A VISUAL STUDY OF FLUID FLOW ACROSS A TUBE BANK

By

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A VISUAL STUDY OF FLUID FLOW ACROSS A TUBE BANK

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PREFACE

It was the purpose of this investigation to design, build, and render operational experimental apparatus that can be utilized in the study of the flow of non-Newtonian fluids normal to tube banks.

Such an experimental unit has been built, and contained in this thesis is a study made with it on water. The motion of the water through the tube bank was traced by following drops of an organic liquid mixture, and their movements were recorded by a motion picture camera. This study is particularly interesting in that all flow situations encountered were in the transition region between laminar and turbulent flow, thus exhibiting characteristics of both. It is the conclusion of the author that this apparatus and these methods will prove to be readily adaptable to the study of non-Newtonian flow normal to tube banks.

The author wishes to express his appreciation to Dr. Kenneth J. Bell of the School of Chemical Engineering, Oklahoma State University, for his continued interest in the research conducted in this thesis; to Dr. John B. West, for his suggestion to use organic liquid droplets as tracer particles, to Dr. James W. Fulton, Mr. Gene McCroskey, and the staff of the Research Apparatus Development Laboratory, all of the Oklahoma State University, for their many helpful suggestions; to Prof. Wilson J. Bentley of the School of Industrial Engineering, Oklahoma State University, for the loan of the motion picture camera used in this study; and to the Office of Engineering Research, Oklahoma State University, which provided the necessary funds to carry out this research work.

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CHAPTER I

INTRODUCTION

Motivation for This Study

A thorough knowledge of the flow characteristics of non-Newtonian fluids is necessary to the advance of modern technology, particularly that of Chemical Engineering. Non-Newtonianism is encountered in such diverse fluids as drilling muds, lithographic ink, foaming materials, and high polymeric systems.

Newtonian laminar flow is defined by Newton's equation stating that viscosity is equal to the ratio of shear stress to shear rate, and is characterized by the fact that the viscosity is constant and independent of the shear stress.

$$\mu = \tau / (du/dy) \qquad (1)$$

μ = viscosity

du/dy = shear rate

τ = shear stress

It is further stipulated that in Newtonian flow shear stress is linear with shear rate, and they both become zero simultaneously. Non-Newtonian behavior is defined as an entirely reversible viscosity change due to the application of a shear stress. In the case of very high polymeric systems, however, permanent viscosity changes have been noticed at high shear stresses.

One important flow situation in need of extensive investigation is fluid flow normal to tube banks. Such a situation is encountered on the shell side of a shell-and-tube heat exchanger, for example. In the shell side phase of heat exchanger design the least understood facet is the pattern of fluid flow. The problem here is aggravated by the fact that most industrial exchangers operate in the transition or turbulent flow regimes, which are only slightly understood at the present time.

Previous Work

Most of the previous research in this area has been concerned with determining heat transfer coefficients and friction factors, rather than with the fluid mechanics involved. Of the investigations which have been conducted into the fluid flow mechanisms, most have been concerned with, or have at least considered, the effects of bypass flow around the main tube bundle (1,2).

Various methods have been employed in tracing the flow through tube banks. Qualitative observations have been made using tiny metallic particles, notably pointing out eddy action between tubes (cited in (1)). Attempts at quantitative measurements using larger particles may also be found in the literature, for example (1). In this case, the particles employed were roughly spherical bits of Styron

480, 1/16 in. in diameter, with a density somewhat higher than that of the water into which they were injected.

Present Work

The objective of this investigation was to develop apparatus and methods to be applied to the specific problem of visually studying non-Newtonian flow patterns normal to a tube bank. One of the first side effects to be eliminated was the bypass phenomenon usually present. This was accomplished by making all the peripheral tubes in the bank half-tubes joined to the walls of the container (see Figure 2, page 8). Thus there was no avenue available for bypass flow in the present tube bank.

Because of the essentially developmental nature of this work, the experimental design was kept as elementary as possible. The in-line square tube arrangement was chosen, rather than the more complex triangular or staggered square arrangements. Water was designated as the test fluid because of ready and economical supply and the availability of large amounts of data for comparison purposes. Modification of the apparatus to other tube arrangements and fluids for further studies will be quite simple.

It was originally expected that a close approximation to the actual fluid flow pattern could be obtained by introducing small spherical pellets of nearly neutral density into the stream. Polyethylene pellets with a diameter of approximately 1/8 in. were chosen. Their density was adjusted to equal that of water by inserting a sliver of steel through the middle of each one, and then painting them with aluminum paint.

The use of these pellets, however, proved to be experimentally impractical (see CHAPTER IV). They were replaced by droplets of an organic liquid mixture, which worked quite well. The paths of these droplets through the tube bank were photographed by a 16 mm motion picture camera focused directly on the top of the bank (see Figure 4, page 12). A frame-by-frame study of the resulting motion pictures provided the data on the motion of the water through the tube bank.

CHAPTER II

APPARATUS

The container of the tube bank was a sheet metal box with an overall length of 5 ft. 2 in., a depth of 1 ft., and a width of 6 in. (see Figure 1, page 6). The tube bank itself consisted of five 2 in. aluminum tubes in the center of the container, with five half-tubes on each side. As shown in Figure 2, page 8, the tubes were in a symmetrical, in-line arrangement, separated by 1 in. laterally and 15/16 in. longitudinally.

The bank was located in the center of its container. The hollow tubes were filled with polystyrene to prevent leakage into them and flow across their tops, and to facilitate visual observation. The tubes in the center row were welded at their bottoms to a removable sheet metal plate which was wedged into place in the bottom of the container. The half-tubes on the sides were welded to flat sheet metal plates, which were in turn welded to the sides of the container.

The tube bank covered the center 14 in. of the container. On either side of it there was a 1 ft. long section of the container of full cross-sectional area. Then, as may

Figure 1

Scale Diagram of the Tube Bank

Container (Scale: 1" = 1')

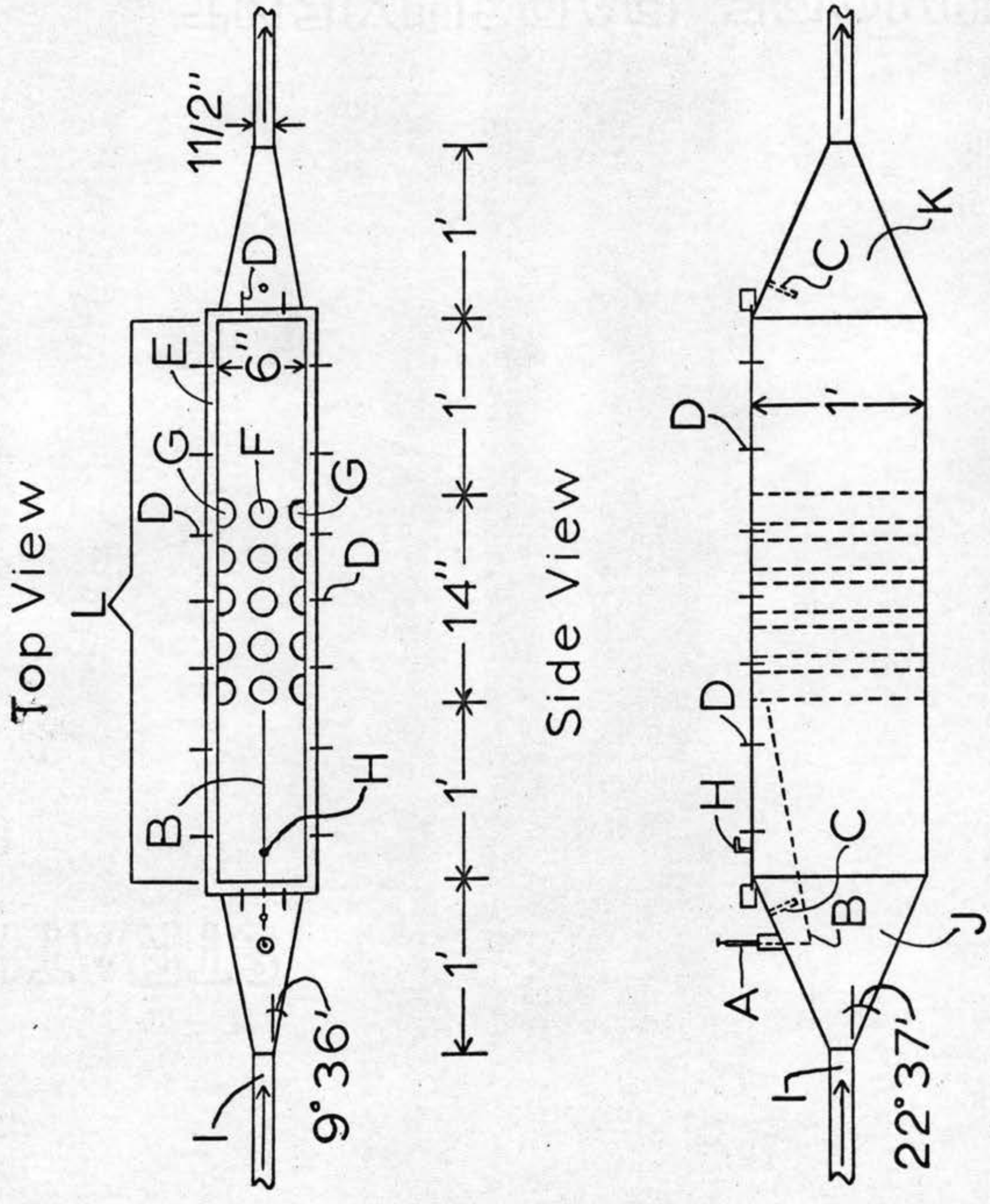


TABLE I

LEGEND FOR FIGURE 1

A. All-glass syringe

B. Steel capillary tubing

C. Copper-constantan thermocouples

D. One-inch "C" clamps

E. Lip around top of tube bank container

F. Full-sized centerline tubes, 1 7/8 inches O. D.

G. Half-tubes along sides of container

H. Bleeder valve in plexiglas top

I. 1 1/2 inch standard weight schedule 40 steel pipe

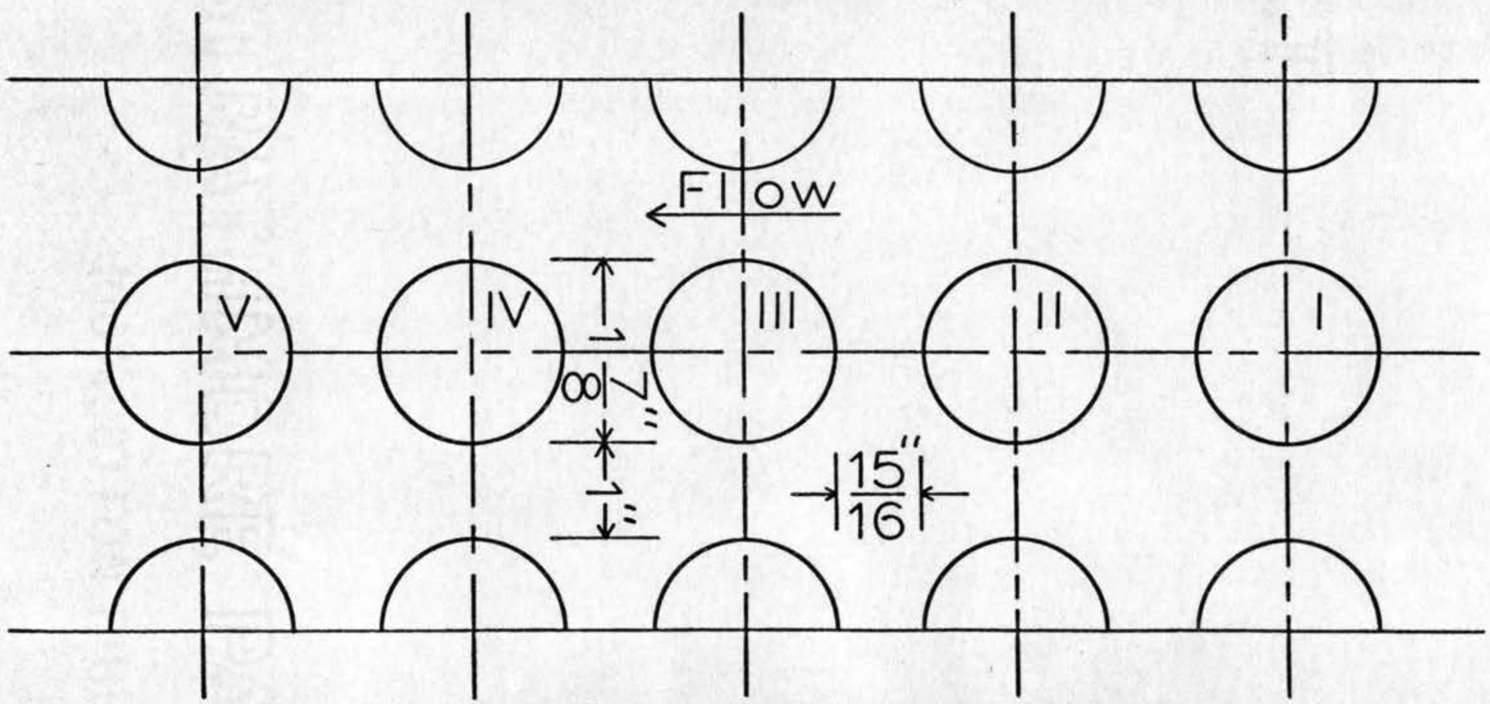
J. Expanding section

K. Contracting section

L. Observation area

Figure 2

Top View of Tube Bank (Scale: 1" = 2")



be seen in Figure 1, page 6, on either end of the container there was a 1 ft. long section which expanded the flow from the 1 1/2 in. pipe of the system to the 1 ft. by 6 in. cross section of the observation area.

Since the tracer particles were to be of the same density as the fluid under study, it was assumed that vertical motion of the particles would be insignificant, and that their horizontal motion would be of primary interest. Therefore, the entire 3 ft. 2 in. length of the observation area was left open at the top, but no side ports were provided.

The open top of the container was covered by a 1/4 in. thick sheet of plexiglas. The upper edge of the container was turned over into a 1 in. lip to support the plexiglas lid. The seal between the lip and the lid was made by common rope putty. The lid was secured by seven 1 in. "C" clamps on each side, and by two 1 in. "C" clamps on either end. The pressure on the lid from the clamps was spread fairly evenly by 1/8 in. thick strips of aluminum, covering the entire upper edge of the lid and the lower edge of the lip. With proper care in assembly, this arrangement effectively eliminated the leakage of air into the flow stream and water out of it.

A bleeder valve in the plexiglas top, 1 in. from its upstream end, provided an avenue for the escape of the air trapped in the tube bank container when the system was filled with water. Liquid overflow through this bleeder valve was channeled through 1/4 in. copper tubing into a suitable container.

The tracer droplets were injected about 1/4 in. from the upstream edge of the tube bank through a steel capillary tube. This steel tube entered the flow stream 4 in. upstream from the intersection of the expanding section with the observation area through a 1/4 in. copper tube (see Figure 3, page 11). The copper tube jutted into the flow pattern 4 in., and was sealed at either end by a rubber cap. It in turn passed through the center of a brass nut, and the two were soldered together. The nut was screwed onto a nipple welded to the top of the expanding section. All these associated junctions proved to be watertight.

The temperature of the water was monitored both upstream and downstream of the tube bank by copper-constantan thermocouples. These thermocouples were sealed in two-hole ceramic conduits, which were sealed into 4 in. lengths of 1/4 in. copper tubing with Epoxy resin (see Figure 1, page 6, for the positions of the thermocouples). The thermocouple wires were connected to a potentiometer through a multipole switch.

The motion pictures were taken with a Bell and Howell Filmo 70D-A roll camera for 16 mm film. It was situated 3 ft. 3 in. above the plexiglas top, and a 375 watt photoflood lamp was placed at either end of the observation area, about 6 in. above the plexiglas top (the camera and flood lamps are not shown in their correct positions in Figure 4,

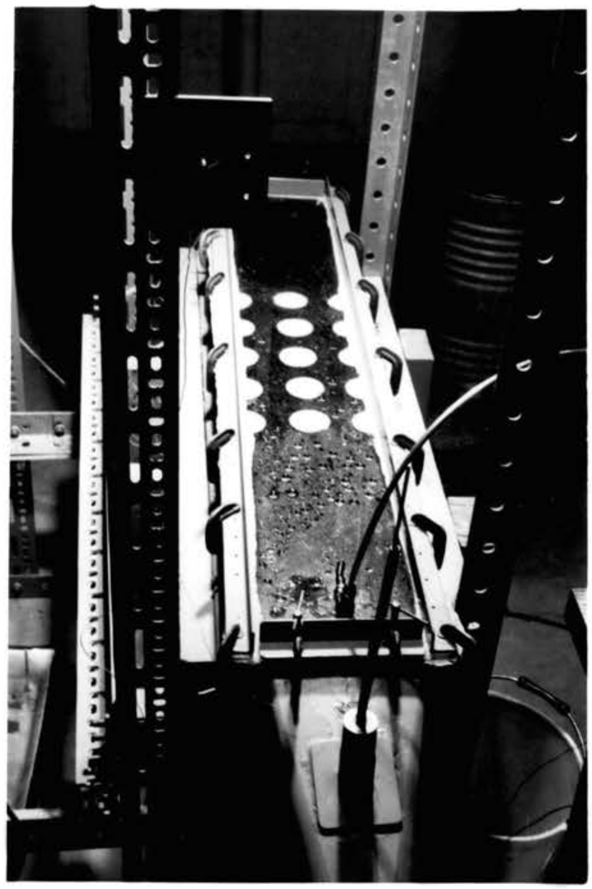


Figure 3

End View of Tube Bank

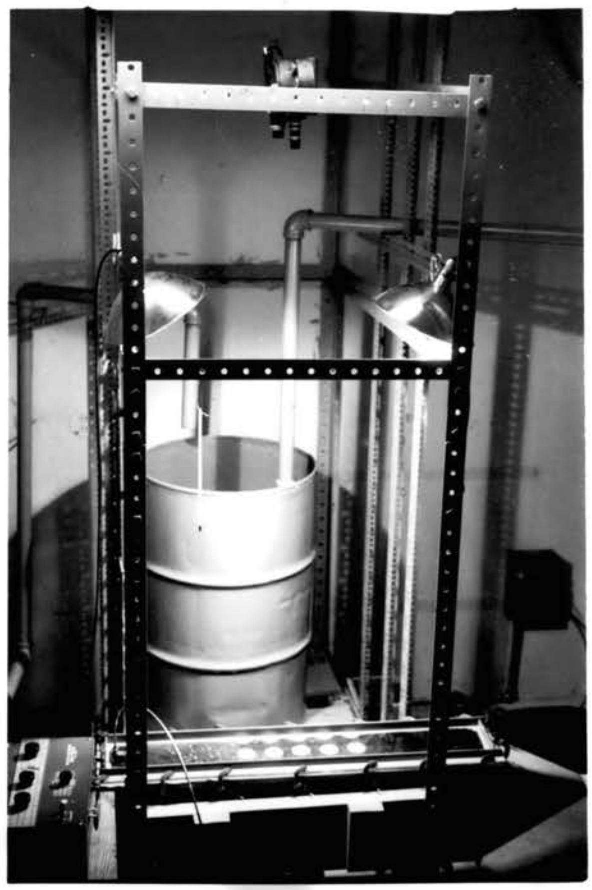


Figure 4

Front View of Apparatus

page 12). The film used was Kodak Plus-X reversal 16 mm black and white roll movie film.

All the piping in the system was 1 1/2 in. Schedule 40 steel pipe. Downstream from the tube bank there was a gate valve on the flow line, upstream of which was a branch line fitted with another gate valve (see Figure 5, page 14). When the flow line valve was closed and the branch-line valve was opened, all the fluid flowing through the tube bank was diverted into a tared drum. This drum was placed on scales, and this setup, together with a stop watch, was used to determine mass flow rates through the system for various pump speeds.

When the flow-line valve was open, and the branch-line valve was closed, the fluid flowed into the top of the 42 gallon storage drum, the fluid leaving the pipe above the surface of the fluid in the drum. The fluid level in the storage drum was kept at a constant level throughout the tests. Below the storage drum was situated a Moyno 1L6, type CDQ positive displacement pump fitted with a hydraulic gear reducer, and driven by a 3 hp. electric motor.

The fluid flowed horizontally for 3 ft. downstream of the pump, then vertically upward for 5 ft. Six in. from the top of this vertical section of pipe was an orifice plate with a 23/32 in. diameter circular hole in it. Tubing taps on either side of this orifice plate were connected by 1/4 in. copper tubing to the arms of a water-over-mercury U-tube manometer. The manometer was fitted with 1/4 in.

Figure 5

Flow Sheet of the System

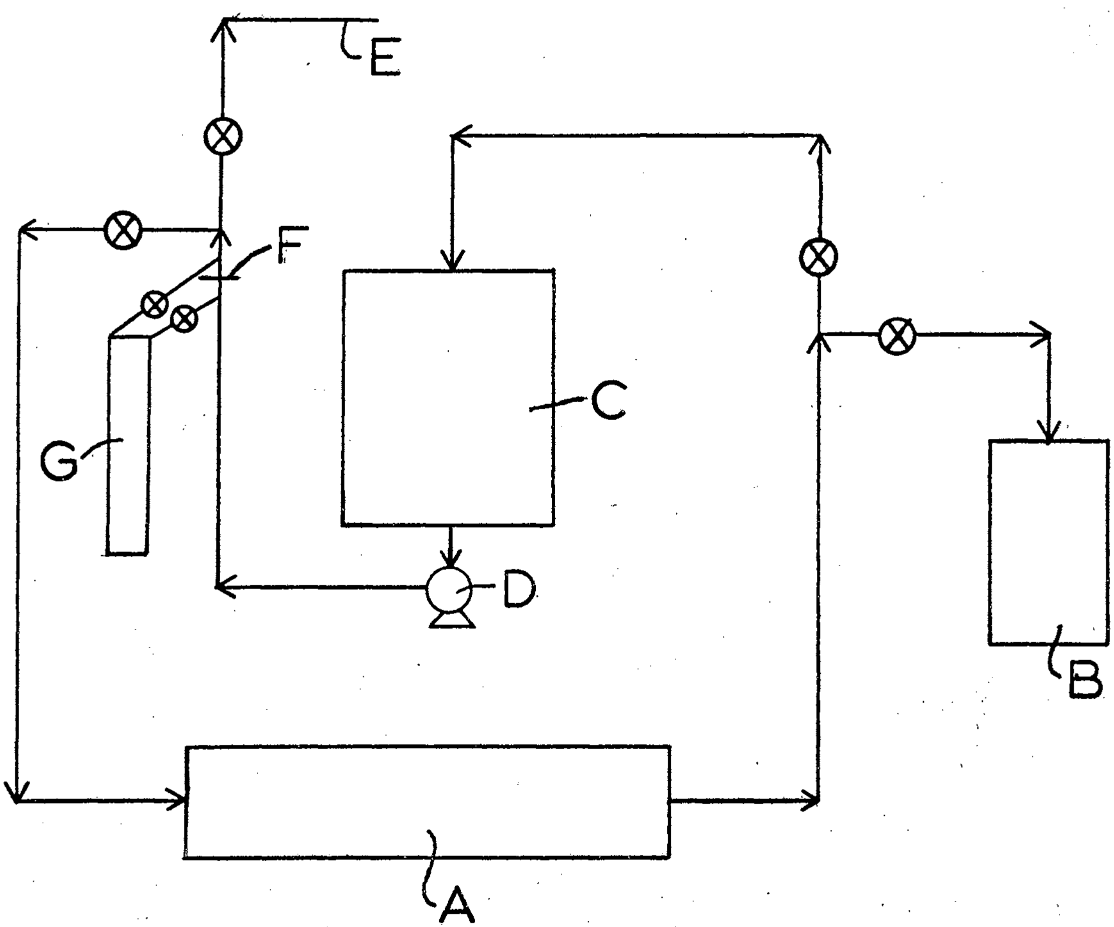


TABLE II

LEGEND FOR FIGURE 5

A. Tube bank container

B. Tared drum

C. 42 gallon storage drum

D. Moyno 1L6, type CDQ positive displacement pump

E. Branch line leading to another tube bank studying heat transfer coefficients

F. Orifice plate, with a 23/32 in. diameter hole

G. Mercury-under-water U-tube manometer

valves on the input lines to control fluctuations, and 1/4 in. valves directly above the arms to allow the air in the arms to be bled off as the manometer filled with water.

The first tracer particles tried in the apparatus were polyethylene pellets which were roughly spherical and about 1/8 in. in diameter. These pellets were of slightly lower density than water, so various methods were tried to make them heavier. After a bit of experimenting, it was found that the desired effect could be produced by driving an ordinary staple through the center of each pellet. When this was done, and their surfaces were filed smooth and painted with aluminum paint, the pellets proved to have densities almost exactly the same as water.

When these pellets proved to be unsuitable (see CHAPTER IV), and it was decided to try injecting the particles at the face of the tube-bank, it was suggested that the simplest type of tracer particle for this purpose would be a liquid droplet. Such a liquid would have to have the following properties: (1) The same density as water; (2) Ability to dissolve some light-colored substance if it were not sufficiently visible with its own color; (3) Insolubility in water; and (4) A high enough surface tension relative to water that a droplet of it would not appreciably deform in the flow stream.

A search for a pure liquid compound of this type proved fruitless. It was, however, suggested that a proper mixture of benzene and carbon tetrachloride might serve the purpose

(4,5). A mixture of 82.8% benzene and 17.2% carbon tetrachloride was prepared, having a specific gravity of 1.000. There are no single compound white or yellow dyes available that are water insoluble, so lead chromate ($PbCrO_4$) was tried. It, however, formed an unsatisfactory suspension in the droplets, and produced serious problems of plugging up the steel capillary tubing through which the droplets were to be injected into the flow stream.

A yellow-colored paint tint (a mixture, not a single compound) was finally decided upon as the proper coloring agent. The specific gravity of the mixture was adjusted to 0.996, and when the tint was added the resulting final mixture was suitable in every respect. When injected into the flow stream, droplets of this mixture were very nearly spherical in shape, with a diameter of about 1/16 in.

CHAPTER III

EXPERIMENTAL PROCEDURE

Apparatus Operation

Two types of auxiliary measurements were associated with the filming of the tracer particles. The first was measurement of the temperature of the fluid both upstream and downstream of the tube bank. This was done by measuring the potential difference across the junction of a copper-constantan thermocouple using a Leeds and Northrop potentiometer. These readings were easily converted to temperatures by means of a table provided with the potentiometer. The thermocouples were carefully calibrated to with $\pm$ 0.1°F. Such precision, however, was unnecessary since the temperature readings were used only to determine the density and viscosity of the water. Therefore, the thermocouple calibration data are not included in this thesis.

The other auxiliary measurement taken was the difference in mercury level in the water-over-mercury U-tube manometer attached to tubing taps located on either side of the orifice plate. The differences in mercury level indicated by the manometer were calibrated against mass flow rate by diverting the flow stream into the tared drum and noting the time required for a certain weight of fluid to flow into the drum. The results of this calibration technique may be seen in Figure 16, page 42, and Table III, page 41.

The polyethylene pellets were injected into the flow stream through a 1/4 in. copper tube (see Figure 3, page 11) which protruded about 4 in. into the flow pattern. The lower end of this copper tube was covered by a spring-loaded flapper valve surfaced with a foam rubber gasket. A steel rod was used as a plunger to force the pellets out of the tube, past the flapper valve. In this manner, the pellets entered the water about halfway through the expanding section.

For the final filming, the camera was set on f/5.5 and the film speed set at 1000 frames/min. Pictures were taken through a standard 1 in. lens and through a 2 in. telephoto lens during each of the six runs. The droplets were forced through the steel capillary tubing with an all-glass syringe, and entered the flowing fluid 1/4 in. from the face of the tube bank. The lighting was provided by two 375 watt photoflood lamps located directly on top of the plexiglas, one at each end of the observation area.

Film Study

The study of the completed film was rather simple, but required a great deal of care. The motion picture was projected onto a white screen and studied one frame at a time.

The projector was situated at such a distance from the screen that the picture on the screen was actual size. This was determined by comparing a standard rule with one placed on the plexiglas top over the tubes while the pictures were being made.

The progress of the droplets through the tube bank was followed in the vicinity of the center three tubes. A suitable droplet was chosen and marked by a point on a piece of tracing weight graph paper. The tops of the bottom and middle rows of tubes had been drawn on this graph paper, so it could be correlated accurately with the picture.

After the initial mark had been made, the position of the droplet was marked every fourth frame thereafter. Since the camera was set at 1000 frames/min., each four frame sequence covered 0.24 sec. of the history of the droplet. Every frame in each four frame sequence was focused and studied carefully to insure that the path of the droplet under study was not confused with the path of another droplet. The times of the beginning and end of the path of each droplet were indicated by numbering the sequences (see Figures 8 through 15, pages 29 through 36), starting with zero at the initial point of the first droplet studied in each run. In this manner, 2610 frames of the film were individually studied to produce the 679 data points contained in Figures 7 through 15, pages 28 through 36.

CHAPTER IV

RESULTS AND DISCUSSION

As stated in the PREFACE, the primary purpose of this investigation was the development of experimental apparatus and methods for the study of non-Newtonian flow normal to tube banks. However, a number of interesting observations have been made, and these will be discussed in this chapter.

The transition regime between laminar and turbulent flow across tube banks covers a range of Re from about 200 to about 5000, and therefore all flow patterns studied in this work were in transition (3, page 337). The Reynolds number range in the study using the polyethylene pellets was 950 to 2950, and was 1130 to 2610 in the study using the liquid droplets. The characteristic length used in calculating these Reynolds numbers was the outside diameter of the tubes, and the velocity used was the average mass flow velocity calculated at the point of minimum cross-sectional area.

$$Re = (D)(V_b)(\rho)/(\mu) \qquad (2)$$

Polyethylene Pellets

An unexpected result was observed when the pellets were released in the flowing stream. They rotated in a large vertical eddy (see Figure 6, below) instead of proceeding through the tube bank. This fact was noticed during runs covering a spectrum of Reynolds numbers from 950 to 2950. The eddy did not veer away from the center of the flowing fluid. Indeed, the eddy action was toward and across the centerline flow area, and then against the flow back towards the point of release.

Figure 6 (below) gives a general idea of the path of the eddy. The pellets always emerged from the top of the expanding section into the observation area, and went back upstream close to the bottom, usually stopping at point A for a time about equal to the time spent in the eddy. There was, however, no regularity at all in the distances traveled downstream, the lateral points of emergence from the expanding section, or the residence times in the expanding section between rotations in the eddy. These irregularities were noticed for one particle at different times, and for several particles traveling together. One would expect to observe some eddy effects in this type of flow, but perhaps not quite the same effect as was the actual case.

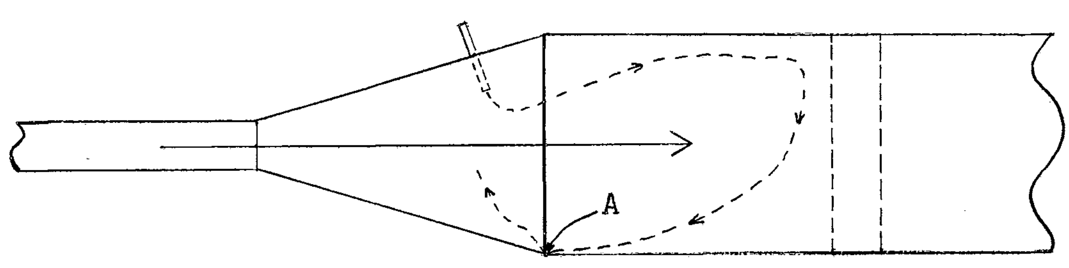


Figure 6

Schematic Diagram of Entrance Section Eddy

One explanation advanced for the presence of the eddy was that turbulent effects arising from the 4 ft. vertical section of pipe and 90° elbow immediately downstream from the expanding section contributed to the eddy action. In order to test this theory, twelve 1/4 in. copper tubes, each 1 1/2 ft. long, were bound together and placed in the pipe upstream of the expanding section. This bundle of tubing very nearly filled the 1 1/2 in. pipe.

The length to diameter ratio of these tubes was 72 based on O.D., and 100 based on I.D. This should have been sufficient to damp out some of the eddy, if indeed the elbow and vertical pipe were contributing significantly to it. Not only did the bundle of tubes fail to damp out the eddy, but it in fact appeared to aggravate the situation somewhat. After it had been inserted, the pellets had a noticeably longer residence time in the expanding section, some even becoming trapped out of sight permanently. But when the pellets did emerge into view, their travel with the eddy was no different in general than before.

At one point when several pellets were rotating together in the eddy at a fairly high value of Re (about 2900), the pump speed was cut back sharply to about Re = 1100. When this was done, all the pellets dropped out of the eddy (which was still present), fell to the bottom, and rolled out into the tube bank, some of them going all the way through it.

At other times, when the mass flow rate was very low and most of the pellets were trapped in the expanding section, the pump speed was sharply increased. This caused the pellets to follow the eddy partway, then again fall to the bottom and roll out into the tube bank. Several variations of the above steps were tried, with similar results. Of the fifty pellets studied, only one traveled through the tube bank in the main flow stream, and for no apparent reason.

It soon became obvious that the eddy was more of a built-in feature of the apparatus than it was a consequence of the transition regime flow involved. The most feasible explanation seemed to be that the angle of the expanding section was much too large. It is generally agreed that the maximum allowable angle on the expanding section of a Venturi meter, above which boundary layer separation will occur, is 7° (6, page 406). This value of 7° is smaller than the angle of 22° 37' on the side of the present expanding section, and 9° 36' on its top (refer to Figure 1, page 6).

Apparently the only alternative to rebuilding the apparatus to eliminate the eddy was to inject the tracer particles downstream of the eddy, right at the face of the tube bank. This would be a rather awkward procedure using the polyethylene pellets, so another type of tracer was sought.

Droplets

It was finally decided to use liquid droplets as the tracers (see CHAPTER II). The injection system was modified to its present form, as described in CHAPTER II, by inserting the steel capillary tubing through the 1/4 in. copper tube used to inject the polyethylene pellets. When the droplets were released in the flowing water, 1/4 to 1/2 in. from the face of the tube bank, they performed exactly as desired. They retained their spherical shape, and most of them neither rose nor sank as they progressed downstream. Droplet trajectories at six different flow rates were photographed.

Film Study

The method of the frame-by-frame analysis of the completed film is described in detail in CHAPTER III, on page 20. The distance covered during each four frame sequence on Figure 11, page 32, was measured to the nearest 1/40 in., introducing an error in the velocity calculation of $\pm$ 0.009 ft./sec. If the camera were running at constant speed, each four frame sequence lasted for 0.24 sec. Subsequent testing revealed that when the camera was set on 1000 frames/min., as in this study, the maximum variation during a run was from 995 to 1005 frames/min. This variation would produce a negligible error in the velocity ($\pm$0.0003 ft./sec.). Thus, the total error in the velocity from these two sources was $\pm$0.0093 ft./sec., at a maximum.

One further possible source of error in the velocity calculations is the expected distortion of the three-dimensional system when depicted on the two-dimensional film (optical parallax). This effect was minimized by concentrating on the droplet motion in the vicinity of tubes II, III, and IV of the bottom and middle rows, over which the camera was situated. Even though minimized, this effect was not, of course, completely eliminated.

The velocities of nine different droplets were measured as they crossed the centerline of tube III in run 4. At this point, it was expected that the droplet velocities would be approximately equal to V_b for the same run, where V_b is the average velocity calculated at the point of minimum cross-sectional area. The average of these nine values was calculated to be 0.120 ft./sec. (see Table VI, page 45). This is 0.037 ft./sec., or 24%, lower than $V_b = 0.157$ ft./sec. for run 4. As may be seen in Figures 11 and 15, pages 32 and 36, these particles were not caught in an eddy, and were not particularly close to the tubes, so eddy action and wall drag against the tubes can not account for their lower velocities.

There are at least two possible explanations for this difference, both associated with the fact that the droplets were released close to the plexiglas top (within 1 in.) to aid the photography. The first is that one would expect the velocity to be lower close to the boundaries of the system, due to wall drag against the top. If the velocity were measured close enough to the boundary, its numerical value would be less than the average. In addition, since the entrance section eddy proceeded downstream very close to the plexiglas top, and dropped down just before reaching the face of the tube bank, it is conceivable that it would have had a retarding effect on the flow at the top of the tube bank. A definite conclusion could hardly be reached on this problem, however, since a larger sample would be necessary if the results were to be believed statistically.

The motions of the droplets through the tube bank were devoid of any discernible regularity. For instance, comparing the paths of the particles marked ⊡ and X on Figure 11, page 32, in the vicinity of tube III, one notices that the first accelerated at the point of closest approach, and then decelerated between tubes III and IV, just as would be expected. But the second droplet, which reached the centerline of tube III about 1/2 sec. later, did exactly the opposite. There was too great a difference in this case to be accounted for by experimental error, so it was evident that such unsteady-state fluctuations in the flow pattern were indeed occurring. Numerous other examples of unsteady-state behavior may be found in Figures 7 through 15, pages 28 through 36.

Figure 7

Droplet Trajectories, Run 1

Actual Size

← Flow

Re = 1130

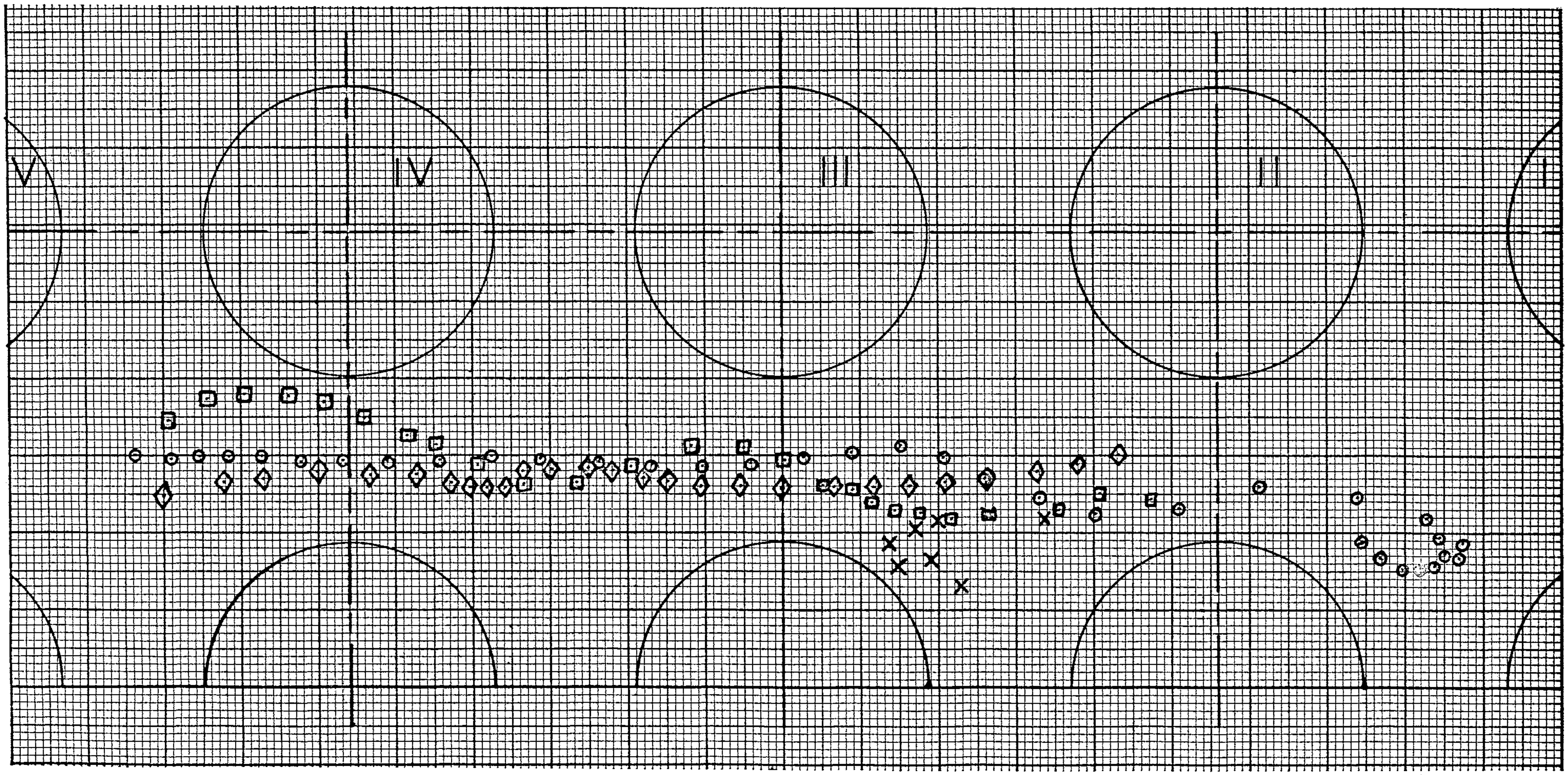


Figure 8

Droplet Trajectories, Run 1

Actual Size

← Flow

Re = 1130

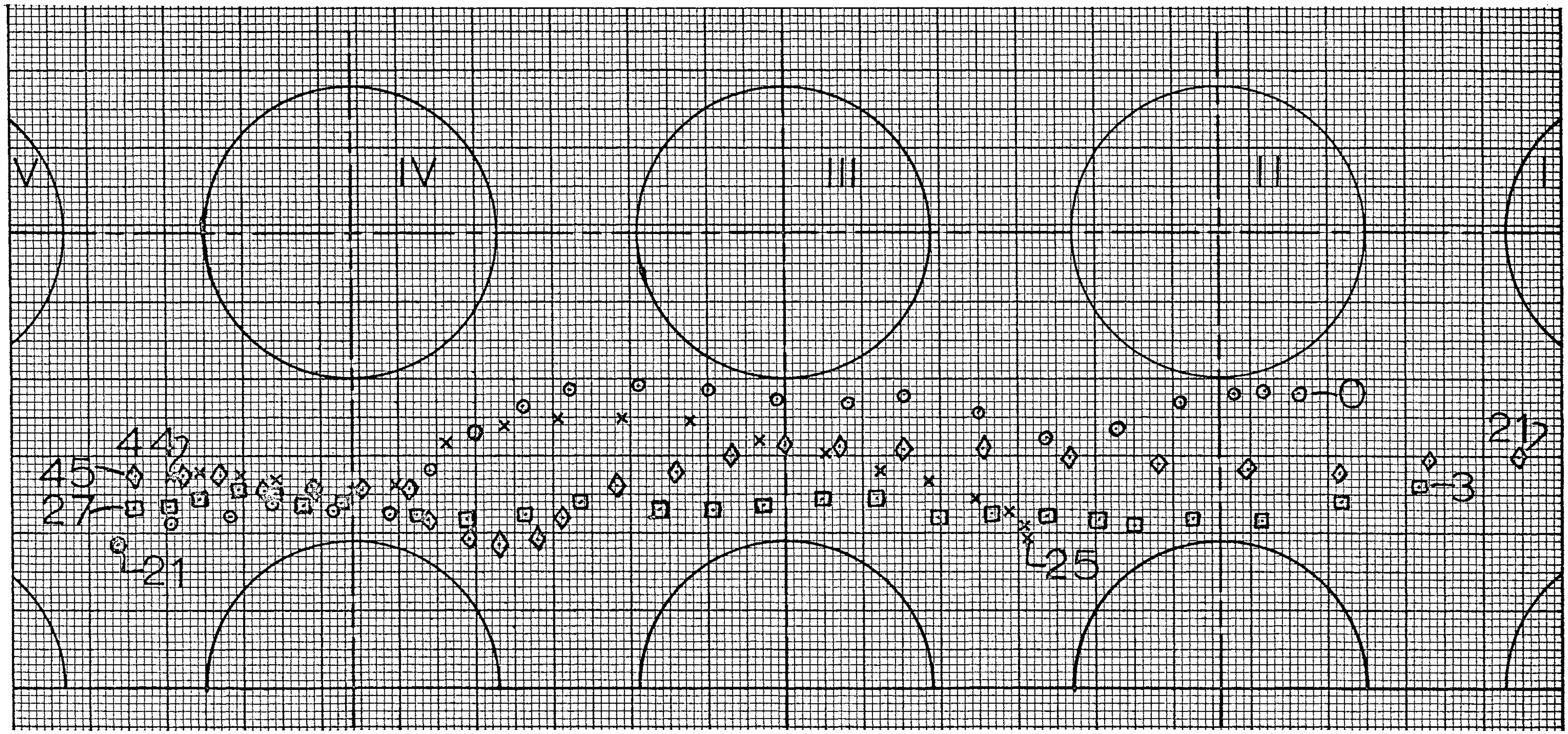


Figure 9

Droplet Trajectories, Run 2

Actual Size ← Flow Re = 1590

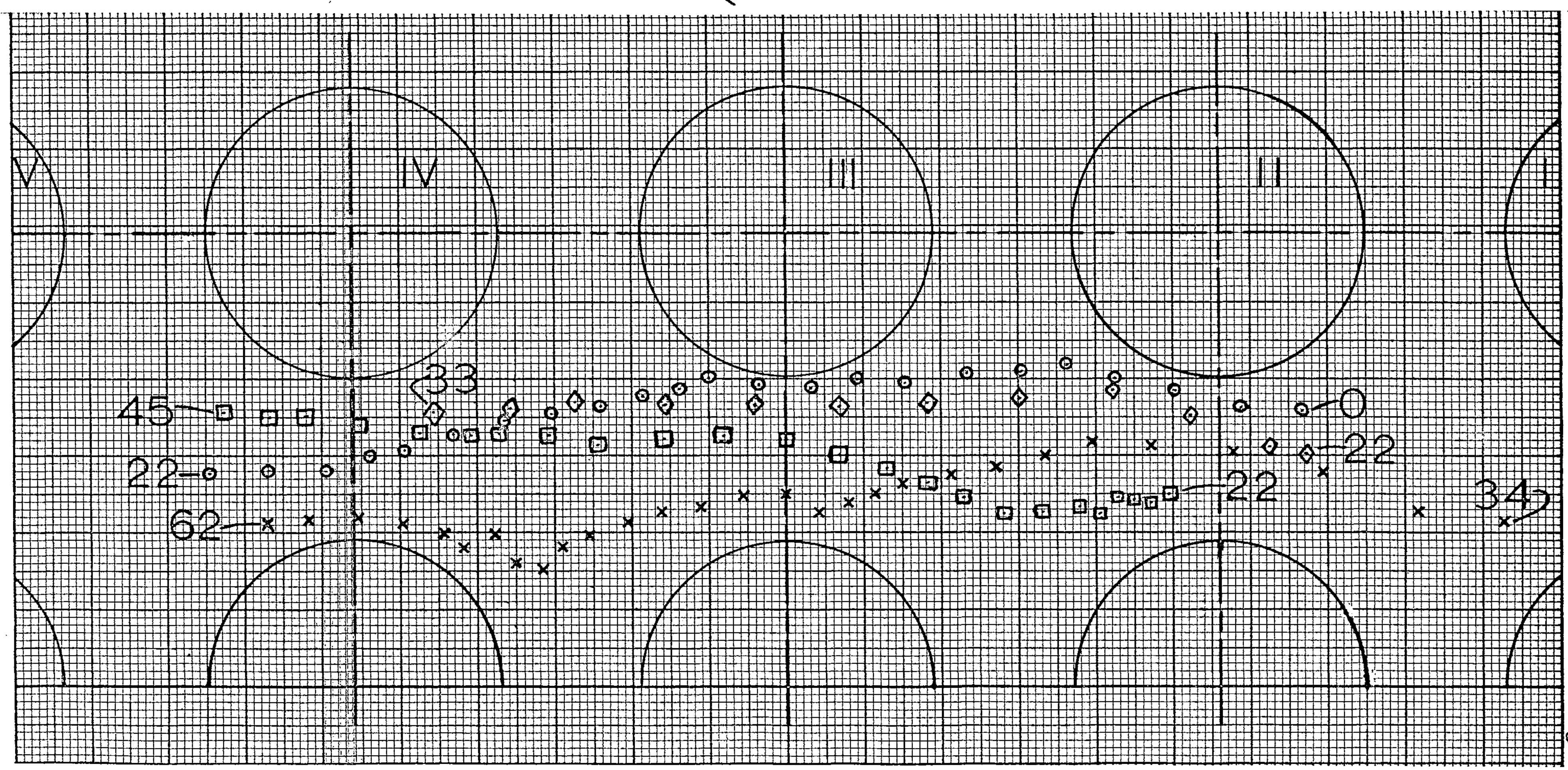


Figure 10

Droplet Trajectories, Run 3

Actual Size

← Flow

Re = 1900

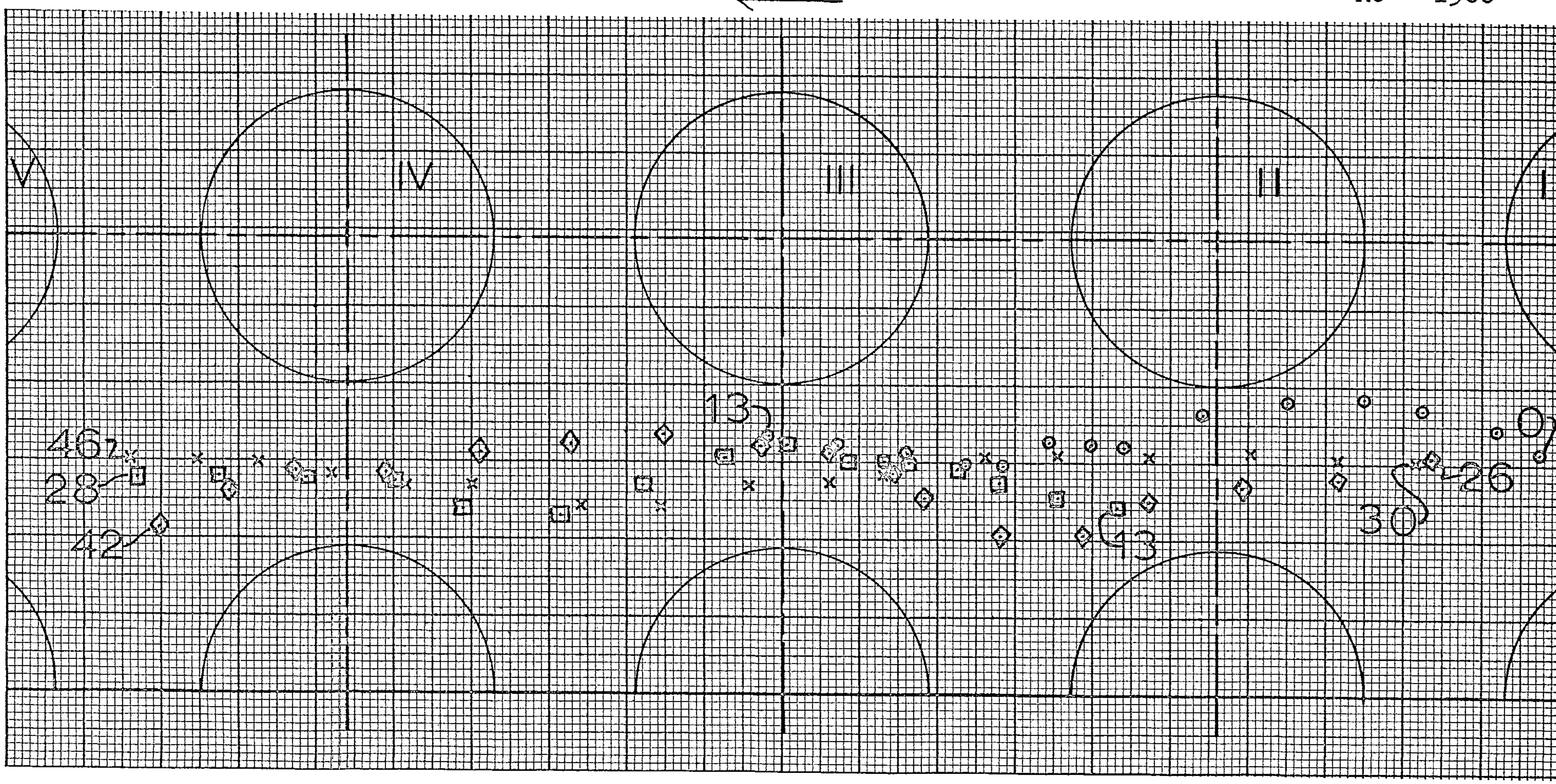


Figure 11

Droplet Trajectories, Run 4

Actual Size

← Flow

Re = 2160

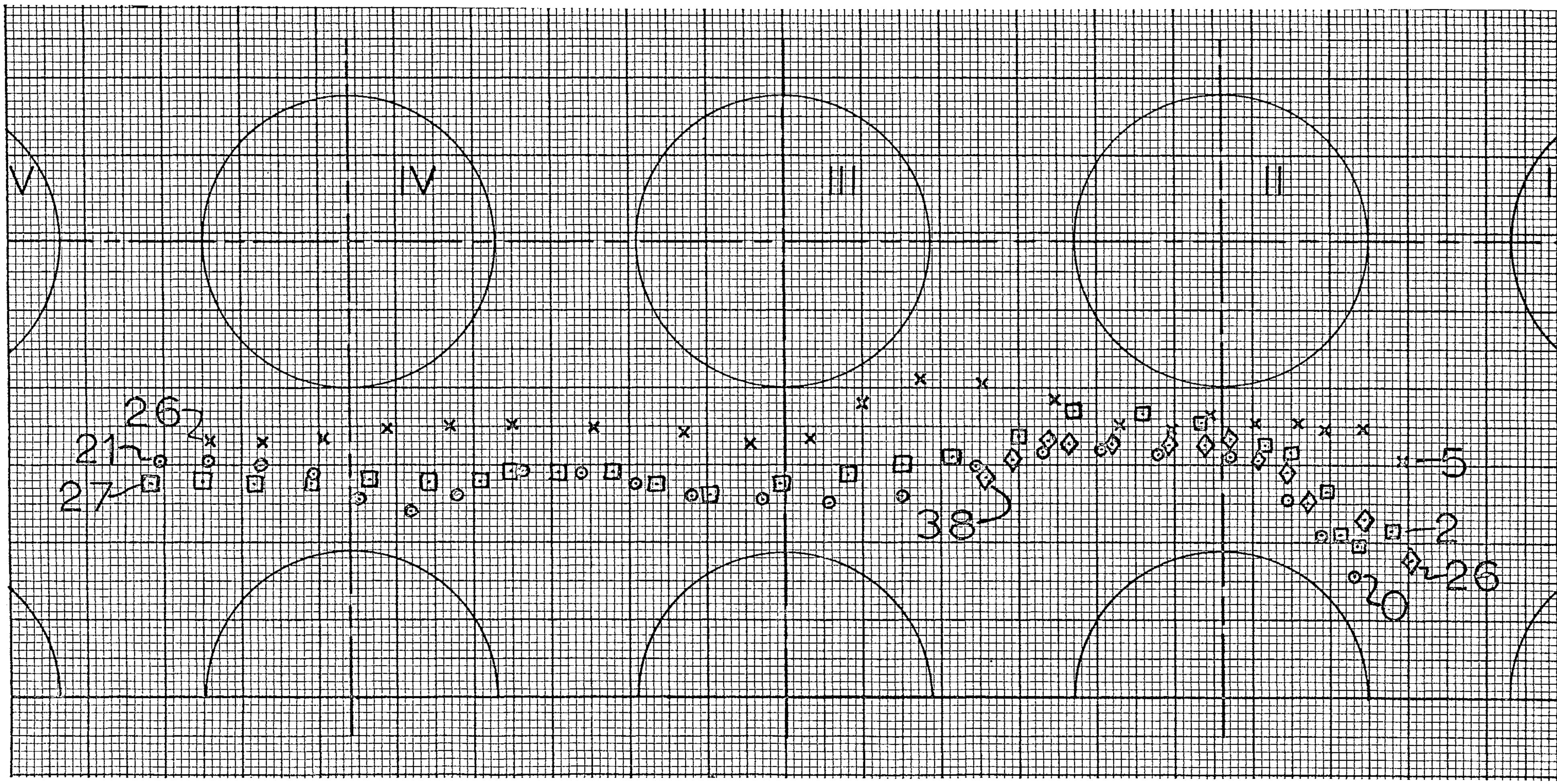


Figure 12
Droplet Trajectories, Run 5

Actual Size

Flow

Re = 2390

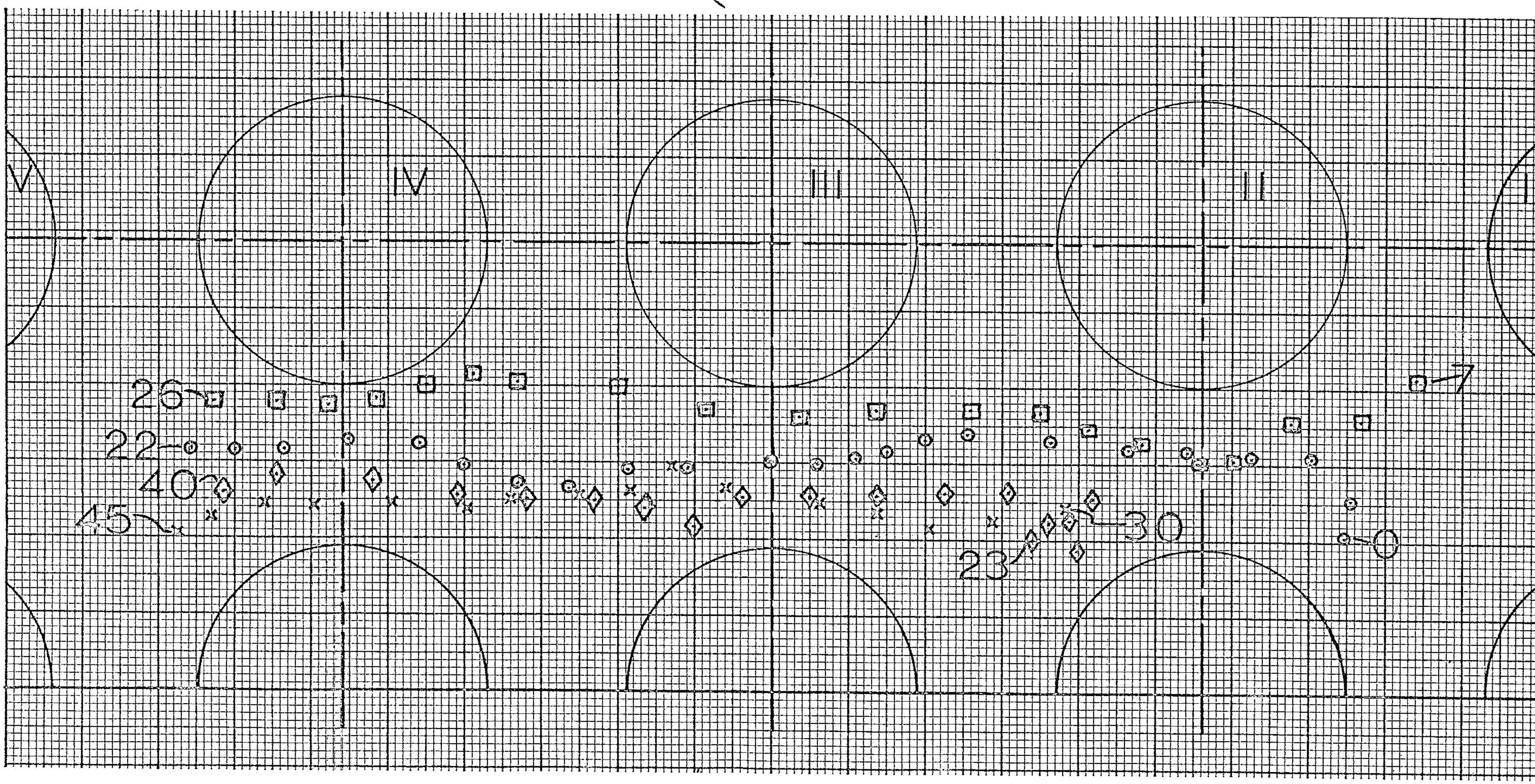


Figure 13
Droplet Trajectories, Run 6

Actual Size

← Flow

Re = 2610

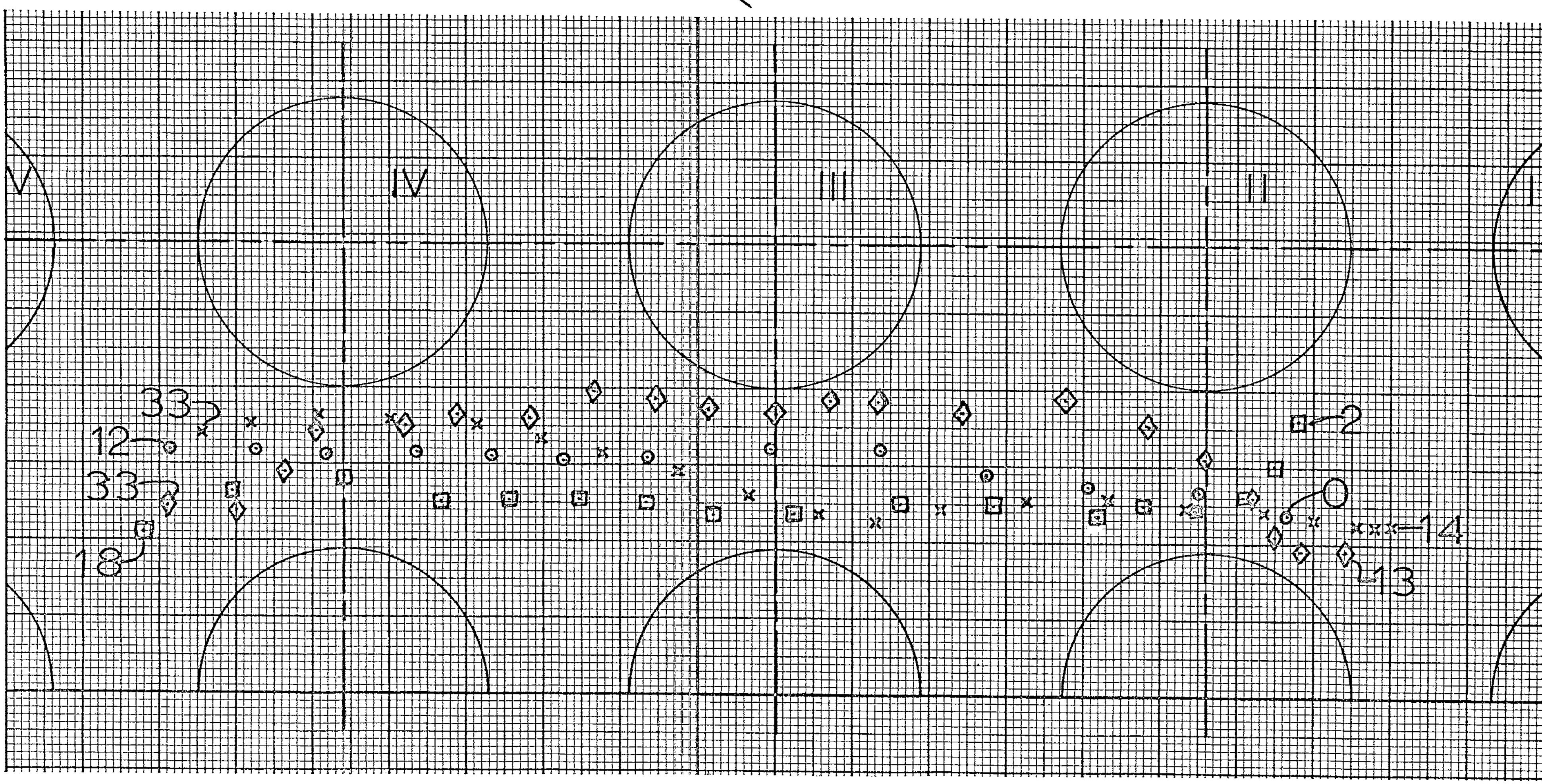


Figure 14

Droplet Trajectories, Run 6

Actual Size

Flow

Re = 2610

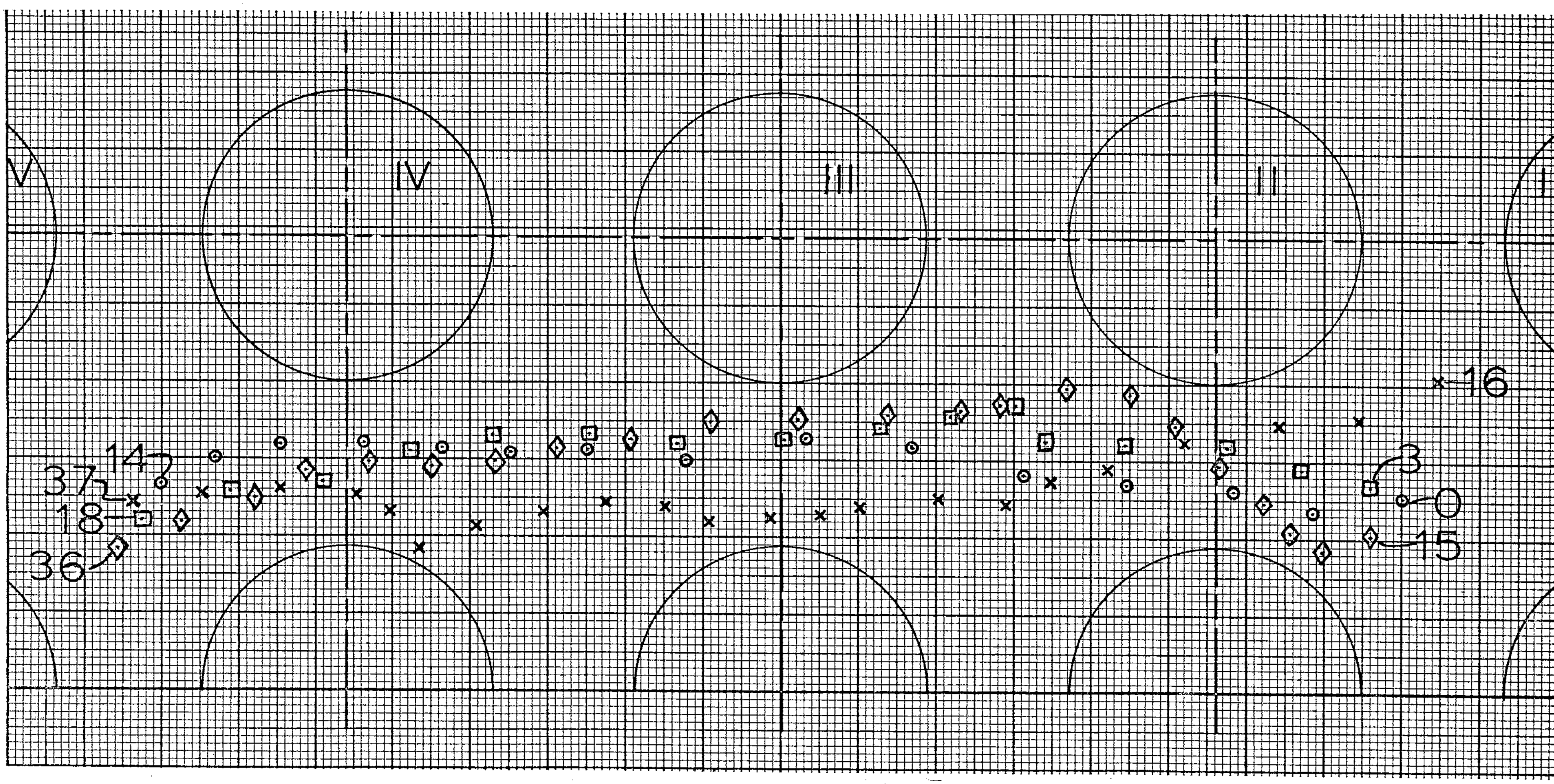
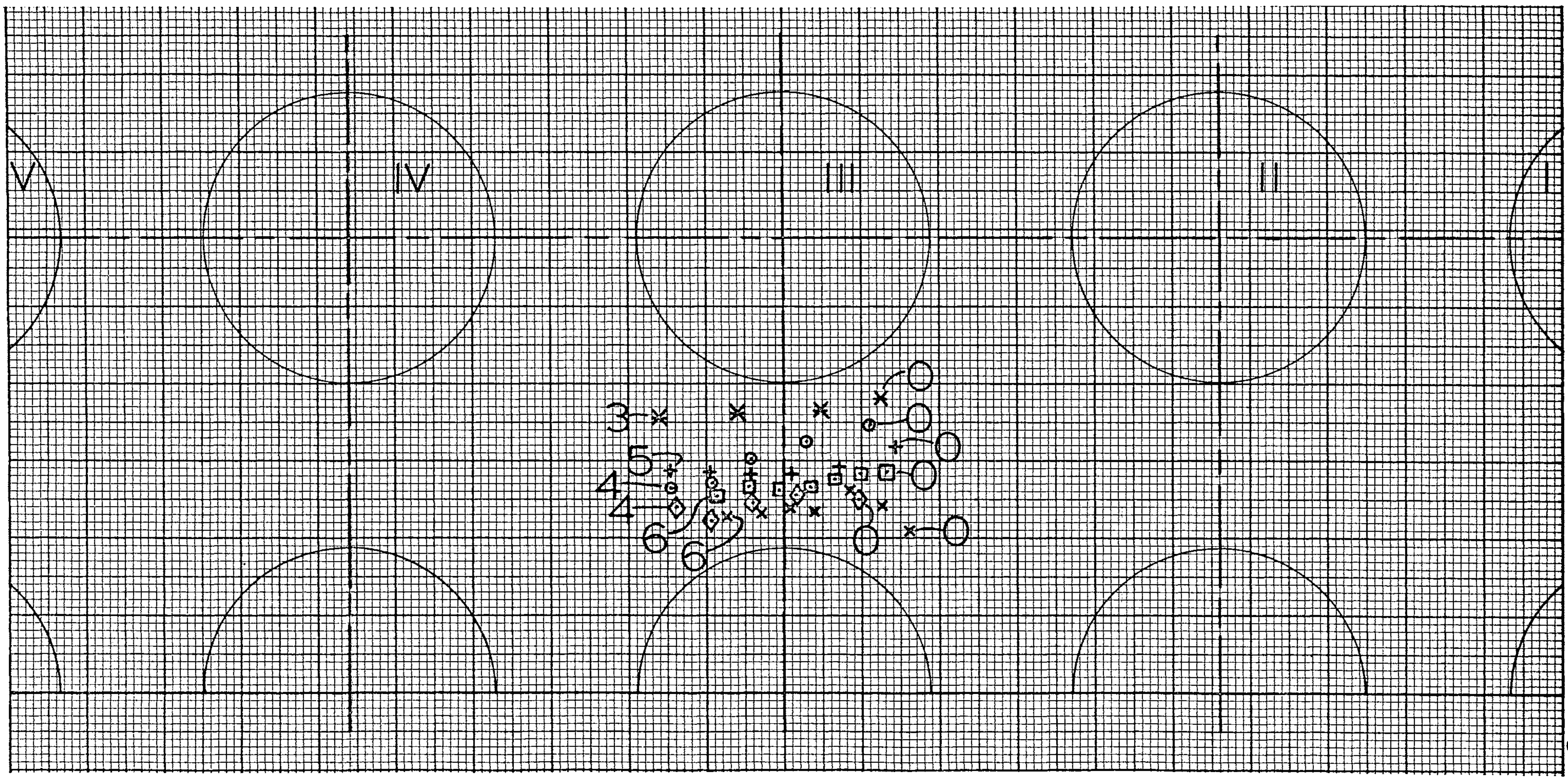


Figure 15

Droplet Trajectories, Run 4

Actual Size ← Flow Re = 2160



CHAPTER V

SUMMARY

With regard to the stated purpose of this thesis to develop an apparatus and methods to study non-Newtonian flow normal to tube banks, the author feels that the efforts described herein have been successful. Because of the fluctuating nature of the transition flow encountered in this study, it is rather difficult for one to have a quantitative appreciation for the data produced. But qualitatively, this research appears to be basically sound, and suggests many areas for further study.

Recommendations

(1) If a stop watch were placed on the plexiglas top during the filming, one could obtain a more accurate measurement of time.

(2) If new apparatus were to be built along the lines of the present arrangement, the expanding and contracting section angles should be less than 7° in order to help eliminate the entrance section eddy.

(3) It would be quite interesting to obtain a pump capable of much lower flow rates than the present pump and study water in laminar flow through the tube bank.

(4) The particles should be injected much lower in the flow stream so as to eliminate the wall drag effects of the plexiglas top.

(5) After the above four suggestions have been followed, the next step to be taken would be to study several common non-Newtonian fluids.

(6) Finally, tube arrangements other than the in-line square arrangement used in this work should be studied.

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APPENDIX A

NUMERICAL DATA AND CALCULATED VALUES

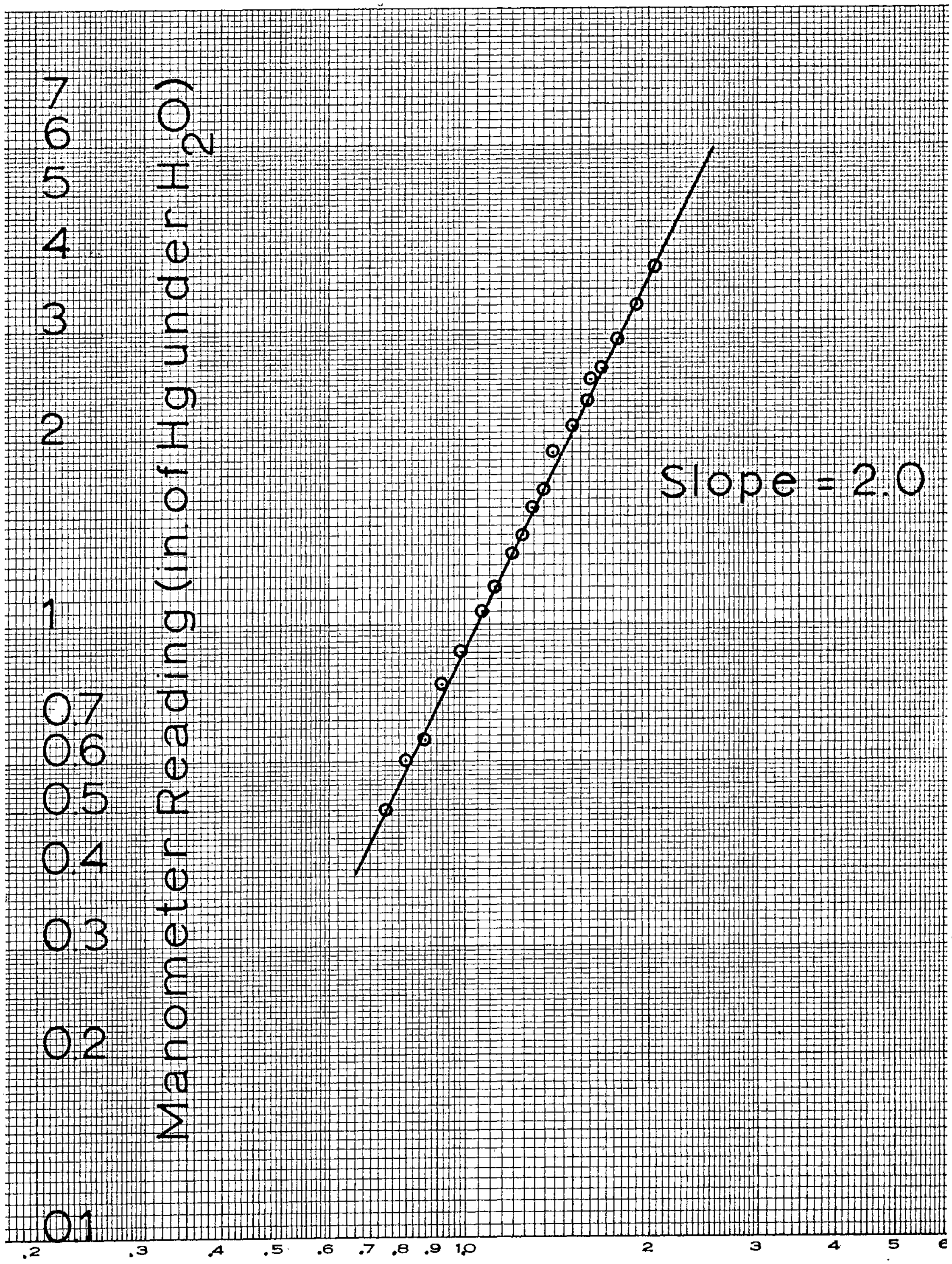
TABLE III

ORIFICE PLATE CALIBRATION DATA

Manometer Reading (in. of Hg under H_2O)	W (lb./sec.)	T_{in} (°F)	T_{out} (°F)
2.50	1.61	61	61
2.10	1.49	61	61
1.90	1.39	61	61
1.65	1.35	62	62
1.55	1.29	62	62
1.40	1.24	62	62
1.30	1.20	63	63
1.15	1.12	63	63
1.05	1.06	63	63
0.90	0.99	63	63
0.80	0.92	63	63
0.65	0.86	64	64
0.60	0.80	64	64
0.50	0.74	64	64
2.60	1.68	64	64
2.30	1.58	64	64
2.90	1.76	64	64
3.30	1.91	64	64
3.80	2.04	64	64

Figure 16

Orifice Plate Calibration on Water



Mass Flow Rate (lb./sec.)

TABLE IV

FLOW DATA FOR RUNS 1-6

Run	Manometer Reading (in. of Hg under H_2O)	W (lb./sec.)	V_b(ft./sec.)	Re
1	0.70	0.88	0.082	1130
2	1.40	1.24	0.116	1590
3	2.00	1.48	0.138	1900
4	2.60	1.68	0.157	2160
5	3.20	1.87	0.174	2390
6	3.80	2.04	0.190	2610

TABLE V

DROPLET VELOCITIES CALCULATED FROM FIGURE 11

Sequence (4 frames)	Velocities (ft./sec.) of Indicated Droplets (± 0.0093 ft./sec.)			
	⊙	⊡	×	◊
0 - 1	0.113			
1 - 2	0.113			
2 - 3	0.173	0.087		
3 - 4	0.157	0.053		
4 - 5	0.122	0.104		
5 - 6	0.130	0.122	0.113	
6 - 7	0.157	0.061	0.087	
7 - 8	0.173	0.157	0.069	
8 - 9	0.157	0.130	0.096	
9 - 10	0.148	0.157	0.104	
10 - 11	0.157	0.139	0.104	
11 - 12	0.130	0.157	0.122	
12 - 13	0.130	0.113	0.157	
13 - 14	0.130	0.130	0.173	
14 - 15	0.157	0.148	0.139	
15 - 16	0.113	0.157	0.139	
16 - 17	0.122	0.122	0.139	
17 - 18	0.122	0.104	0.130	
18 - 19	0.122	0.122	0.148	
19 - 20	0.122	0.104	0.208	
20 - 21	0.113	0.078	0.173	
21 - 22		0.113	0.148	
22 - 23		0.130	0.139	
23 - 24		0.130	0.148	
24 - 25		0.130	0.130	
25 - 26		0.113	0.122	
26 - 27		0.122		0.139
27 - 28				0.130
28 - 29				0.087
29 - 30				0.069
30 - 31				0.087
31 - 32				0.053
32 - 33				0.087
33 - 34				0.130
34 - 35				0.096
35 - 36				0.053
36 - 37				0.087
37 - 38				0.078

TABLE VI

DROPLET VELOCITIES ACROSS CENTERLINE OF TUBE III

	Droplet	Velocity (ft./sec.) (± 0.0093 ft./sec.)
Figure 11	⊙	0.148
	⊡	0.148
	×	0.130
Figure 15	⊙	0.130
	⊡	0.069
	◈	0.096
	×	0.069
	⋇	0.183
	+	0.104

NOTE: The average of the above nine velocities is 0.120 ft./sec., as compared to V_b = 0.157 ft./sec. calculated for run 4.

APPENDIX B

MISCELLANEOUS

Sample Calculations

The following sample calculations are for the droplet indicated by (X) in run 4, for the sequence (17 - 18).

Average Bulk Velocity

Manometer Reading = 2.60 in. of Hg under H_2O
(Table IV, page 43)

W = 1.68 lb./sec. (Figure 16, page 42)

V_b = W (lb./sec.) x $(1/\rho)$(1/lb./ft.^{3}) x (1/A)(1/ft.^{2})

W = 1.68 lb./sec.

ρ = 62.4 lb./ft.^{3} (@ T_{in} = T_{out} = 64°F, for run 4)

A = (2 in.) x(12 in.) / (144 in.^{2}/ft.^{2})

= 0.170 ft.^{2}

Therefore: V_b = (1.68) x (1/62.4) x (1/0.170) = 0.157 $\frac{ft.}{sec.}$

Reynolds Number

Re = D (ft.) x V_b(ft./sec.) x ρ(lb./ft.^{3}) / μ (lb./ft. sec.)

D = tube diameter = 1.875 in. = 0.156 ft.

μ = 7.096 x 10^{-4} lb./ft. sec. (@ 64°F)

Therefore: Re = (0.156) x (0.157) x (62.4)/(7.096 x 10^{-4})

= 2160

Note: The characteristic length for this Reynolds number is the outside diameter of the tube, and the velocity used is V_b.

Droplet Velocity

Distance traversed during
sequence (17 - 18) = 0.375 in. (Figure 11, page 32)

Time = (4 frames/seq.) x (60 sec./min.)/(1000 frames/min.)

= 0.240 sec./sequence

Therefore:

Velocity of seq. (17 - 18) = (0.355 in.) x (1 ft./12 in.)

x (1/0.240 sec.)

= 0.130 ft./sec.

Nomenclature

Quantity	Symbol	Units
Area, cross-sectional, at point of closest approach between the tubes	A	ft.^{2}
Density	ρ (Rho)	lb./ft.^{3}
Diameter, tube, outside	D	ft.
Mass flow rate	W	lb./sec.
Reynolds number (based on V_b and D)	Re	-----
Shear rate	du/dy	(sec.)$^{-1}$
Shear stress	τ (Tau)	lb./ft. sec.^{2}
Temperature		
Inlet	T_{in}	°F
Outlet	T_{out}	°F
Velocity, average, based on W and A	V_b	ft./sec.
Viscosity	μ (mu)	lb./ft. sec.

Location of Original Data

The original data taken in the experimental work of this thesis, including the motion picture film, are in the possession of Professor Kenneth J. Bell of the School of Chemical Engineering, Oklahoma State University, Stillwater, Oklahoma.

The design and experimental work of this thesis was performed in Building Q-2, Oklahoma State University, between October, 1962 and February, 1964.

VITA

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