EXPERIMENTAL STUDY OF TWO PHASE FLOW - EFFECT OF SURFACE TENSION ON PRESSURE DROP

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SUMMARY

The results of an experimental investigation of the isothermal flow of water-air mixtures are discussed.

The investigation was undertaken to determine the effect of surface tension on the pressure drop of a two phase system flowing in a horizontal tube.

The pressure drop data are compared with data given in the published literature on the two phase flow of fluids.

Restrictions imposed during the investigation were: both phases in turbulent isothermal flow, no mass transfer or heat transfer between phases, surface tension values between 34 dynes/cm and 74 dynes/cm, one test section of 1" ID clear plastic pipe was used, vapor to liquid ratio limited to values between 2 and 16 approximately (based on average temperature and pressure in pipe).

Two conclusions are drawn, viz: the variation of surface tension of the liquid phase had no effect on the pressure drop within the limitations of the experiment; the data obtained in this investigation are in reasonable agreement with other published correlations.

CHAPTER I

THE PROBLEM

Importance.--Pressure drop in piping systems during two phase flow is of interest in various branches of engineering. Petroleum engineers have perhaps been more interested in the subject than any other group. The intense interest of this group has been due to the problem of handling mixtures of liquids and gases during drilling and pumping operations. Also, engineers working with heat transfer phenomena have devoted considerable time to a study of this field of fluid dynamics. In recent years the aircraft industry and military services have become especially interested in the subject of two phase flow. This interest is due to the high altitudes and accompanying low atmospheric pressures to which military aircraft are subject; these conditions impose restraints on the fuel piping system which must be understood.

The military services object to pressurized fuel tanks due to the fire hazard in case of fuel tank puncture; however, if the fuel tanks are left open to atmospheric pressure, the fuel components having a low boiling point will rapidly increase the ratio of vapor to liquid (V/L) that must be handled by the fuel pumps. The pressure drop in the fuel lines between the fuel tanks and the engine driven fuel pumps affects considerably the V/L ratio that must be handled by the pumps. Considerable attention has been given to a study of the mechanisms contributing to pressure drop in fuel lines when two phase (liquid-gas) flow prevails.

This thesis was originated as a result of a study of some of the fuel line pressure drop problems.

Previous Work.--Considerable work has been done, both theoretical and experimental, in attempts to understand the mechanisms contributing to pressure drops in two phase flow. Many of the correlations resulting from these studies have led to equations of such a complicated nature as to be literally unusable for practical purposes. The most widely accepted correlation at present is that of Lockhart and Martinelli[1*]. This particular correlation is relatively simple and suitable for design purposes, but is subject to two restrictive assumptions: viz, static pressure drop for the liquid phase must equal the static pressure drop for the gas phase regardless of the flow pattern as long as an appreciable radial static pressure difference does not exist; the volume occupied by the liquid plus the volume occupied by the gas at any instant must equal the total volume of the pipe. These assumptions infer that the flow pattern does not change along the pipe length, and thus "slug" flow, in which alternate slugs of liquid and gas move down the tube, is eliminated from consideration.

Notwithstanding the volume of previous work on the general problem of two phase flow, very little has been done to establish the effect of surface tension of the liquid phase on the problem at hand. A literature search[7] reveals that articles by Kosterin and Rubanovich[2], and Taylor[3] are the only two papers published on this subject. Each paper reports

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[*] Superscript numbers refer to references listed in the bibliography.

that for a low value of surface tension of the liquid phase the pressure drop is the same as that for a higher value of surface tension.

<u>Object of Present Investigation</u>.—The object of this investigation was to study the effect of varying the surface tension of the liquid phase and to provide additional experimental evidence to substantiate the statements of the above authors or to permit making a new statement regarding the effect of the surface tension.

CHAPTER II

EXPERIMENTAL PROCEDURE

In order to obtain experimental evidence, the proposal was made to measure pressure drop for a fixed length of test section (see details under Section III of this paper) using air and water as the gas and liquid phases, respectively. Each phase was to be in turbulent flow at all times.

The experiments were conducted under conditions of isothermal flow (the variation in temperature during any run was a maximum of two degrees Fahrenheit). The liquid flow rate was varied from 2.20 gpm to 16 gpm (arbitrarily selected for convenience) while the air flow rate was varied from a minimum to a maximum for each value of liquid flow rate. (The minimum and maximum values were not known at the time of planning the experiment. Based on an average pressure and temperature in the pipe, the air flow varied from about 4.7 cfm up to 34 cfm giving values of the vapor-liquid ratio ranging from 2 to 16 approximately.)

The pressure drop across the test section was measured for each of the various combinations of flow rates for a given value of surface tension for the liquid. This series of measurements using a given value of surface tension was called a "run." The procedure was repeated for five different runs using five different values of surface tension of the liquid phase, varying from 74 dynes/cm to 34 dynes/cm. Data obtained in this manner were examined in the light of the method proposed by

Lockhart and Martinelli. This method of correlation will be discussed in a subsequent section of this thesis.

CHAPTER III

DESCRIPTION OF EQUIPMENT

Schematic Diagram

The equipment used in this experiment is shown schematically in Figure (12). When operating the fluids flowing are in the directions indicated by the arrows.

Detailed Descriptions

Test Section.--All experiments were conducted using a 1.00 inch ID clear plastic pipe as the test section. The total length was approximately 30 feet and consisted of two sections approximately 15 feet long joined by flanges that were solvent welded to the pipe. The outer ends of the section of plastic pipe were fitted with solvent welded flanges to match a 125# standard 1" flange. Each end of the plastic section was attached to a 1" iron pipe by means of these flanges. All flanged connections were carefully fitted so that no disturbance of flow pattern could be noted at the connections. The distance between pressure taps was 20.67 feet; this measurement determines the length of the test section. The pressure taps were connected to mercury manometers with tygon tubing in such a manner as to indicate the pressure drop between pressure taps and the upstream static pressure.

Pressure Measurement.--During two phase flow the indications read from mercury manometers vary widely and an effort must be made to estimate an average reading. The difficulty here is doubled if an attempt is made to read both legs of the manometer. For this reason, the graphs shown in Figures (2) and (3) were drawn showing pressure differential and static pressure, respectively, as a function of the reading on the left leg of the manometer. These graphs include corrections for differences in elevation and the difference in density of water and mercury. The assumption was made (perhaps optimistically) that all tabulated values of manometer readings have a maximum error of ±0.5 inches of mercury.

<u>Measurement of Flow Rates</u>.--Liquid flow rate and air flow rate were measured by Fischer and Porter Rotameters. Both of these instruments were calibrated before beginning the experiment. The Rotameter used to measure liquid flow rates was calibrated by setting the float at a given position and measuring the time required to pass a given quantity of water. The rate of flow was then computed and the procedure was repeated for a different float position. The calibration of the Rotameter used to measure air flow rates was more involved and a detailed description is given in the Appendix (page 32). The calibration curves for the air Rotameter and liquid Rotameter respectively are shown in Figures 1 and 4.

<u>Air Supply</u>.--Air was supplied from a compressor at 90 to 120 psig pressure and was throttled through a pressure reducing valve before entering the air Rotameter. Variation of pressure in the Rotameter was controlled by valves before and after the Rotameter. In order to provide more exact control of air flow, a gate valve and a globe valve were used upstream from the Rotameter. The gate valve was

regulated to maintain approximate desired float position and the globe valve was used to obtain a fine adjustment at the desired position.

Circulation Equipment.--Liquid circulation was accomplished by a Goulds motor-driven centrifugal pump. Water enters the pump from the bottom of the liquid tank and after discharge from the pump it may be allowed to enter the test section or may be bypassed back into the tank. Assuming the bypass valve to be closed, the liquid discharged from the pump enters the test section, the flow rate being controlled by the valves before and after the liquid Rotameter. After passing through the test section, the water returns to the liquid tank through a cyclone type separator consisting of a $1\frac{1}{2}$" pipe brazed to provide tangential entry to an 8" pipe. The cyclone separator was used to release at least a portion of the air entrained in the water.

Mixing of Phases.--Experiment showed that the point at which air was mixed with the water had a definite effect on the flow pattern developed. In order to reduce the severe vibrations from slugging flow, the best arrangement was found to be the introduction of air vertically downward into the water, with no obstructions such as valves or elbows between the point of introduction of air and the test section. This was accomplished by a 1" screwed pipe tee. The relative location of this point is shown on the schematic diagram (Figure 12).

Control of Surface Tension.--Surface tension of the water was controlled by the addition of a commercially obtainable wetting agent sold under the trade name of "Victawet." This wetting agent is sold by the

Victor Chemical Company. The chemical composition was not available. First experiments with this wetting agent showed a decrease in surface tension with the addition of only a slight amount of wetting agent. After setting overnight, however, the surface tension returned to its original value. A plausible conclusion is that the wetting agent was reacting with the iron in the system and that given sufficient time the surface tension would on each future occasion return to its original value. Although the time required for completing a run was short enough that there should be no appreciable change of surface tension during the test, an effort was made to complete a run as rapidly as possible and thus minimize the effect of this change on the results of the experiment.

CHAPTER IV

PERFORMANCE OF TESTS

Checking Equipment Calibration.--After calibration of both Rotameters, tests were run first using all air and then using all water. Pressure drops were measured with a micromanometer and the results used to compute the Weisbach friction factor for the test section. The results are shown in graphical form in Figure 5. This figure also compares these results with each other and with the theoretical friction factor for a "smooth" pipe. The results indicate that the calibrations are substantially correct and suitable for the purposes of this experiment. (The calibration is actually closer than might be implied by a cursory glance at Figure 5 since the flow rate is squared when computing the friction factor, thus magnifying any error in calibration).

Introduction of Wetting Agent.--Prior to each test the tank was filled with water (about 900 pounds) and 2 or 3 cc of the wetting agent added. The pump was operated for about 30 minutes with the bypass open and the test section closed. Since the bypass emptied into the tank below the surface of the water, there was no opportunity to introduce air and thus affect the value of surface tension. Samples were taken every five minutes at the same location in the tank and the surface tension was measured by a Cenco duNuoy Tensiometer as manufactured by the Central Scientific Company. Additional amounts of the wetting agent were added until the desired value of surface tension was obtained.

Measurements Obtained.--Tests were begun as soon as the desired value of surface tension was reached. For each value of surface tension the tests were conducted in the same order. That is, a given minimum liquid flow rate was maintained (by regulating the throttling valves before and after the liquid Rotameter) while various air rates were used. Then a higher liquid rate was used and another series of air rates was used. Six different values of liquid flow rate were used and a maximum of seven values of air rates were used. Where a smaller number of air rates appears, it was due to limitations of the air supply.

A total of 184 tests were made, exclusive of calibration runs and runs using no air.

CHAPTER V

DESCRIPTION OF FLOW PATTERNS OBTAINED

Notes were made as to prevailing flow patterns for each condition of flow. No attempt has been made to correlate these flow patterns with flow rates, nevertheless a record of the patterns was made.

Terms used to describe flow patterns are essentially in agreement with established practice. However, the following comments seem to be appropriate.

The equipment used in this experiment could not be made to produce stratified flow. However, this term will be used in leading up to a description of other flow patterns.

Stratified flow usually exists at very low air rates and very low liquid rates. In this flow pattern the air occupies the upper part of the pipe and water occupies the lower part. As the air flow rate increases, the air velocity increases and intermittently lifts slugs of water from the liquid surface. If these slugs cover the entire cross section of the pipe, the flow is called "slug" flow. If the slugs form but do not cover the entire cross section of the pipe, the flow is called "cresting" flow.

If the air flow is increased further after reaching cresting flow, a continuous flow of liquid will be seen to cover the entire inner pipe surface. This has been called "cresting-semi-annular" flow. With further increase of air flow, the crests cease to form but a continuous film of liquid covers the entire inner pipe surface. This has been called "semi annular" flow.

The flow patterns described as "slug-semi annular" are the same as "cresting-semi annular" except for the characteristics mentioned above that distinguish between slug flow and cresting flow.

Although no attempt was made to use the flow patterns in any kind of correlation, the type of flow for each combination of flow rates is indicated in Table 2.

CHAPTER VI

ANALYSIS OF DATA AND CONCLUSIONS

Sample Calculations.--The correlation proposed by Lockhart and Martinneli involves three definitions:

$$\phi_L^2 = \frac{\left(\frac{\Delta P}{\Delta L}\right)_{TP}}{\left(\frac{\Delta P}{\Delta L}\right)_L}$$

$$\phi_G^2 = \frac{\left(\frac{\Delta P}{\Delta L}\right)_{TP}}{\left(\frac{\Delta P}{\Delta L}\right)_G}$$

$$X^2 = \frac{\left(\frac{\Delta P}{\Delta L}\right)_L}{\left(\frac{\Delta P}{\Delta L}\right)_G}$$

where $\left(\frac{\Delta P}{\Delta L}\right)_{TP}$ = pressure drop per unit length during two phase flow.

$\left(\frac{\Delta P}{\Delta L}\right)_L$ = pressure drop per unit length when only liquid is flowing.

$\left(\frac{\Delta P}{\Delta L}\right)_G$ = pressure drop per unit length when only the gas is flowing.

It should be noted that $X^2 = \frac{\phi_G^2}{\phi_L^2}$.

The Lockhart and Martinelli correlation is based on the postulate and verified experimentally that:

$$\phi_L^2 = F_1(X)$$

$$\phi_G^2 = F_2(X)$$

Now for the results of the present study the values for $(\Delta P)_{TP}$ and $(\Delta P)_L$ can be read directly from the data (Tables 2 and 1). The values for $(\Delta P)_G$ can be read from Figure 6 if the weight rate of air flow is converted to a volume rate of flow based on the average pressure and temperature in the test section. This involves an assumption of linear pressure variation with pipe length plus an assumption that the absolute pressure was equal to atmospheric pressure at the exit end of the test section. Thus, the average values of the absolute pressure tabulated in Table 2 were obtained by adding one half of the upstream static pressure to the atmospheric pressure.

The plan of correlation followed in this experiment was to plot the correlation of Lockhart and Martinelli based on their values of ϕ_L^2 for the case of both phases in turbulent flow and compare this with the results of the present experiment, using the Weber Number as a parameter. The Weber Number is a dimensionless term involving the ratio of inertia forces to capillary forces and is defined by

$$N_{W_e} = \frac{L \rho V^2}{\sigma g_c}$$

where L = pipe diameter

ρ = density of the liquid

V = velocity of the liquid, based on the full cross sectional area of the pipe

σ = surface tension of the liquid

g_c = dimensional constant

The Weber Number of the liquid phase can be written for a 1" ID pipe as

$$N_{W_e} = \frac{(39.2)(Q^2)}{\sigma}$$

where Q = gpm flowing

σ = dynes/cm

V = velocity of the liquid phase based on only the liquid flowing

The plots of ϕ_L^2 as a function of X^2 appear in Figures 7 through 11.

Discussion of Results.--A study of Figures 7 through 11 shows that ϕ_L^2 is in reasonable agreement with the Lockhart and Martinelli correlation. The correlation of Lockhart and Martinelli is reported by these authors to be accurate within + 44% and -51% as plotted in Figures 7 through 11. This upper and lower limit is indicated by the dotted lines above and below the accepted correlation curve. Values of ϕ_L^2 are consistently higher than predicted by the Lockhart and Martinneli recommendations, but there is essentially no change in relative position of the values of ϕ_L^2 as the surface tension was varied from 34 dynes/cm to 74 dynes/cm.

One conclusion obviously is that varying the surface tension of the liquid phase within the confines of this experiment had no effect on pressure drop. Another conclusion is that the correlation of Lockhart and Martinelli for this set of data is independent of the surface tension of the liquid phase.

The effect of surface tension in the development of the Lockhart and Martinelli Correlation[1] is empirically implied. The present investigation provides experimental evidence of the effect of surface tension on the Lockhart and Martinelli correlation for the case of isothermal flow where there is no mass transfer or heat transfer between phases.

CHAPTER VII

SUGGESTIONS FOR FUTURE WORK

This experiment was one of an exploratory nature and was subject to very limited conditions. Some of the limiting conditions could be enumerated as:

1. Both phases in turbulent flow.
2. Only two fluids were considered.
3. Flow was isothermal.
4. No mass transfer or heat transfer between phases.
5. Surface tension of the liquid was subject to a maximum variation of about 2 to 1 (34 dynes/cm to 74 dynes/cm).
6. Only one test section was considered.
7. Ranges of flow rates for both phases were limited by equipment characteristics.

More experiments should be conducted to determine the influence of the surface tension on the pressure drop under a wide range of conditions. Further, more experimental evidence under a wide range of conditions is needed to establish the effect of variable Weber Number on the Lockhart and Martinelli correlation.

APPENDIX

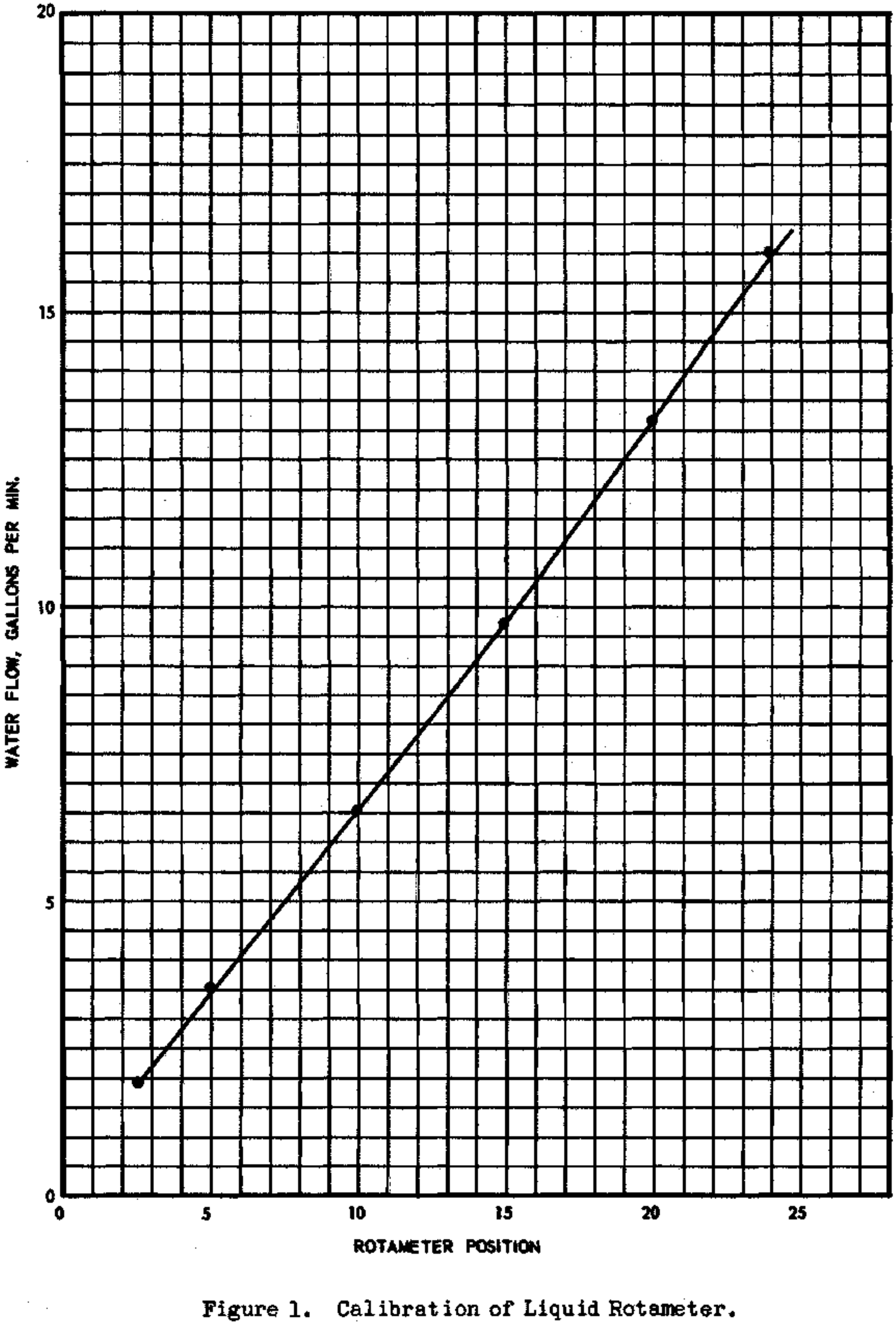

Figure 1. Calibration of Liquid Rotameter.

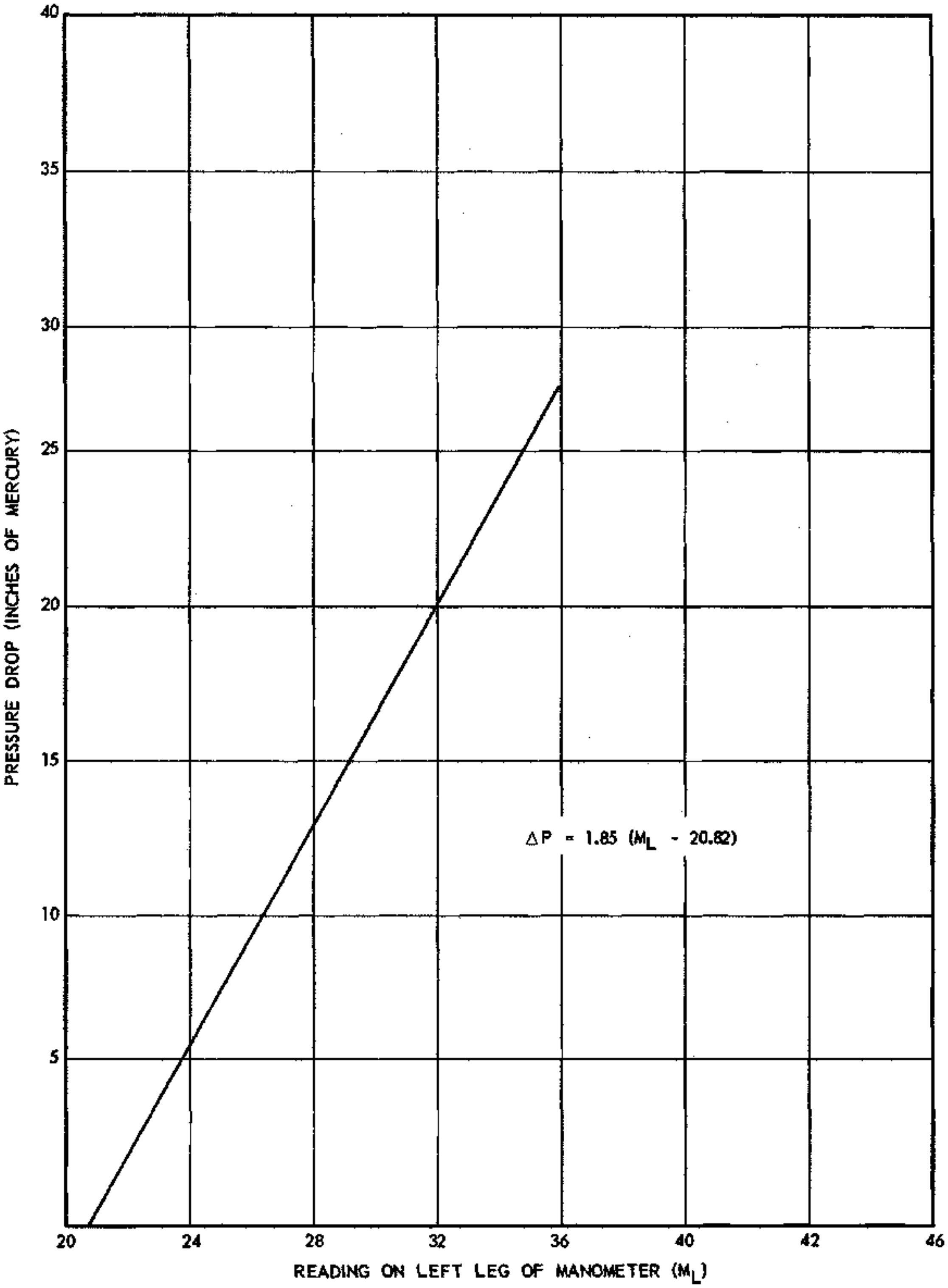

Figure 2. Pressure Drop Across Test Section as a Function of Mercury Position on Left Leg of Manometer.

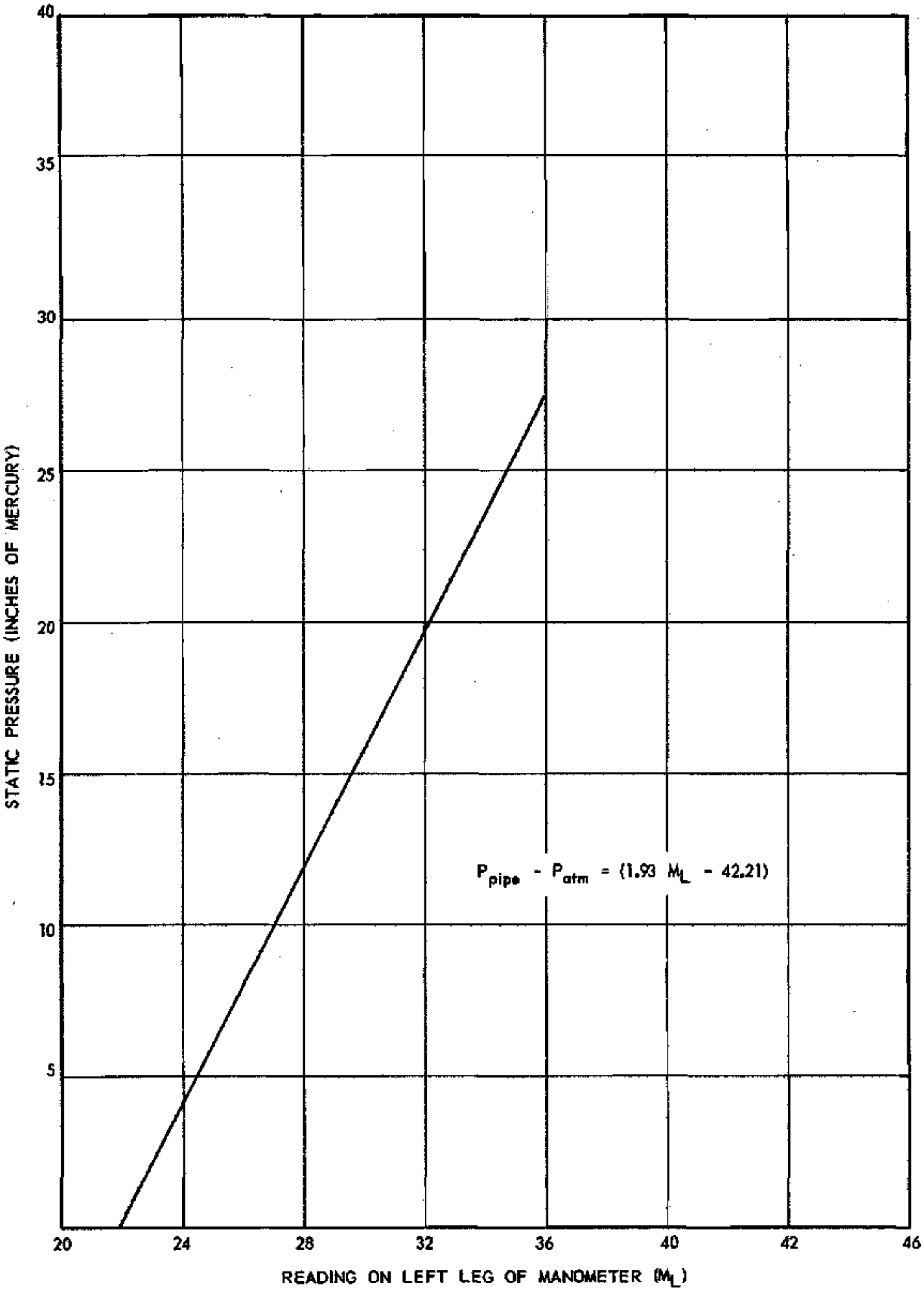

Figure 3. Static Pressure at Entrance to Test Section as a Function of Mercury Position on Left Leg of Manometer.

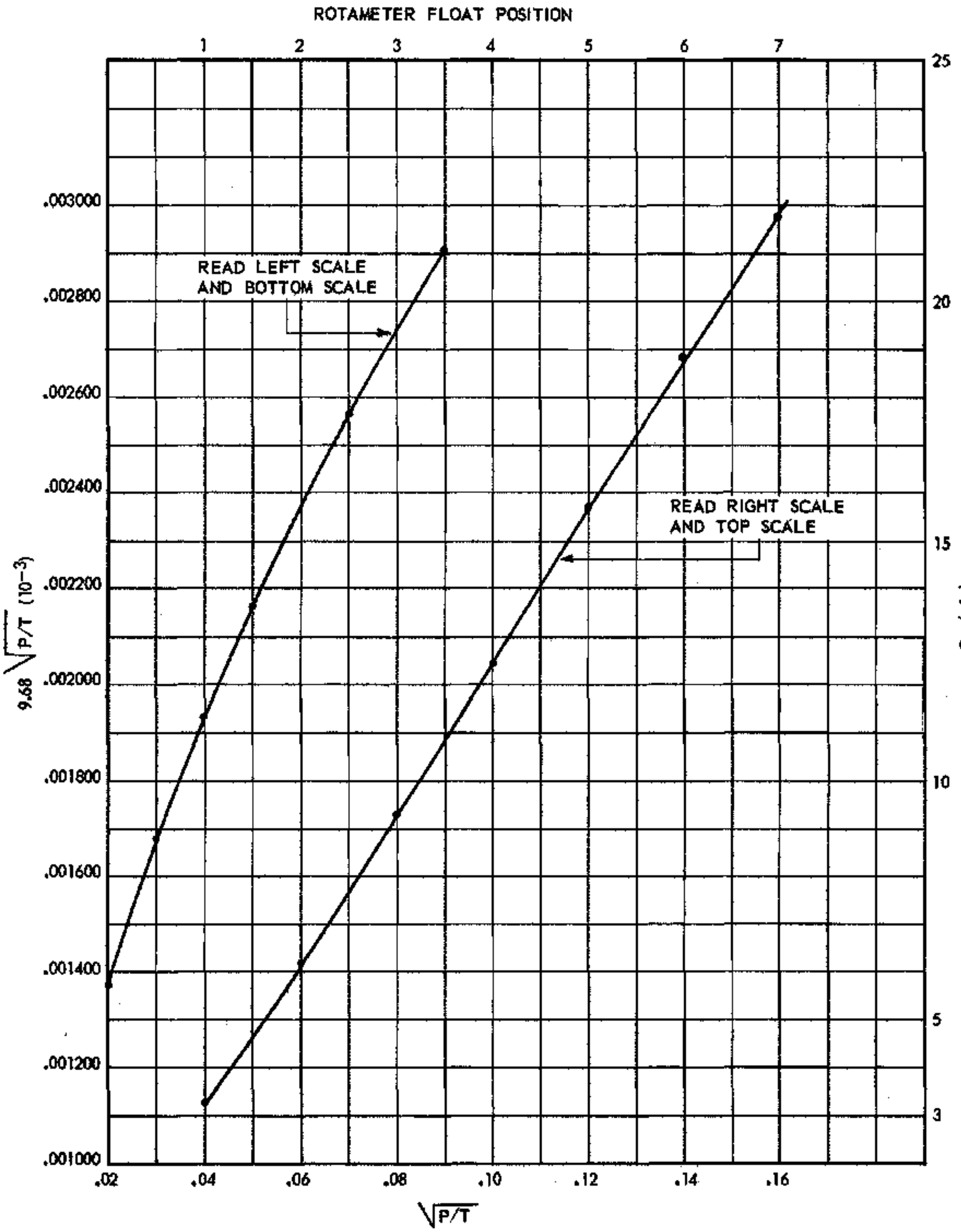

Figure 4. Air Rotameter Calibration.

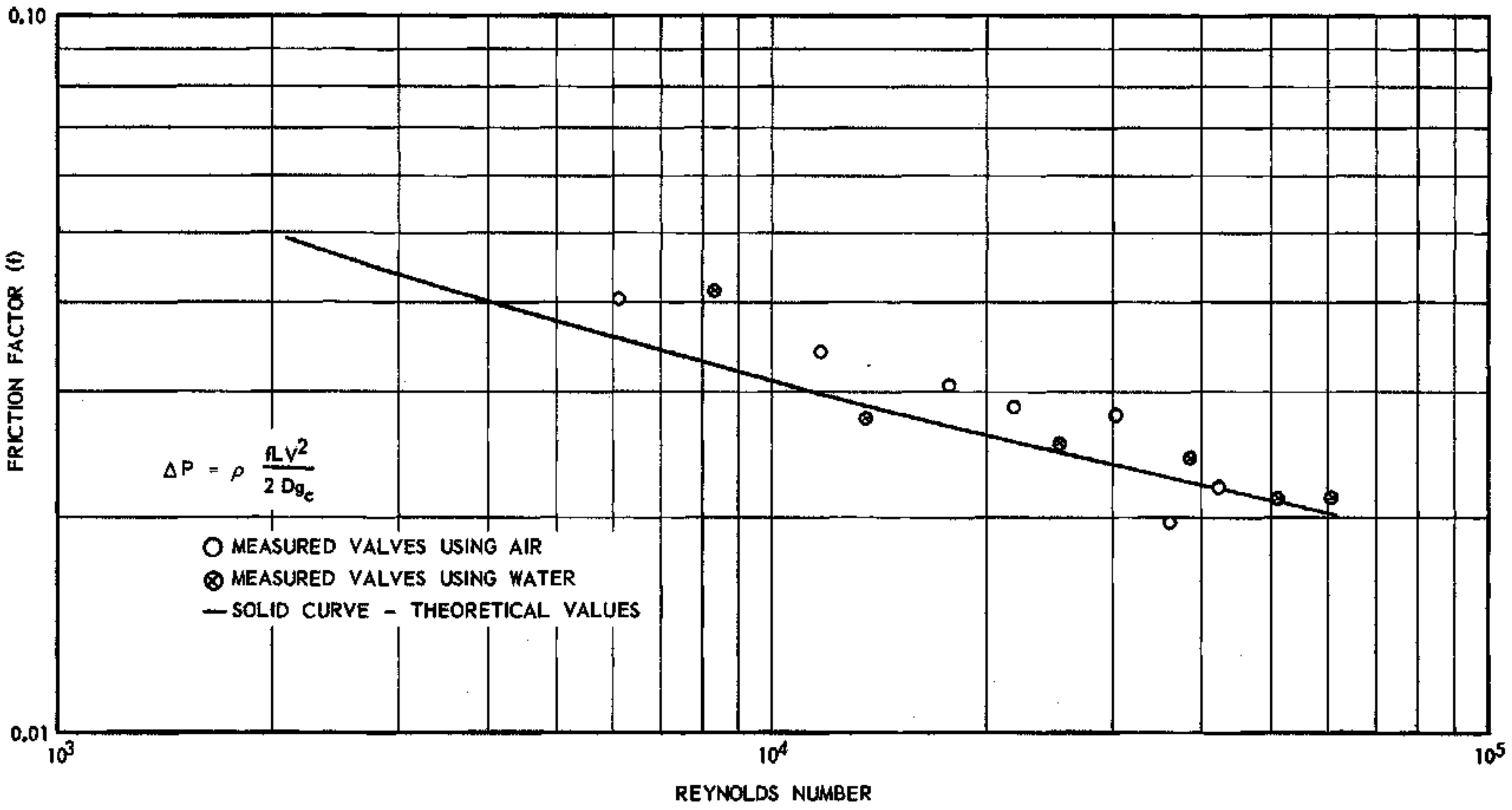

Figure 5. Comparison of Theoretical Friction Factors and Experimental Friction Factors for the Test Section.

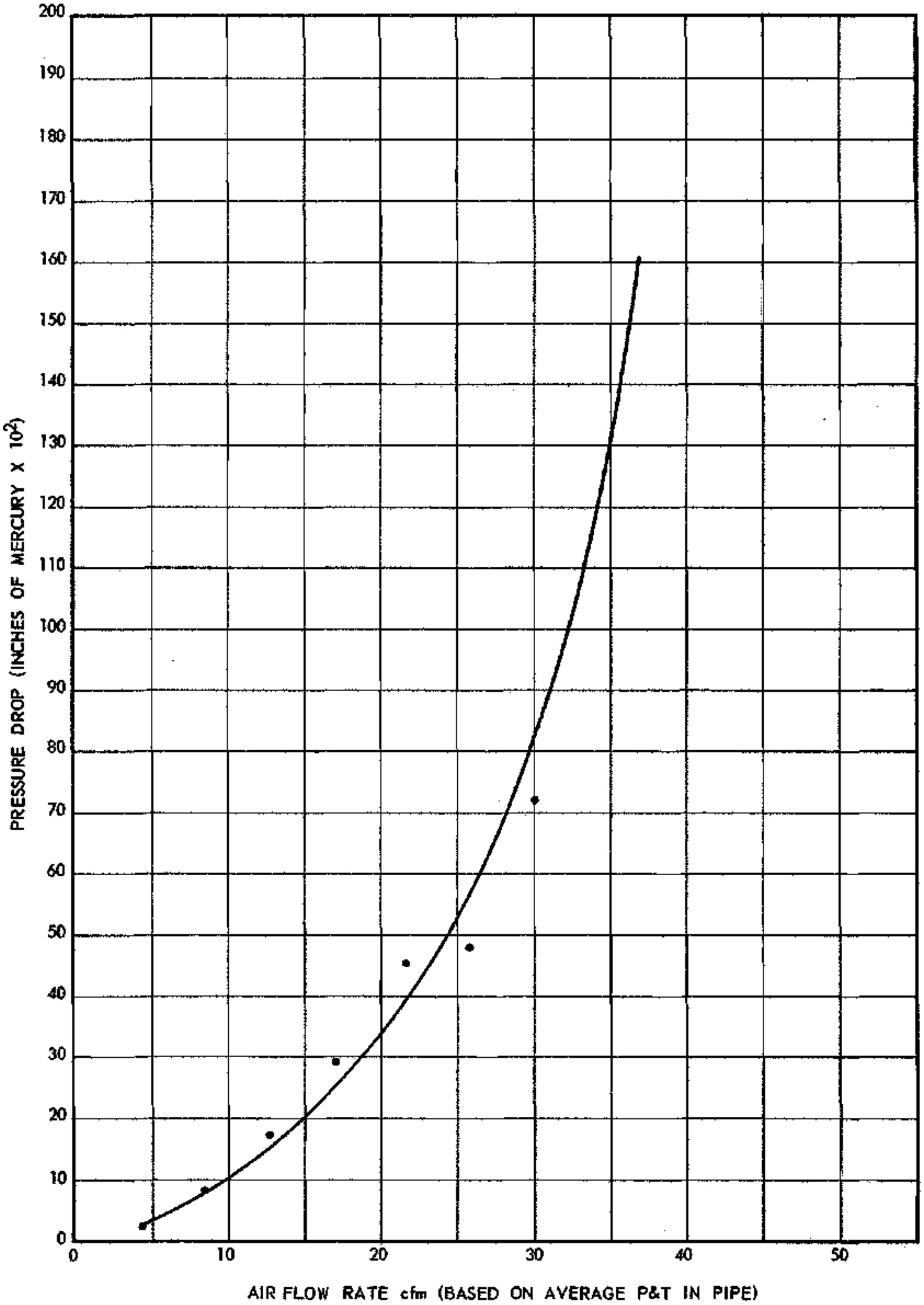

Figure 6. Pressure Drop in Test Section as a Function of Air Flow Rate.

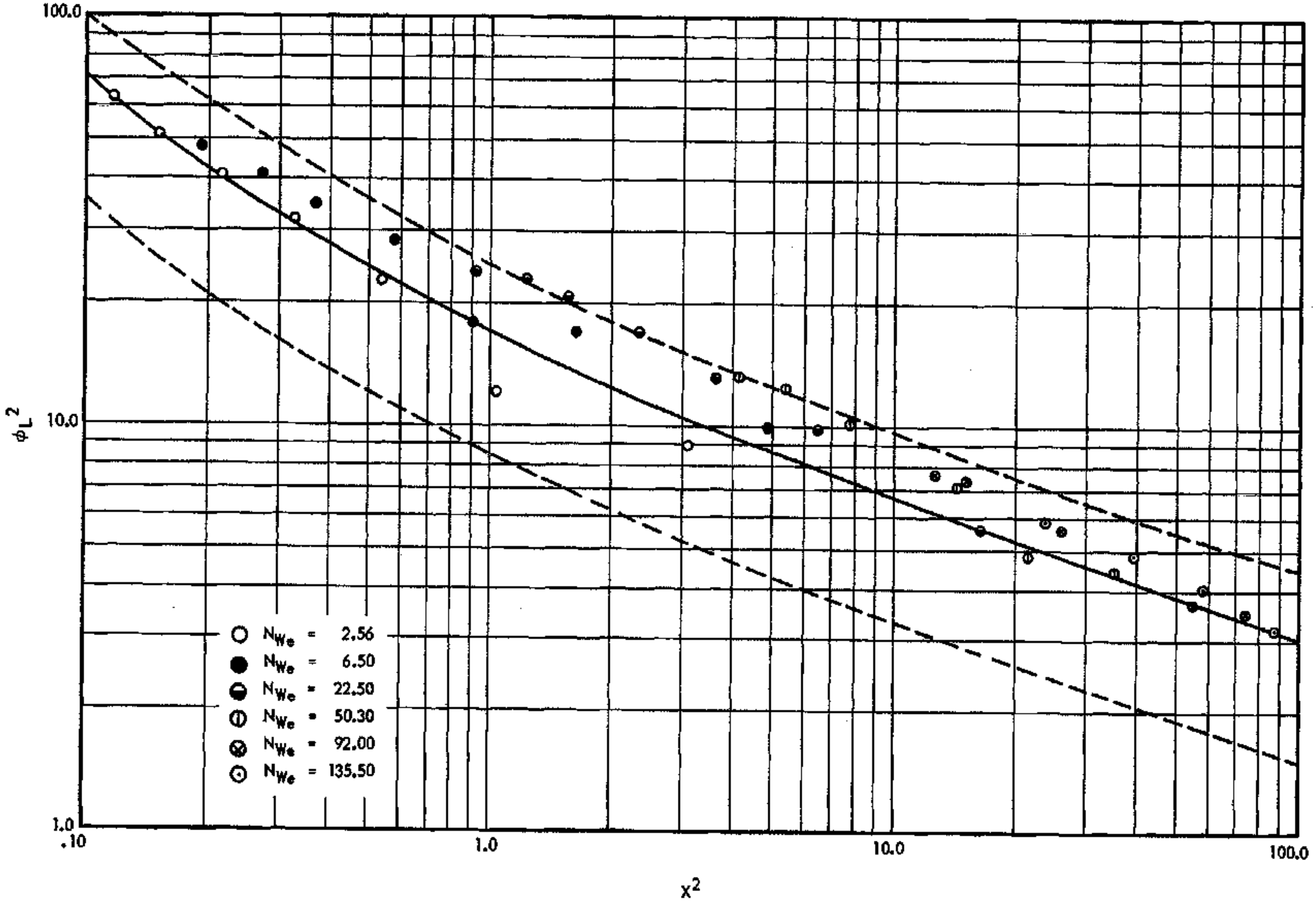

Figure 7. Correlation of Data Taken in Run No. 1.

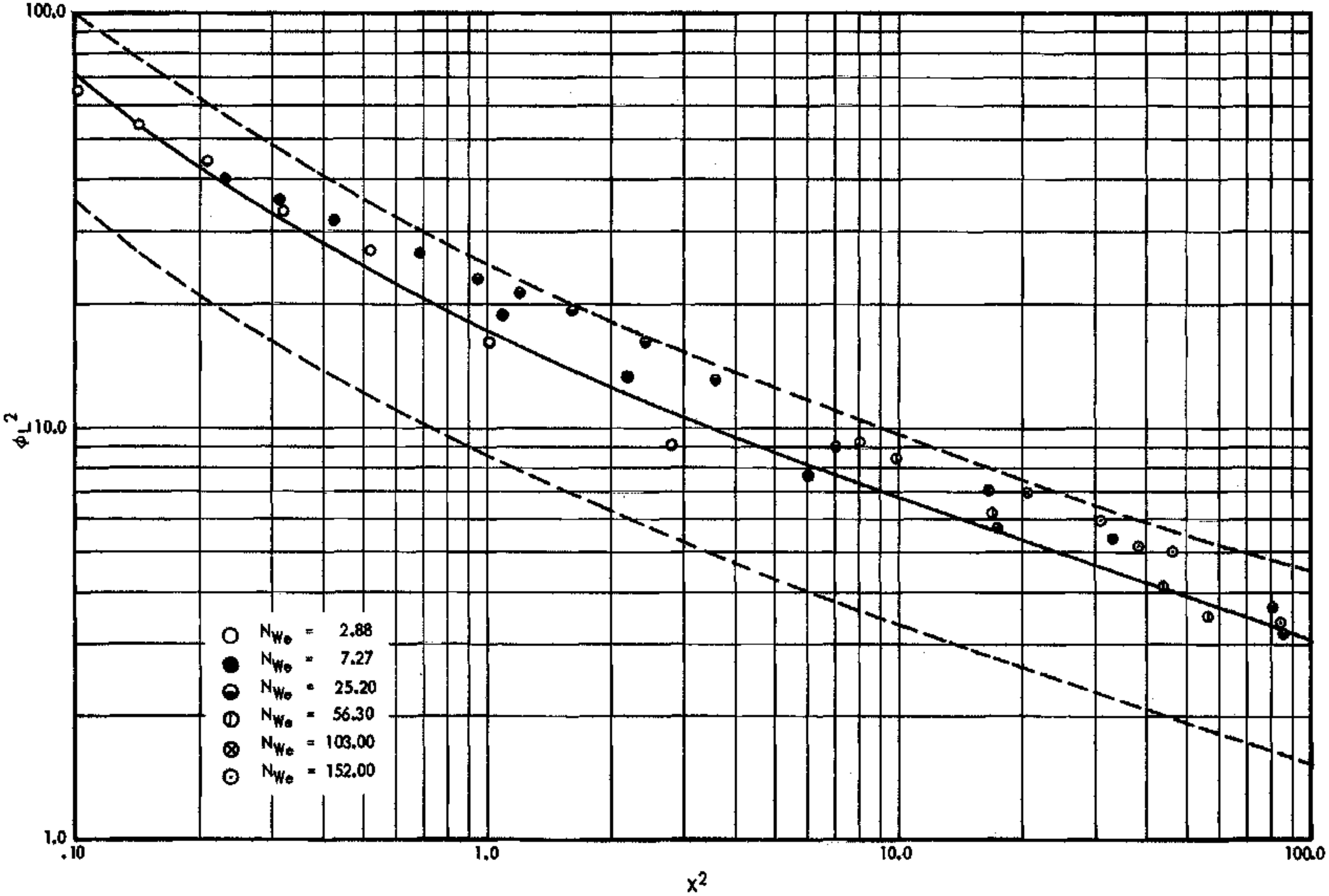

Figure 8. Correlation of Data Taken in Run No. 2.

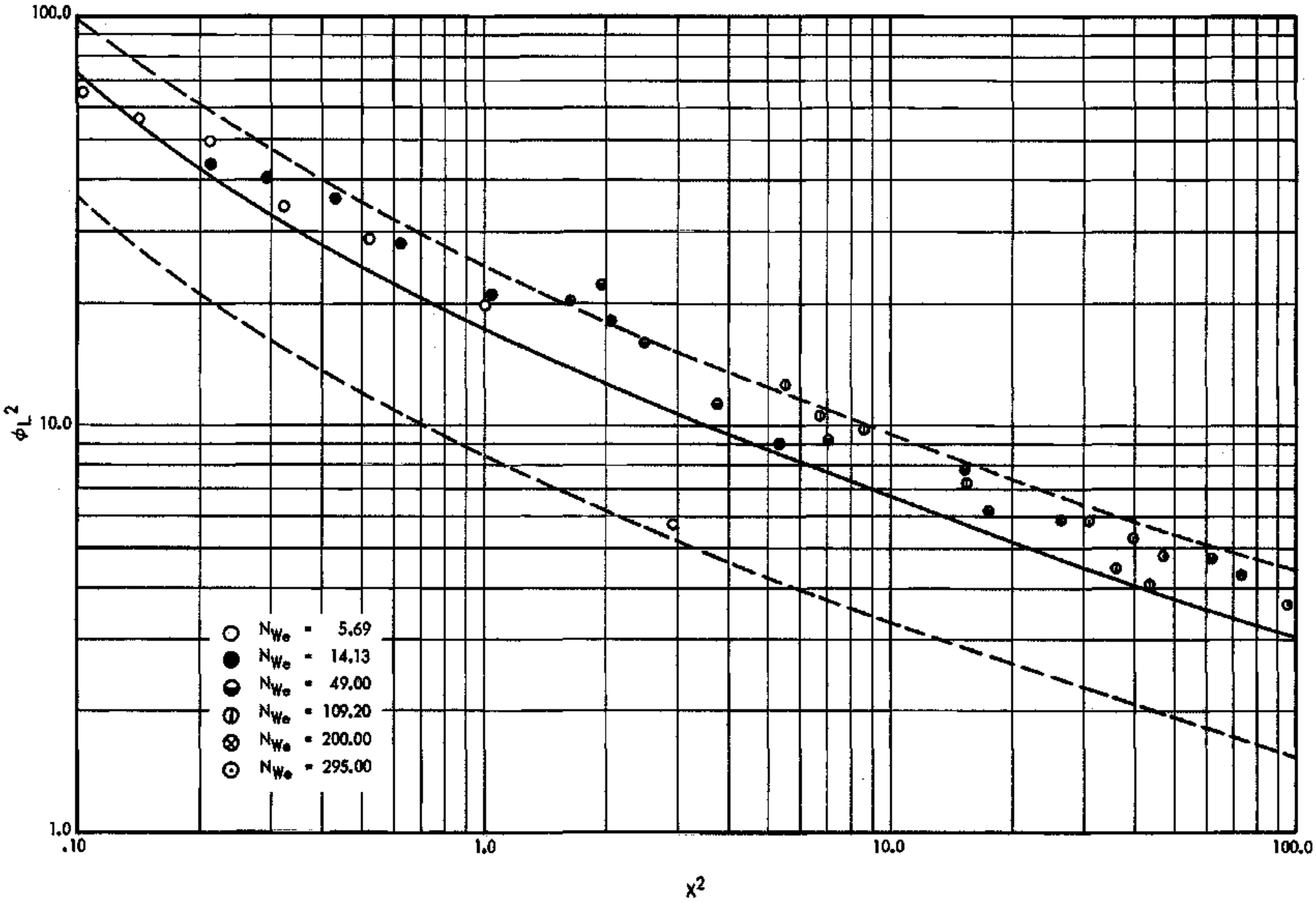

Figure 9. Correlation of Data Taken in Run No. 3.

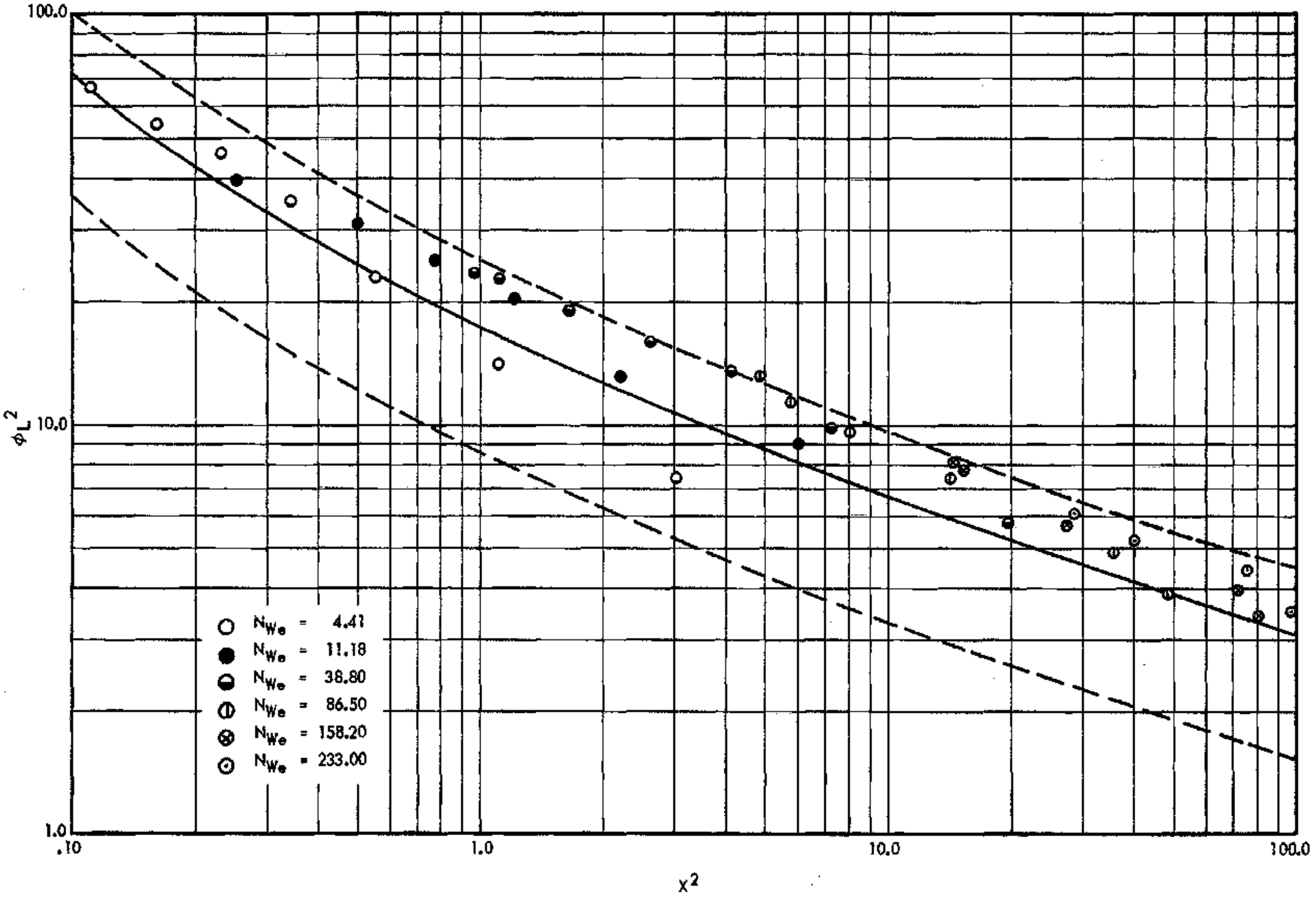

Figure 10. Correlation of Data Taken in Run No. 4.

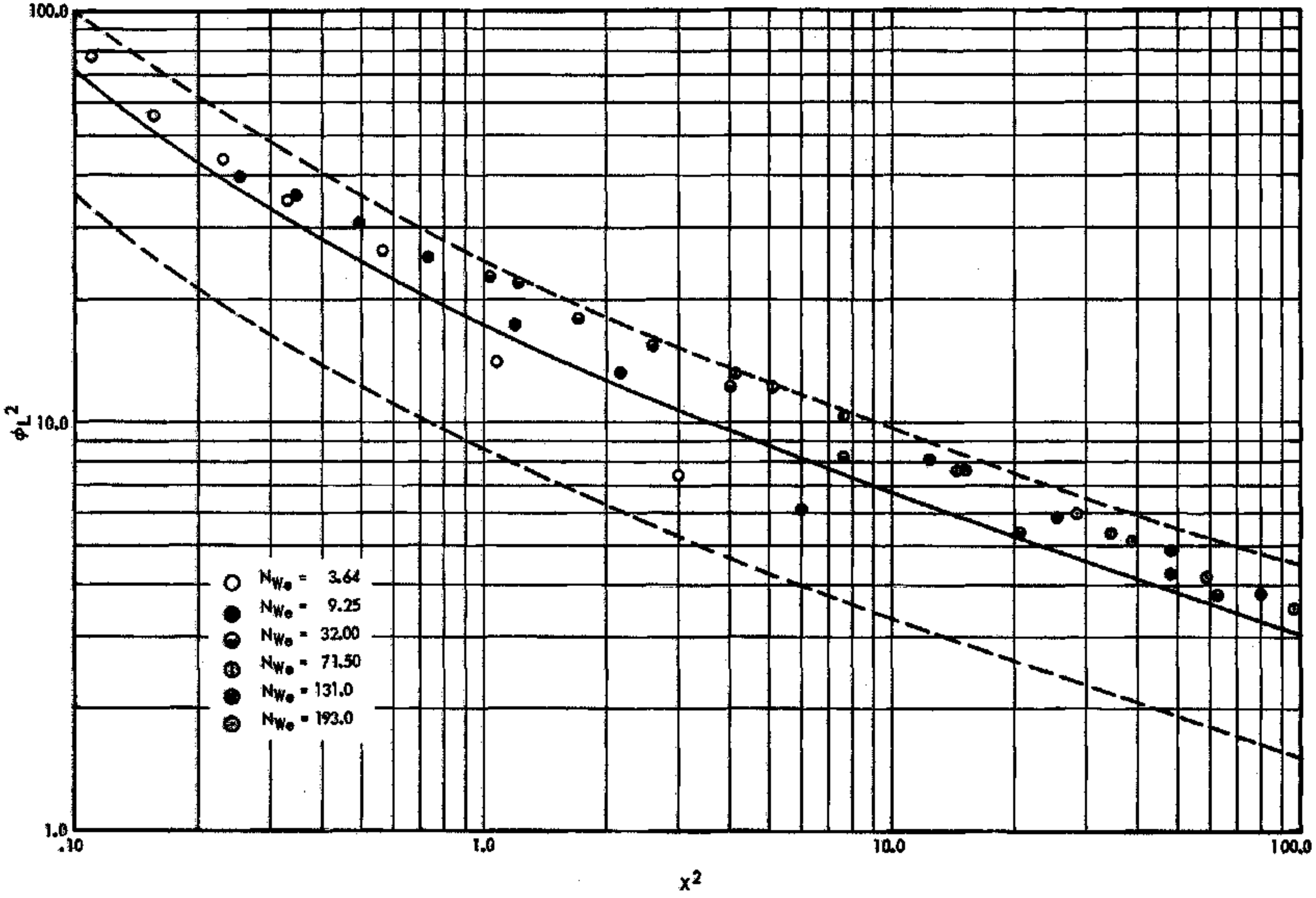

Figure 11. Correlation of Data Taken in Run No. 5.

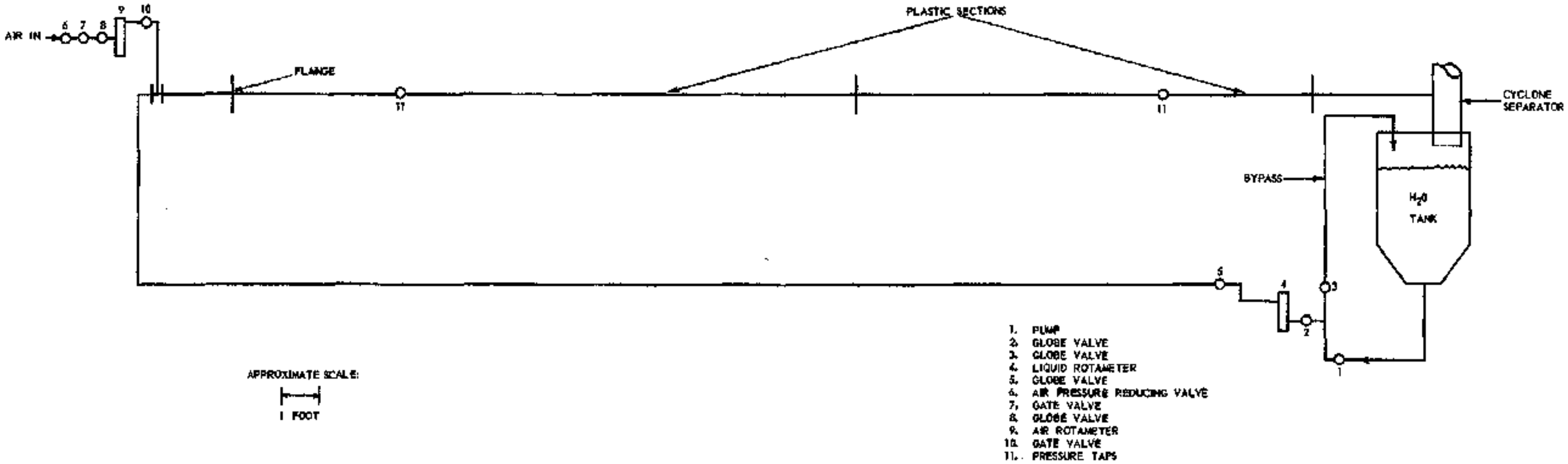

Figure 12. Schematic Diagram of Experimental Equipment.

CALIBRATION OF THE AIR ROTAMETER

The Rotameter used for measuring air was equipped with a tube calibrated to read gallons per minute at the specific gravity 1.0 compared to water at 60° F. Calibration for air service was as follows, assuming air to follow the perfect gas relation

$$pv = RT$$

From the theory of the Rotameter, it can be shown that the weight rate of flow of air is given by:

$$W = \frac{M}{R}\sqrt{\frac{P_s}{T_s}}\,(Q)\sqrt{\frac{P}{T}} \qquad (1)$$

Where W = lb/sec of air flowing

M = apparent molecular weight of air

Q = rate of flow at reference conditions

Subscript s indicates "standard conditions" or reference state.

Calibration was accomplished by attaching a bellows type volume gas meter on the discharge side of the Rotameter. The gas meter reads volume actually passing through at the conditions inside the meter.

A pressure of 0 psig was maintained inside the gas meter and a pressure of 10.9 psig was maintained inside the Rotameter. Barometer reading was 14.20 psia. Temperature of the air was 78° F.

Data were recorded as follows:

Rotameter Position	Time (min) for 10 ft^3 through gas meter Run #1	Run #2	Average Cfm at gas meter conditions	Q Average Cfm through Rotameter*
1	1.76	1.72	5.75	3.25
2	0.92	0.91	10.94	6.18
3	0.62	0.60	16.40	9.27
4	0.46	0.45	22.00	12.43
5	0.36	0.36	27.79	15.70
6	0.30	0.30	33.33	18.81
7	0.26	0.26	38.45	21.75
7.5	0.26	0.24	40.08	22.65

---

*Obtained by applying $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$ where $T_1 = T_2$.

Subscript 1 indicates Rotameter conditions and Subscript 2 indicates gas meter conditions:

$$V_1 = \left(\frac{P_2}{P_1}\right)\left(V_2\right) = \left(\frac{14.20}{25.1}\right)\left(V_2\right) = 0.565\ V_2$$

Substituting the conditions of the reference state into Equation (1) gives:

$$W = 9.68\ Q\sqrt{\frac{P}{T}}\,(10^{-3})$$

where P = absolute pressure in Rotameter (psia)

T = absolute temperature in Rotameter (°R)

Q = value as tabulated in calibration table above.

Figure (4) is a plot of this relation used to obtain the mass flow rate of air through the Rotameter when Rotameter reading, pressure, and temperature are known.

Table 1. Pressure Drop (in hg) for Various Values of Surface Tension When Only Liquid is Flowing

Liquid Rate gpm	Run #1 σ = 74	Run #2 σ = 66	Run #3 σ = 34	Run #4 σ = 43	Run #5 σ = 52 dynes/cm
2.20	.12	.12	.12	.12	.12
3.50	.20	.24	.22	.24	.24
6.52	.66	.70	.70	.70	.72
9.74	1.40	1.68	1.44	1.44	1.44
13.18	2.41	2.64	2.40	2.40	2.40
15.99	3.49	3.36	3.36	3.38	3.40

Table 2. Experimental Data

Run #1
Surface Tension = 74 dynes/cm
Air Temperature = 88° F.
Water Temperature = 84° F.
Barometer = 14.20 psia

Air Rate lb/sec	Liquid Rate gpm	ΔP "H_g	Average Pressure psia	ΔP_G "H_g	ϕ_G^2	ϕ_L^2	X^2	N_{W_e}	Flow Type*
.00660	2.20	1.10	14.20	.040	27.5	9.0	3.1	2.56	1
.01255		1.50	14.20	.12	12.5	12.2	1.0		1
.0188		2.80	14.30	.23	12.2	22.8	0.54		2
.0253		4.05	14.80	.37	10.8	32.9	0.33		2
.0319		5.20	15.18	.55	9.5	42.3	0.22		2
.0382		6.50	15.67	.81	8.0	52.4	0.15		3
.0441		7.95	16.21	1.07	7.4	64.6	0.12		3
.00660	3.50	2.00	14.20	.040	50.0	10.1	5.0	6.50	1
.01255		3.40	14.40	.12	28.3	17.2	1.6		1
.0188		3.60	14.70	.22	16.4	18.2	0.90		1
.0253		5.70	15.20	.35	16.3	28.8	0.57		2
.0319		7.05	15.77	.54	13.1	35.6	0.37		2
.0382		8.30	16.31	.72	11.5	41.9	0.27		3
.0441		9.60	16.65	1.02	9.4	48.5	0.19		3
.00660	6.52	3.80	14.89	.040	95.0	5.8	16.5	22.5	1
.01255		6.70	15.67	.10	67.0	10.1	6.6		1
.0188		8.90	16.26	.18	49.5	13.5	3.7		1
.0257		11.45	17.22	.28	40.8	17.3	2.4		2
.0334		14.00	18.08	.43	32.5	21.2	1.5		2
.0413		15.60	18.54	.54	28.9	23.6	1.2		4
.0449		16.00	19.19	.72	22.2	24.2	0.92		4

(continued)

Table 2. Experimental Data (continued)

Air Rate lb/sec	Liquid Rate gpm	ΔP "H_g	Average Pressure psia	ΔP_G "H_g	ϕ_G^2	ϕ_L^2	X^2	N_{W_e}	Flow Type*
.00602	9.74	6.20	15.43	.040	155.0	4.4	35.0	50.3	1
.00724		6.70	15.77	.065	103.0	4.8	21.5		1
.0138		10.10	16.88	.10	101.0	7.2	14.0		2
.0207		14.30	18.30	.18	79.5	10.2	7.8		4
.0330		19.10	20.14	.34	56.2	13.6	4.1		4
.0278		17.65	19.75	.26	67.8	12.6	5.4		4
.00630	13.18	8.75	16.34	.033	265.0	3.6	73.3	92.0	1
.00738		9.25	16.53	.044	210.0	3.8	54.7		1
.01404		14.00	18.20	.092	152.0	5.8	26.2		2
.0211		18.00	19.77	.16	112.3	7.5	15.0		4
.0235		19.00	20.14	.19	100.0	7.9	12.7		4
.00660	15.99	10.90	17.07	.033	330.0	3.1	105.2	135.5	2
.00755		11.30	17.29	.040	282.0	3.2	87.0		2
.01068		14.00	18.32	.060	233.0	4.0	58.1		2
.01433		17.00	19.45	.088	193.0	4.9	39.7		2
.0194		19.50	20.38	.15	130.0	5.6	23.3		2

Run #2
Surface Tension = 66 dynes/cm
Air Temperature = 84° F.
Water Temperature = 88° F.
Barometer = 14.30 psia

.00680	2.20	1.1	14.30	.043	25.6	9.2	2.8	2.88	1
.01294		2.0	14.30	.12	16.7	16.7	1.0		1
.01940		3.3	14.59	.23	14.3	27.5	0.52		2
.0261		4.1	14.86	.38	10.8	34.2	0.32		2
.0329		5.4	15.36	.57	9.5	45.0	0.21		2

(continued)

Table 2. Experimental Data (continued)

Air Rate lb/sec	Liquid Rate gpm	ΔP "H_g	Average Pressure psia	ΔP_G "H_g	Φ_G^2	Φ_L^2	X^2	N_{We}	Flow Type*
.0394	2.20	6.5	15.75	.84	7.8	54.1	0.14	2.88	3
.0455	2.20	7.8	16.16	1.20	6.5	65.0	0.10	2.88	3
.00680	3.50	1.9	14.42	.040	47.5	7.9	6.0	7.27	1
.01294		3.3	14.89	.11	30.0	13.7	2.2		1
.01940		4.6	15.16	.22	20.9	19.2	1.1		1
.0261		6.5	15.65	.35	18.5	27.1	0.68		2
.0329		7.8	15.97	.57	13.7	32.5	0.42		2
.0394		8.7	16.44	.75	11.6	36.2	0.32		3
.0455		9.8	16.83	1.05	9.3	40.7	0.23		3
.00680	6.52	4.1	15.04	.040	102.3	5.9	17.4	25.20	1
.01294		6.3	15.60	.10	63.0	9.1	7.0		1
.01940		9.3	16.44	.19	49.0	13.4	3.6		2
.0261		11.7	17.24	.29	40.3	16.8	2.4		2
.0334		13.3	17.93	.43	30.9	19.1	1.6		4
.0412		15.1	18.70	.60	25.2	21.7	1.2		4
.0452		16.2	19.06	.73	22.2	23.3	0.95		4
.0239	9.74	15.8	18.89	.21	75.3	9.4	8.0	56.30	6
.0203		14.3	18.40	.17	84.1	8.5	9.9		4
.0136		10.5	16.98	.10	105.0	6.3	16.8		2
.00715		6.8	15.82	.040	170.0	4.1	42.0		1
.00605		5.9	15.65	.030	196.7	3.5	56.0		1
.0215	13.18	18.9	20.07	.16	118.1	7.2	16.5	103.0	6
.0196		18.5	20.00	.13	142.3	7.0	20.4		6
.0131		14.3	18.30	.080	179.0	5.4	33.0		2
.00689		9.8	16.83	.033	297.0	3.7	80.0		1
.00640		8.5	16.58	.031	274.0	3.2	85.1		1

(continued)

Table 2. Experimental Data (continued)

Air Rate lb/sec	Liquid Rate gpm	ΔP "H_g	Average Pressure psia	ΔP_G "H_g	ϕ_G^2	ϕ_L^2	X^2	N_{W_e}	Flow Type*
.0181	15.99	20.0	20.53	.11	181.8	6.0	30.6	152.0	6
.0145		17.3	19.60	.088	196.5	5.2	38.2		4
.00765		11.6	17.49	.040	290.0	3.5	84.0		1
.00670		11.0	17.22	.031	355.0	3.3	108.5		1
.0140		16.9	19.40	.073	232.0	5.0	46.1		2

Run #3
Surface Tension = 34 dynes/cm
Air Temperature = 84° F.
Water Temperature = 88° F.
Barometer = 14.30 psia

.00681	2.20	0.7	14.30	.041	17.1	5.8	2.9	5.69	1
.0129		2.4	14.30	.12	20.0	20.0	1.0		1
.0194		3.5	14.64	.23	15.2	29.2	0.52		1
.0261		4.2	15.26	.36	11.2	35.0	0.32		2
.0329		6.0	15.42	.56	10.7	50.0	0.21		3
.0394		6.9	15.82	.83	8.3	57.5	0.14		3
.0456		7.9	16.21	1.18	6.7	65.9	0.10		3
.0456	3.50	9.8	16.92	1.04	9.4	45.4	0.21	14.13	3
.0394		8.9	16.53	.74	12.0	41.2	0.29		3
.0329		7.9	16.26	.50	15.8	36.6	0.43		2
.0261		6.1	15.65	.35	17.4	28.2	0.62		2
.0194		4.6	15.23	.21	21.9	21.3	1.0		1
.0129		3.9	14.59	.11	35.5	18.0	2.0		1
.00681		2.0	14.30	.041	48.8	9.3	5.3		1

(continued)

Table 2. Experimental Data (continued)

Air Rate lb/sec	Liquid Rate gpm	ΔP "H_g	Average Pressure psia	ΔP_G "H_g	ϕ_G^2	ϕ_L^2	X^2	N_{W_e}	Flow Type*
.00681	6.52	4.4	14.91	.040	110.0	6.3	17.4	49.00	1
.0129		6.5	15.72	.10	65.0	9.4	7.0		2
.0194		7.9	16.63	.18	43.8	11.4	3.9		2
.0256		11.3	17.39	.28	40.4	16.2	2.5		2
.0337		14.2	18.15	.43	33.0	20.4	1.6		3
.0418		15.6	18.88	.62	43.4	22.4	1.9		3
.00606	9.74	5.9	15.72	.033	179.0	4.1	43.6	109.2	1
.00715		6.5	15.72	.040	162.5	4.5	36.0		1
.0136		10.5	17.12	.094	111.7	7.3	15.3		1
.0203		14.3	18.40	.17	84.0	9.9	8.5		1
.0239		15.6	19.01	.21	74.2	10.8	6.9		2
.0283		18.6	19.73	.26	71.5	12.9	5.5		5
.00640	13.18	10.5	16.53	.033	318.0	4.4	72.7	200.0	1
.00753		11.4	16.88	.040	287.0	4.8	60.4		1
.0143		14.2	18.55	.091	156.0	5.9	26.3		2
.0215		18.8	20.14	.16	117.4	7.8	15.0		6
.00670	15.99	11.4	17.24	.033	345.0	3.4	101.8	295.0	1
.00765		12.3	17.79	.035	352.0	3.7	96.1		1
.0127		16.2	19.11	.071	228.0	4.8	47.3		2
.0146		17.8	19.67	.085	209.0	5.3	39.4		2
.0181		19.8	20.45	.11	180.0	5.9	30.5		1

(continued)

Table 2. Experimental Data (continued)

Run #4
Surface Tension = 43 dynes/cm
Air Temperature = 78° F.
Water Temperature = 80° F.
Barometer = 14.30 psia

Air Rate lb/sec	Liquid Rate gpm	ΔP "H_g	Average Pressure psia	ΔP_G "H_g	ϕ_G^2	ϕ_L^2	X^2	N_{W_e}	Flow Type*
.00668	2.20	0.9	14.30	.040	22.5	7.5	3.0	4.41	1
.0127		1.7	14.30	.11	15.5	14.2	1.1		1
.01904		2.8	14.64	.22	12.7	23.3	0.55		1
.0256		4.3	14.96	.35	12.3	35.8	0.34		2
.0323		5.6	15.41	.53	10.6	46.7	0.23		2
.0387		6.5	15.82	.75	8.7	54.1	0.16		3
.0447		8.0	16.16	1.08	7.4	66.6	0.11		3
.00668	3.50	2.2	14.45	.040	55.0	9.2	6.0	11.18	1
.0127		3.2	14.69	.11	29.1	13.3	2.2		1
.01904		5.0	15.21	.20	25.0	20.8	1.2		2
.0256		6.1	15.82	.31	19.7	25.4	0.78		2
.0323		7.6	16.16	.48	15.8	31.7	0.50		2
.0387		8.7	16.38	.70	12.4	36.2	0.34		3
.0447		9.6	16.83	.96	10.0	40.0	0.25		3
.00668	6.52	4.1	14.96	.035	117.2	5.9	19.9	38.80	1
.0127		6.9	15.70	.096	71.8	10.0	7.2		1
.01904		9.6	16.48	.17	56.5	13.8	4.1		2
.0256		11.1	17.49	.27	41.1	16.0	2.6		2
.0338		13.6	18.18	.42	32.4	19.6	1.7		2
.0420		16.0	18.89	.61	26.2	23.0	1.1		2
.0458		16.6	19.02	.72	23.0	23.9	0.96		2

(continued)

Table 2. Experimental Data (continued)

Air Rate lb/sec	Liquid Rate gpm	ΔP "H_g	Average Pressure psia	ΔP_G "H_g	ϕ_G^2	ϕ_L^2	X^2	N_{W_e}	Flow Type*
.0324	9.74	19.2	20.55	.30	64.0	13.3	4.8	86.50	4
.0272		16.9	19.35	.25	67.6	11.7	5.8		4
.0214		14.2	18.40	.18	78.8	9.9	8.0		2
.0143		10.5	16.88	.10	105.0	7.5	14.0		1
.00750		7.1	15.97	.040	177.0	4.9	35.9		1
.00608		5.7	15.60	.030	190.0	4.0	48.0		1
.00645	13.18	8.3	16.39	.030	277.0	3.5	80.0	158.2	1
.0231		19.3	20.30	.17	113.5	8.0	14.1		4
.0214		18.8	19.88	.16	117.4	7.8	15.0		2
.0143		13.8	18.55	.088	156.9	5.8	27.3		1
.00750		9.6	16.88	.035	284.0	4.0	71.0		1
.00681	15.99	11.2	17.37	.030	373.0	3.3	112.2	233.0	1
.0190		20.6	20.69	.12	172.0	6.1	28.2		4
.0146		17.5	19.60	.085	206.0	5.2	39.8		6
.0109		15.1	18.77	.045	335.0	4.5	75.0		1
.00770		11.8	17.66	.035	337.0	3.5	96.2		1
.00675		10.8	17.32	.030	360.0	3.2	112.4		1
	Run #5 Surface Tension = 52 dynes/cm Air Temperature = 83° F. Water Temperature = 82° F. Barometer = 14.30 psia								
.00653	2.20	0.9	14.30	.040	22.5	7.5	3.0	3.64	1
.0126	2.20	1.7	14.30	.11	15.4	14.2	1.1	3.64	1

(continued)

Table 2. Experimental Data (continued)

Air Rate lb/sec	Liquid Rate gpm	ΔP "H_g	Average Pressure psia	ΔP_G "H_g	ϕ_G^2	ϕ_L^2	X^2	N_{W_e}	Flow Type*
.0189	2.20	3.2	14.82	.21	15.2	26.7	0.57	3.64	2
.0254		4.2	14.96	.36	11.7	35.2	0.33		2
.0320		5.3	15.41	.53	10.0	44.2	0.23		3
.0384		6.8	15.85	.77	8.9	56.7	0.16		3
.0443		9.4	16.22	1.08	8.7	78.4	0.11		3
.00653	3.50	1.8	14.30	.040	37.5	6.3	6.0	9.25	1
.0126		3.2	14.69	.11	29.1	13.3	2.2		1
.0189		4.2	15.36	.20	21.0	17.5	1.2		2
.0254		6.2	15.60	.33	18.8	25.8	0.73		2
.0320		7.5	16.07	.49	15.3	31.3	0.49		3
.0384		8.5	16.45	.70	12.1	35.4	0.34		3
.0443		9.6	16.88	.95	10.1	40.0	0.25		3
.00653	6.52	3.9	14.84	.035	111.2	5.4	20.5	32.00	1
.0126		6.0	15.80	.095	63.2	8.3	7.6		1
.0189		8.9	16.48	.18	49.5	12.4	4.0		2
.0254		11.3	17.18	.28	40.4	15.7	2.6		6
.0334		13.1	18.18	.42	31.2	18.2	1.7		4
.0416		16.0	19.13	.59	27.1	22.2	1.2		4
.0455		17.0	19.36	.71	24.0	23.6	1.0		4
.00606	9.74	6.3	15.87	.030	210.0	4.4	48.0	71.50	1
.00758		7.8	16.02	.042	186.0	5.4	34.3		1
.01443		11.1	17.37	.10	111.0	7.7	14.3		1
.02164		14.8	18.49	.19	78.0	10.3	7.6		6
.0290		17.5	19.51	.28	62.5	12.2	5.2		4
.0342		18.8	20.25	.35	53.7	13.1	4.1		4

(continued)

Table 2. Experimental Data (continued)

Air Rate lb/sec	Liquid Rate gpm	ΔP "H_g	Average Pressure psia	ΔP_G "H_g	ϕ_G^2	ϕ_L^2	X^2	N_{W_e}	Flow Type*
.0239	13.18	19.7	20.44	.19	103.7	8.2	12.6	131.0	6
.02164		18.8	20.02	.16	117.4	7.8	15.0		6
.01443		14.3	18.40	.093	154.0	6.0	25.9		1
.01073		11.9	17.71	.062	192.0	5.0	38.8		1
.00758		9.4	16.73	.040	245.0	3.9	62.5		1
.00642		9.0	16.68	.030	300.0	3.8	80.0		1
.01900	15.99	20.4	20.54	.12	170.0	6.0	28.3	193.0	4
.01455		17.6	19.55	.086	205.0	5.2	39.6		1
.01083		14.3	18.70	.058	247.0	4.2	58.7		1
.00765		12.0	17.69	.035	343.0	3.5	97.5		1
.00662		10.5	17.17	.030	350.0	3.1	113.2		1

*Flow Type Code:
1. Cresting
2. Cresting-semi annular
3. Semi annular
4. Slug-semi annular
5. Cresting-slug
6. Slug

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