.

The internal geometries used in the static mixer were single and double helices. Each helix was mounted on 3" section of 1/4" diameter aluminum rod, and a combination of 4 sections were used in the mixer. The rods had both a male and a female end, allowing a wide variety of rearrangements to be studied.

Initially, the helices were constructed of aluminum sheet metal, with the perforations and hole patterns being constructed by hand. Later, pre-made perforated metal sheets were found (McMaster-Carr). The following sheets were purchased:

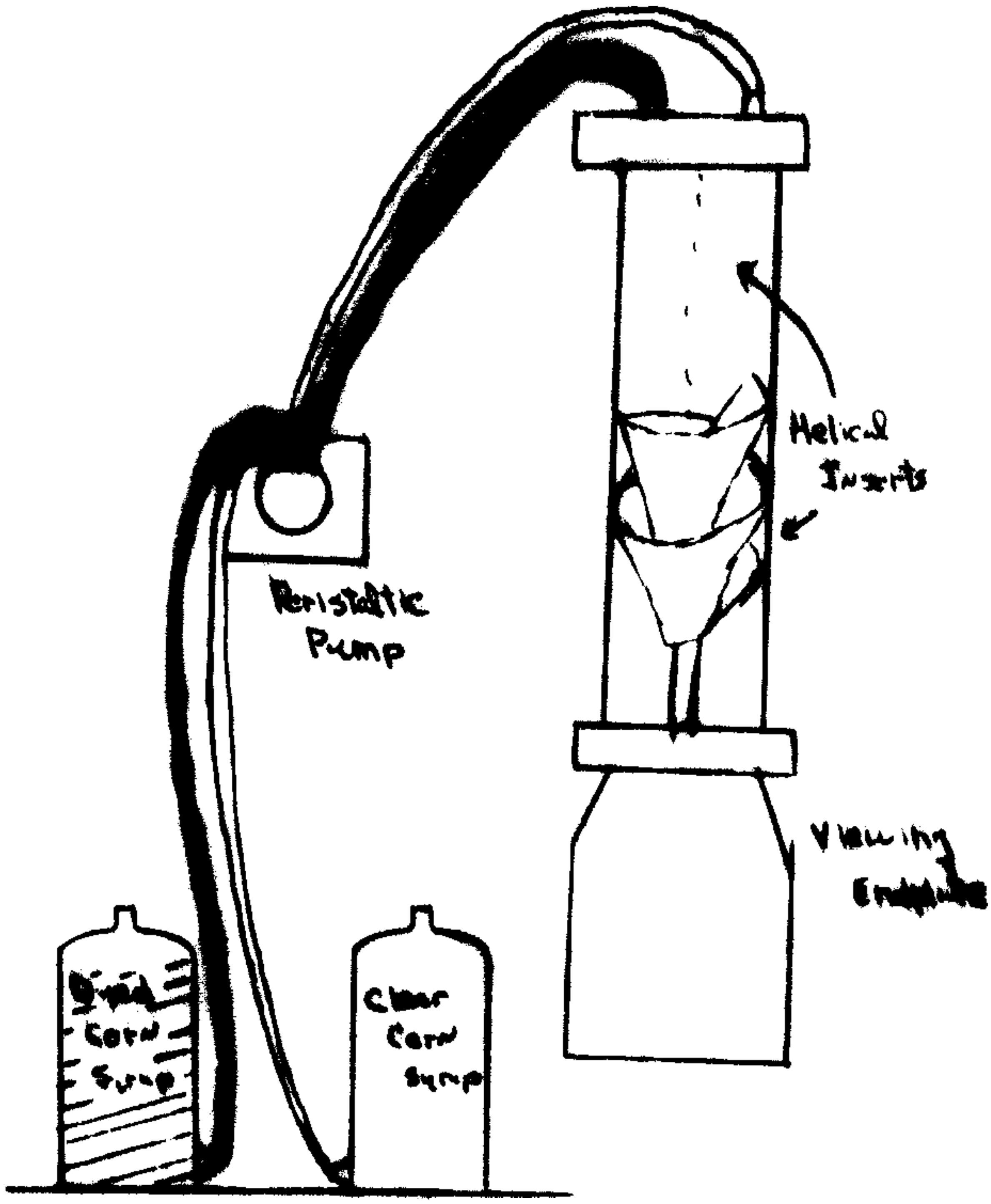


Figure 12. Experimental Schematic

Table 1. Perforated Sheet Parameters

Hole Diameter	% open	Pattern	gauge	Material
.0625 "	23%	staggered	20 ga.	Aluminum
.033"	20%	staggered	24 ga.	Stainless Steel

These pre-made sheets saved a tremendous amount of construction time, and were much sturdier than the previously used aluminum sheet metal. Once the helices were made, a layer of silicon rubber was placed around its edge to protect the plexiglass tube and to seal the edges.

Several types of fluids were utilized in this study. Initially, a water / congo red dyed water pair was used. This led to problems in that there was a tendency for the congo red to diffuse into the clear water. The next fluid pair used was acetic acid and sodium hydroxide with a phenolphthalien indicator. These fluids worked well, but density differences caused sufficient movement to induce turbulence, a mixing mechanism that does not apply to this study.

Glycerine was used to eliminate turbulence in the system. One fluid was clear glycerine, while the other was glycerine with small glass beads suspended in it, causing it to have an opaque color. Upon mixing, the beads would become mixed in the clear glycerine, causing a uniform opaqueness. At the end of an experiment, the mixture was set aside and allowed to settle. The clear glycerine was then be decanted off the top and re-used.

roblems arose for several reasons. First, the striation thickness of the mixture was hard to discern, as the contrast between the two fluids was small. There was a small amount of diffusion occuring between the two fluids, and there was a long settling time for the suspended spheres, causing delays in the experimentation.

The final fluid system used was dyed/clear corn syrup (Staley 1300). By mixing the syrup with various quantities of water, the viscosities could be varied from 1 cp to 1000 cp.

Table 2. Densities and Viscosities for Corn Syrup/Water Mixes

Corn Syrup	Water	Viscosity	Density
1250 ml	750 ml	150 cp	1.27 g/cm^3
1400	600	210	1.31
1600	400	400	1.36
1700	300	740	1.38
1800	200	970	1.40
pure corn syrup		60,000	1.44

Note that these values of viscosity are only approximate, as they were determined by measuring the rate of a falling ball in the fluid.

Because mixing introduced air bubbles into the system, the viscosities used seldom exceeded 750 cp. Higher viscosities would trap the air bubbles, leading to unacceptable delays. The air bubbles could be driven off by heating the mixture, which sufficiently lowered the viscosity to allow the bubbles to rise.

The rate of diffusion was studied to determine if it would play a role in the mixing process. A beaker of clear and dyed corn syrup was set aside, and after an hour was found to show no signs of diffusion. Note that this hour is larger than the maximum residence time observed for the mixer (29 min.).

5.1 EXPERIMENTAL

The static mixer was tested using various helical internal geometries. In all studies, flowrates ranged from 1.05 to 3.92 cm^3/min. Viscosities and densities ranged from 1 cp and 1.00 g/cm^3 to 1000 cp and 1.40 g/cm^3. These led to Reynolds numbers, based on the linear velocity in the tube, of 0.0116 to 0.431.

To begin the experiment, the mixer was filled with the one of the fluids to be tested (the clear one). The pump was then turned on, and the system was allowed to reach steady state. The flow pattern through the channel at the bottom of the apparatus was then used to observe the striation thickness of the resulting mixture. In the best designs, the striation thickness was reduced to approximately one millimeter, which approaches the limit of error in determining the thickness itself.

Various helical geometries were studied. In general, cone and helix angles ranged from 15 to 60 degrees, while perforation hole diameters ranged from 0.033" to 0.094". Studies were also performed using double helices (one helix screwed into another).

At the start of experimentation, all the helices were constructed by hand, including the punching of the perforation holes. These helices were hard to reproduce, i.e. although a series of helices were designed with the same parameters, they did not always come out looking the same. Once a series of helices was made, they were stapled together and affixed t one central support rod. This further complicated matters, as often the helices did not line up in the tube, causing leaking down the sides.

An improvement on the manufacture of the helices was made when the 12" support rod was replaced with 4 - 3" sections. Each of these smaller rods had a male and a female end, allowing sections to be interchanged. This added flexibility to the design process.

The smaller sections were also an improvement because instead of lining up 6 to 8 helices only 1 or 2 had to be aligned for each individual support rod. When these smaller sections were made, the glue was allowed to dry as the helix sat in a section of 2" ID tube, ensuring that they would be aligned. The process was further optimized when plastic shims were inserted between helices to ensure the proper helix angle.

Despite these optimizations in the helix manufacturing technique, the helices still lacked uniformity because of the technique used to punch the perforation holes. Also, it appeared that the smallest available punch size was almost too large for this application (.094").

It was then discovered that perforated sheets are available commercially in a wide range of hole sizes, hole patterns, and construction materials. The two sizes of these sheets that were ordered is listed in the apparatus section. The helices could then be made to a high degree of uniformity, altough the thicker metal was more difficult to work with and some inconsistancies between helices still existed.

6.1 RESULTS AND DISCUSSION

The results of the experimentation with the pre-perforated metal sheets will be given here. The overall mixer design will be discussed first, followed by the particular internal geometries.

6.2 OVERALL DESIGN

Experimentation with all the geometries showed that in order to be effective, the mixer must occupy the entire length of the tube. This is to eliminate the developement of stagnant regions within the mixer. The distance between helix sections must also be minimized for the same reasons.

In some of the original designs, a large stagnant region was observed at the bottom of the mixer to the side of the outlet (Fig. 13). This was due to a predominately helical flow through mixer, in which most of the fluid flowed out the bottom of the helix and into the exit slit. This was eliminated by the blocking of the helix bottom, which caused the entire flow to go through the perforations. While this resulted in excellant mixing, the pressure drop across that section was undoubtedly very large. This was later thought to be unacceptable, and an attempt to eliminate the stagnant region by creating better mixing in the upper stages was made.

Another attempt to reduce the final scale of intensity was made through the use of a fine mesh placed over the outlet slit. This accomplished nothing in the way of mixing, and

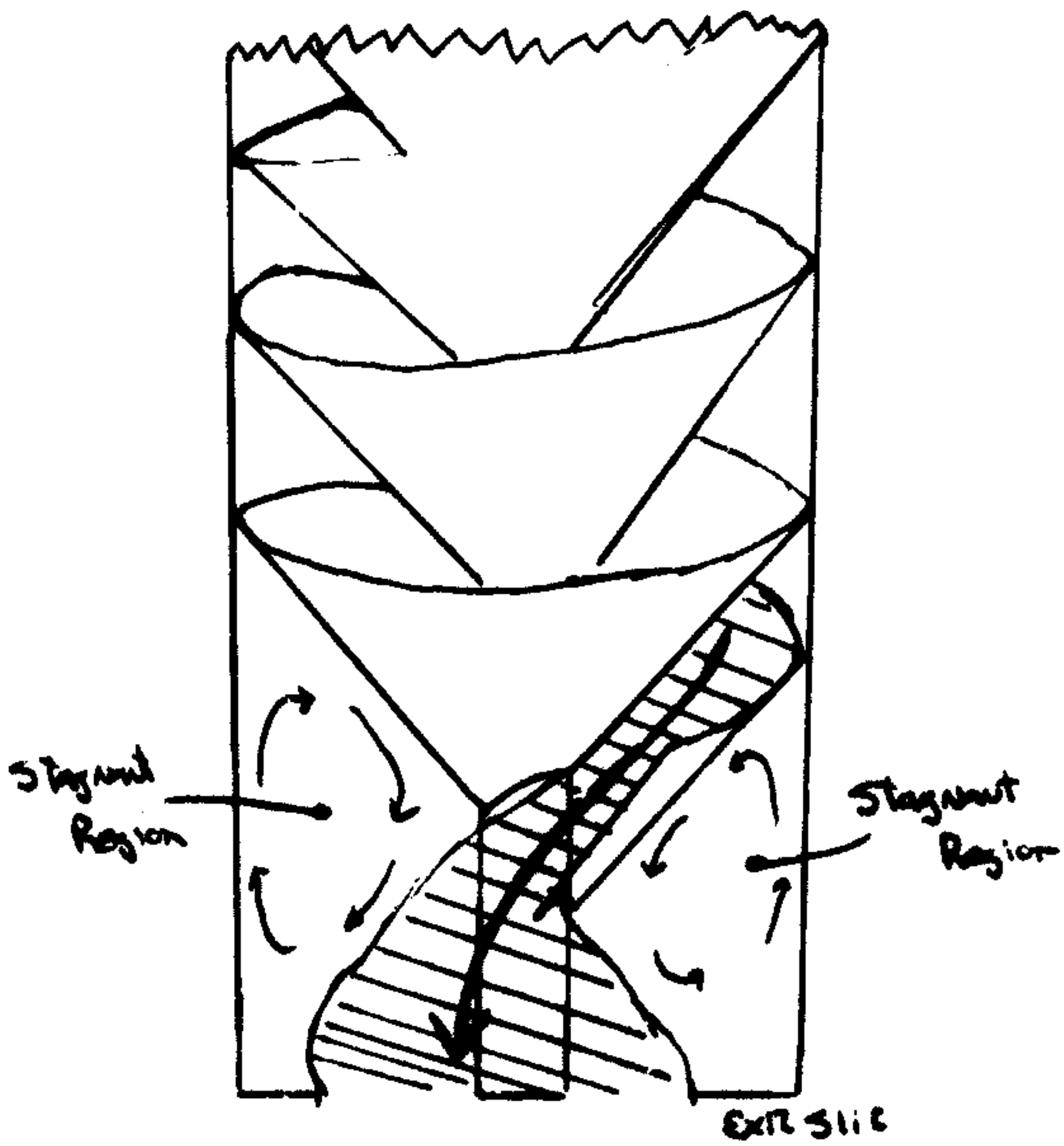


Figure 13. Stagnant Regions in the mixer

added to the pressure drop across the mixer.

6.3 INTERNAL GEOMETRIES

6.3.1 INTRODUCTION

The important parameters involved in the design of a helix are the cone angle, the helix angle, and the hole size. By varying any of these three values the amount of fluid flowing axially or helically may be changed.

Whether a fluid flows axially or helically depends on the pressure drop across the respective path. Axial flow is enhanced by large hole sizes and small channel heights. Helical flow is enhanced by the opposite. In the optimum case, the amount of fluid flowing helically should equal the amount of fluid flowing axially. It should be noted that what works for one set of fluids should work for another set of similar fluids provided the Reynolds number is sufficiently low ($Re < 1$) that the flows cannot be distinguished from one another.

6.3.2 DOUBLE HELICES

Double helices were investigated as a possible alternative to the standard single helix design. The idea behind the double helix was for each fluid to have its own helix, making the mixing to be more uniform. This was thought to be particularly important in the inlet of the mixer.

Problems developed in that they were extremely difficult to manufacture with any degree of uniformity. The pressure drop was also larger than that of a similar single helix because the channel width of the helix w halved. This led to problems in leakage around the sides of the mixer.

6.3.3 SINGLE HELICES

Single helices were the standard design throughout the experimentation. By varying the cone and helix angles, as well as the perforation hole diameter, the amount of axial and helical flow could be varied in a mixer. Ideally, the amount of fluid flowing axially should be equally to that flowing helically.

In these experiments, a 35 degree helix and cone angle was found to provide optimum mixing, just slightly better than the 45 degree cone and helix angle case. 25 degree angles resulted in a predominately axially flow, while 60 degree angles resulted largely in helical flows.

6.3.4 HELIX INVERSION

In the case of two fluids of differing densities, the heavier fluid flowed predominately towards the center, while the lighter fluid flowed towards the outer edge. This resulted in a mixture with a large steaks of the heavy fluid at the center of the viewing plate.

In order to eliminate this problem, the helices were alternatively pointed upwards and downwards (Fig. 14). The effect of the upward facing helix was to redistribute the

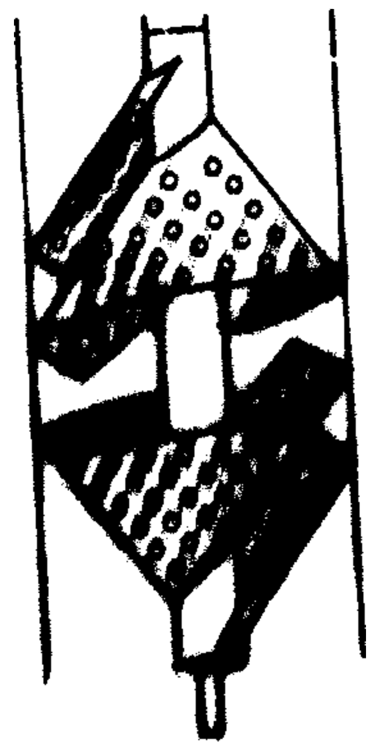


Figure 14. Final Helix Design

heavier fluid throughout the mixer after it had moved to the center during its motion through the downward facing helix. This resulted in an efficient mixer design. In experimentation, the density differences between the fluids could actually be seen to change and become uniform as the fluids flowed through the mixer.

6.3.5 OPTIMAL DESIGN

Based on the experimental results, a 35 degree cone and helix angle single helix was choosen as the optimal helix for mixing two fluids under low Reynolds number conditions. In order to effectively mix fluids of differing viscosities, the helices were alternatively pointed up and down to avoid the heavier fluid from flowing axially down along the support rod. Four - 3" sections (Fig. 14), each with a up and down facing helix, were used. Using this combination, two fluids of approximately 1000 cp could be mixed to the point where the striation thickness was less than 1 millimeter. Water and a 1000 cp corn syrup could also be mixed. This was easier than mixing the two 1000 cp fluids, as in this case the mixing of the corn syrup with water reduced the viscosity substantially. This is important though, as the densities were different.

7.1 CONCLUSIONS

1. A 12" long, 2" ID static mixer with an internal geometry consisting of four 3" sections of alternatively upward and downward facing helices has been developed which effectively mixes water (1 cp) and a 1000 cp corn syrup.

2. The same static mixer also works well at mixing 2 fluids with a viscosity of 1000 cp.

3. The addition of alternatively upward and downward facing helices has eliminated the tendancy for the higher density fluid to move to the center of the helix and flow down around the support rod, as previous designs with exclusively downward facing helices did.

4. Fluids moving in the mixer may either follow the helix or flow through the holes. These tendancies are a function of the pressure drop along the individual route.

4a. Helical flow may be increased by decreasing the hole size of the perforations, increasing the helix angle (pitch), or increasing the cone angle.

4b. Axial flow may be increased by increasing the hole size of the perforations, and by decreasing the helix or cone angles.

5. The mixer geometry must fill the entire region from inlet to outlet to eliminate the problem of stagnant regions developing.

8.1 RECOMMENDATIONS

1. The range of viscosity and density ratios that the mixer can effectivley mix should be extended. In particular, an attempt to mix higher viscosity fluids (10,000+ cp) with water should be attempted. In order to do this, a gear pump and the appropriate piping will be needed. The current peristaltic pump will not pump the corn syrup. The gear pump would allow the corn syrup to be pumped directly into the mixer.
2. Since the mixer appears to work well, an attempt to scale it up should be made. One simple way to accomplish this would be to double the size of all the helix parameters, then cut the edges of the helices so they can fit into the plexiglass tube.
3. As the pressure drop across a mixer is of vital importance, pressure taps should be added to measure it.
4. Design a method to accurately and uniformily manufacture the helices to obtain the desired helix and cone angles.

4a. If the scale-up studies appear favorable, and a method of uniform helix manufacture is devised, a stainless steel tube with the helices welded on could be made and tested industrially.

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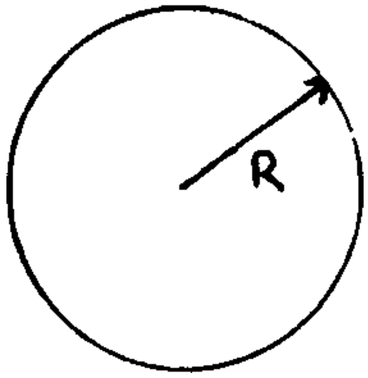
APPENDIX A: DERIVATION OF DESIGN EQUATIONS

Derivation of Design Equations

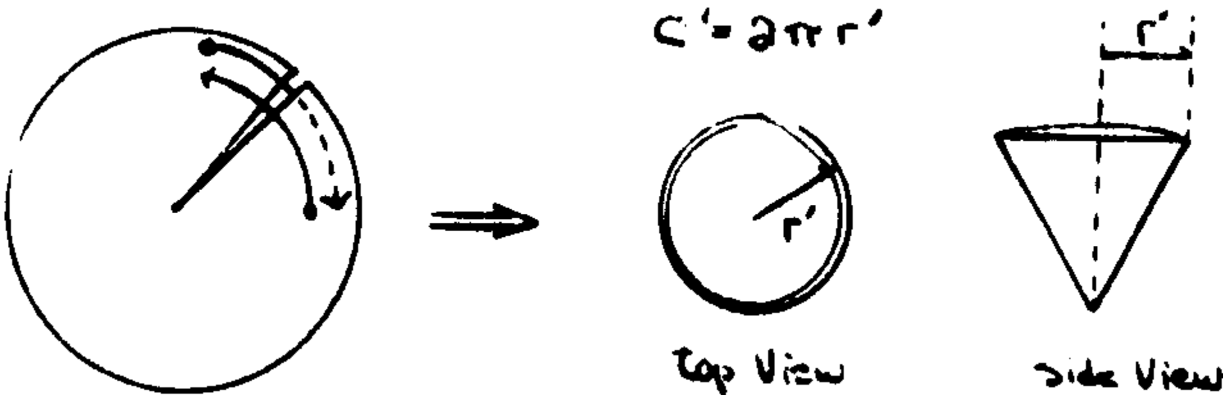
Consider a flat disk of radius R and circumference C,



$$C = 2\pi R$$

If the disk is cut along one of its radii, it may be twisted into a cone of radius r' and circumference C'

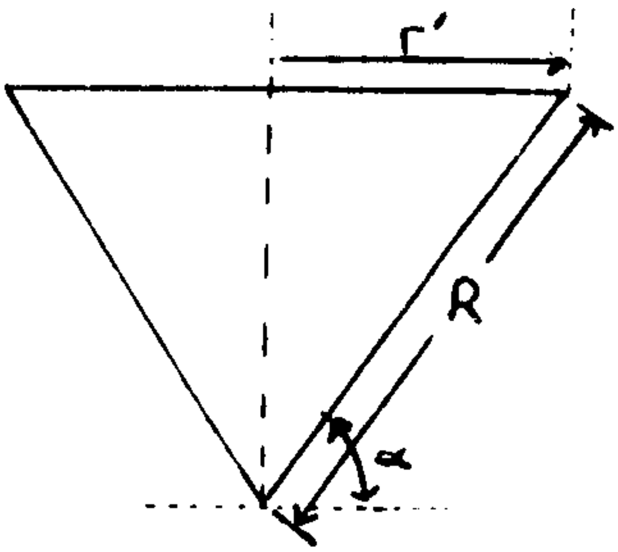
$$C' = 2\pi r'$$



For one 360° twist, the original circumference is halved. In general, the relation between the circumferences is:

$$C' = \frac{C}{n}, \quad \text{where} \quad n = \frac{{}^\circ \text{ of Twist}}{360^\circ} + 1$$

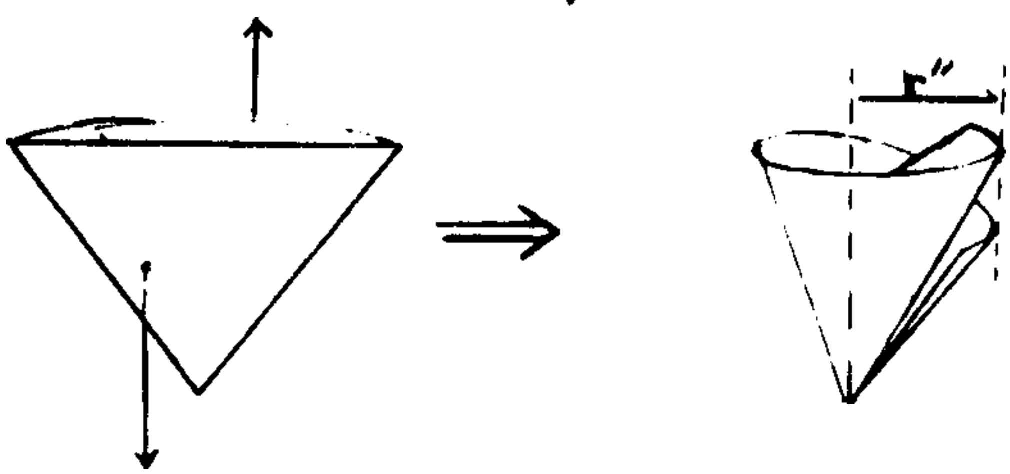
The value of r' may be determined by Trigonometry



α = cone angle

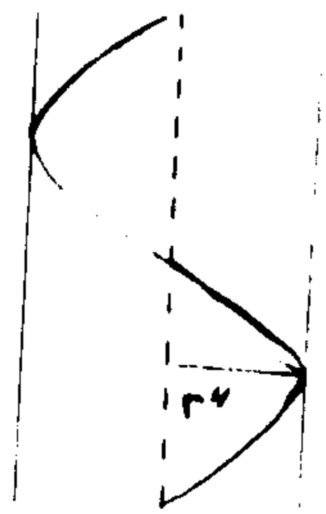
(1) $$\cos(\alpha) = \frac{r'}{R}$$

In order to make a helix, the cone must be stretched vertically

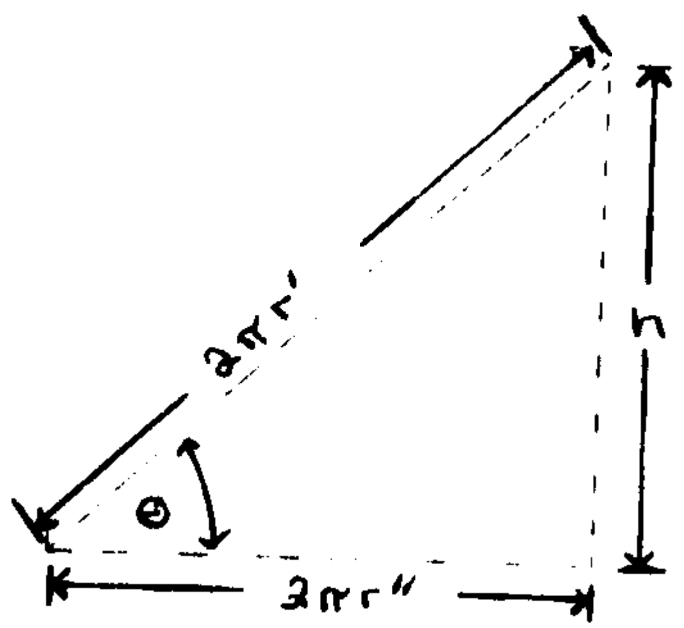


This deformation reduces the radius r' to r''

Again, r" may be determined trigonometrically
Consider the trace of the outer edge of the helix
on an imaginary cylinder



If the cylinder is "unrolled", the following results



(2) $$\cos(\theta) = \frac{r''}{r'}$$

In the design of helices for this project, the radius r" is set by the radius of the mixer tube. By combining equations (1) and (2), we may solve for R

(3) $$R = \frac{r''}{\cos(\alpha)\cos(\theta)}$$

<u>Example</u>

A helix for the mixer (2" ID) is desired to have a helix angle of 30° and a cone angle of 45°. What flat disk size is needed? Assume 1/4" Support Rod.

$$R = \frac{(2''/2)}{\cos(45°)\cos(30°)}$$

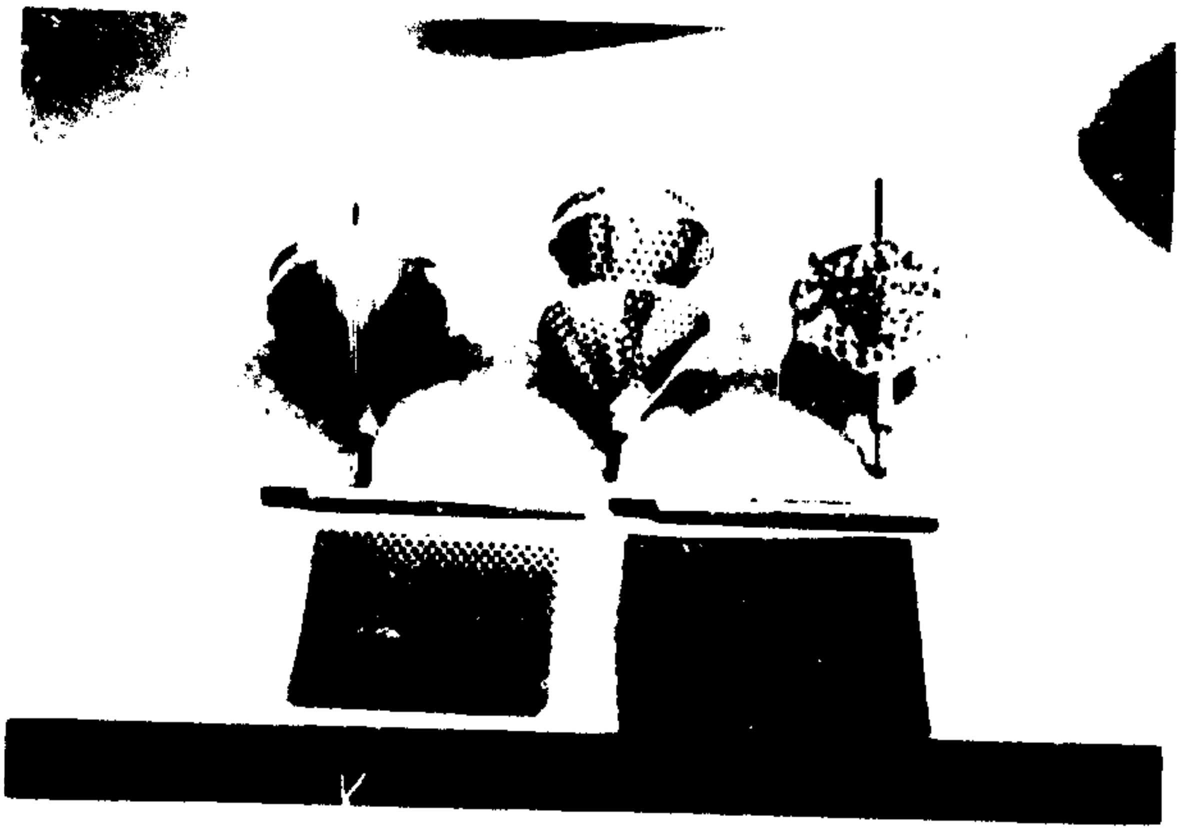
$$R = 1.633''$$

Similarly, the radius for the support rod hole (bottom of the helix) may be found

$$R_s = \frac{(\frac{1}{4})(1/2)}{\cos(45)\cos(30)} \Rightarrow R_s = .204''$$

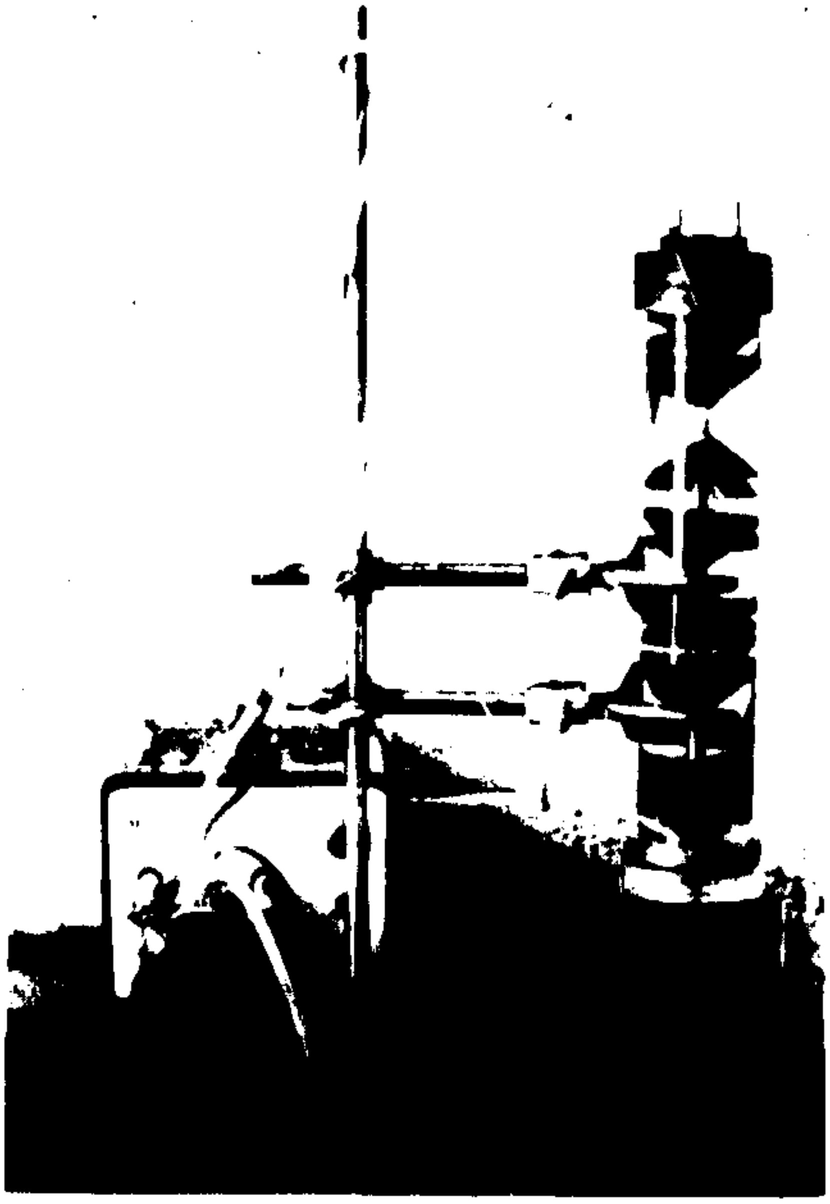
APPENDIX B: PICTURES

Picture 1. Construction Materials



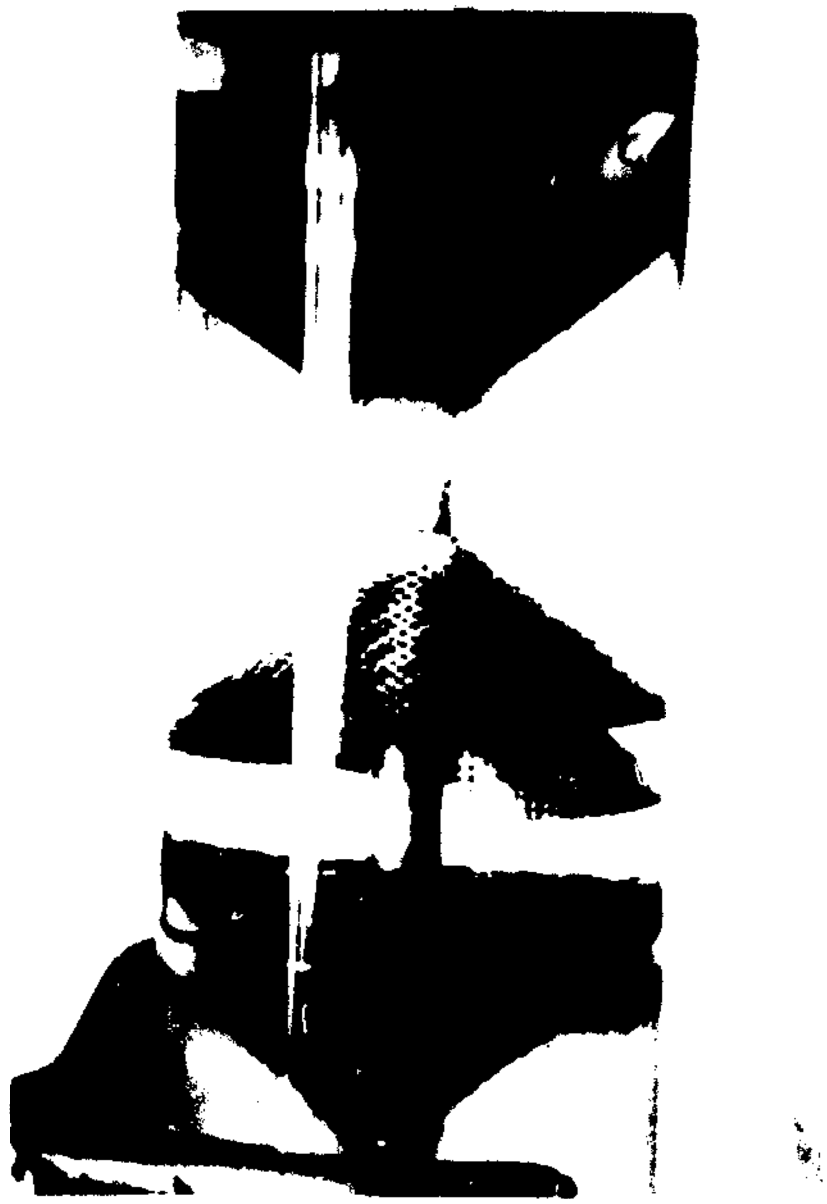
Picture 2. Static Mixer Experimental Set-up

Picture 3. Static Mixer Close-up



Picture 4. Experimental Start-up

Picture 5. Static Mixer, Operation (#1)



Picture 6. Static Mixer, Operation (#2)

Picture 7. Viewing Endplate