EVALUATION OF FLUID FLOW TEST EQUIPMENT

A THESIS

Submitted
to
The Department of Chemical Engineering
of the
University of Tennessee
in
Partial Fulfillment of the Requirements
for the Degree
of
Bachelor of Science

---

by

Malcolm H. Colditz

June 1958

UNIVERSITY OF TENNESSEE
KNOXVILLE

ACKNOWLEDGEMENT

The author wishes to express his appreciation to Professor J. W. Prados for his interest, supervision, and guidance in carrying out this investigation.

TABLE OF CONTENTS

CHAPTER		PAGE
I.	SUMMARY	1
II.	INTRODUCTION	2
	General	2
	Theoretical	3
III.	EXPERIMENTAL EQUIPMENT	5
IV.	EXPERIMENTAL PROCEDURE	11
V.	PRESENTATION OF RESULTS	13
VI.	DISCUSSION OF RESULTS	24
VII.	CONCLUSION AND RECOMMENDATIONS	26
BIBLIOGRAPHY		27
APPENDICIES		29
A.	Sample Calculations	30
B.	Rotameter Calibration	31
C.	Experimental Data	38
D.	Notation	51

LIST OF FIGURES

FIGURE		PAGE
1.	Photographs of Equipment	6
2.	Diagram of Equipment	7
3.	Diagram of Equipment	8
4.	Fanning friction factor vs. Reynolds number - 25°C	21
5.	Fanning friction factor vs. Reynolds number - 10°C	22
6.	Fanning friction factor vs. Reynolds number - 40°C	23
7.	Rotameter No. 1 Calibration - 25°C	32
8.	Rotameter No. 2 Calibration - 25°C	33
9.	Rotameter No. 1 Calibration - 10°C	34
10.	Rotameter No. 2 Calibration - 10°C	35
11.	Rotameter No. 1 Calibration - 40°C	36
12.	Rotameter No. 2 Calibration - 40°C	37

LIST OF TABLES

TABLE		PAGE
I.	Summary of Piping Dimensions	10
II.	Calculated Results - 1/2-Inch Brass At 25°C	14
III.	Calculated Results - 3/4-Inch Brass At 25°C	14
IV.	Calculated Results - 1-Inch Brass At 25°C	15
V.	Calculated Results - 1-Inch Glass At 25°C	15
VI.	Calculated Results - 1-Inch Brass At 10°C	16
VII.	Calculated Results - 3/4-Inch Brass At 10°C	16
VIII.	Calculated Results - 1/2-Inch Brass At 10°C	17
IX.	Calculated Results - 1-Inch Glass At 10°C	17
X.	Calculated Results - 1-Inch Brass At 40°C	18
XI.	Calculated Results - 3/4-Inch Brass At 40°C	18
XII.	Calculated Results - 1/2-Inch Brass At 40°C	19
XIII.	Calculated Results - 1-Inch Glass At 40°C	19
XIV.	Summary of Densities and Viscosities	20
XV.	Experimental Results - 1/2-Inch Brass At 25°C	39
XVI.	Experimental Results - 3/4-Inch Brass At 25°C	40
XVII.	Experimental Results - 1-Inch Brass At 25°C	41
XVIII.	Experimental Results - 1-Inch Glass At 25°C	42
XIX.	Experimental Results - 1-Inch Brass At 10°C	43
XX.	Experimental Results - 3/4-Inch Brass At 10°C	44
XXI.	Experimental Results - 1/2-Inch Brass At 10°C	45
XXII.	Experimental Results - 1-Inch Glass At 10°C	46

TABLE PAGE

XXIII. Experimental Results - 1-Inch Brass At 40°C 47

XXIV. Experimental Results - 3/4-Inch Brass At 40°C 48

XXV. Experimental Results - 1/2-Inch Brass At 40°C 49

XXVI. Experimental Results - 1-Inch Glass At 40°C 50

CHAPTER I

SUMMARY

An investigation of the frictional characteristics of a non-Newtonian milling yellow dye solution has been carried out in the Department of Chemical Engineering at the University of Tennessee by Maung Maung. The present investigation was undertaken in order to substantiate Maung's results and to provide design critera for further studies of this type. This work consisted of an evaluation of the experimental equipment used in Maung's investigation, utilizing water at 10°, 25°, and 40°C as the test fluid. Results were correlated on a single plot of Fanning friction factor vs. Reynolds number for three temperatures considered, and pipe sizes varying from 1/2 inch to 1 inch. Flow rates covered ranges corresponding to Reynolds numbers from 2300 to 107,000, friction factors decreasing from 0.086 to 0.0042 with increasing Reynolds numbers.

Results of the evaluation indicate that all pipes exhibit Fanning friction factors above those expected for new, clean commercial brass pipe. Marked upward deviation of friction factors from literature values was experienced at low flows.

It is recommended that the investigation be repeated, after modifying the experimental equipment to include smaller capacity rotameters, longer calming lengths, and piezometer rings as pressure taps.

CHAPTER II

INTRODUCTION

General

An investigation of the frictional characteristics of a non-Newtonian milling yellow dye solution was carried out in the Department of Chemical Engineering at the University of Tennessee by Maung Maung (1)*. In Maung Maung's study the dye solution under investigation was pumped through a closed loop piping system, and the pressure drops across various pipe test sections were measured as functions of the flow rate through these sections. The results were presented as a unique correlation between Fanning friction factor and Reynolds number for the single solution tested.

The present investigation has been undertaken in order to substantiate the results of this investigation and to provide design critera for further studies of this type. The purpose of the present study was to evaluate the experimental equipment of Maung Maung, using a Newtonian liquid, water, as the test fluid. This objective was accomplished by comparing the Fanning friction factor vs. Reynolds number plots from the literature with those obtained using water at 10°, 25°, and 40°C in the existing apparatus.

---

*Numbers in parenthesis refer to Bibliography entries, page 28.

Theoretical

The Fanning friction factor, f, is used to describe frictional characteristics of fluids flowing through straight pipes (2). It is defined by the equation,

$$f = \frac{-\Delta P_f \, g_c \, D}{2U^2 \rho \, L}, \qquad (1)$$

where

f = Fanning friction factor

ΔP_f = pressure loss due to friction

U = mean flow velocity through the pipe section under investigation

ρ = fluid density

L = pipe length

D = pipe diameter

g_c = force-mass conversion constant

The Fanning friction factor depends on the pipe roughness and degree of turbulence of the fluid in the pipe. This degree of turbulence can be characterized by the magnitude of the Reynolds number, defined as

$$N_{Re} = \frac{DU\rho}{\mu}, \qquad (2)$$

where

N_{Re} = Reynolds number

μ = viscosity of the fluid

Evaluation of the equipment in this experiment was accomplished by measuring the pressure drop across a given test section as a function

of flow rate. Measurement of pressure drop and flow rate enabled the experimenter to calculate the Fanning friction factor from Eq. (1), since the fluid physical properties and system dimensions were known. In like manner, the Reynolds number was calculated from Eq. (2) through a knowledge of fluid velocity and related constants. Plots of Reynolds number vs. Fanning friction factor yielded curves which could be compared with similar data from the literature (3). Significant disagreement between the experimental curves and those in the literature would suggest the presence of consistent sources of error in the equipment under study.

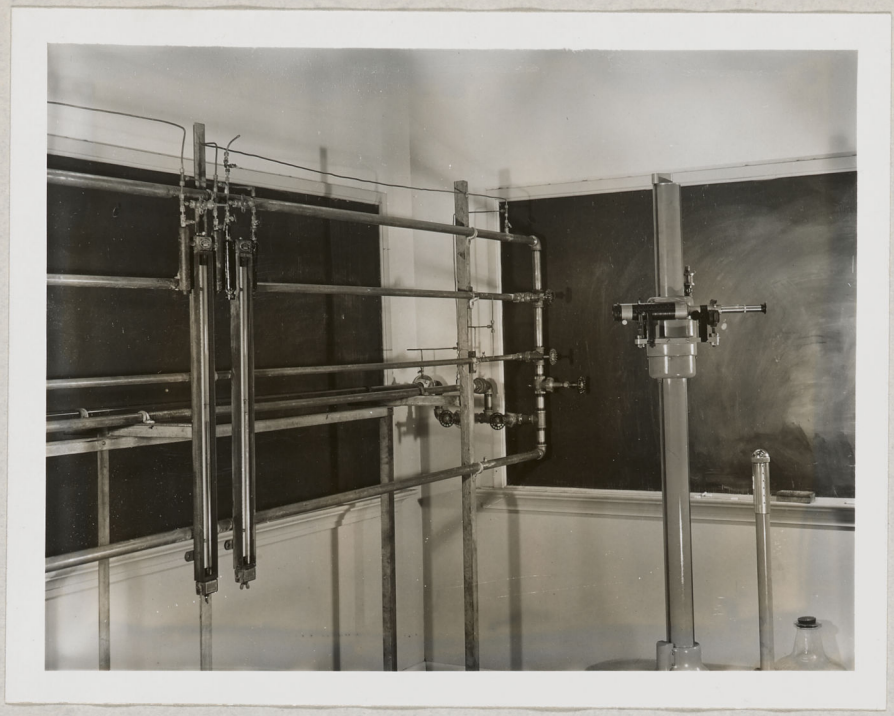
CHAPTER III

EXPERIMENTAL EQUIPMENT

The continuous flow, closed loop piping system which was evaluated is shown in the photographs of Figure 1. Figures 2 and 3 show the major dimensions and layout of the apparatus. Test sections were fabricated from standard 1-, 3/4-, and 1/2-inch diameter brass pipe and 1-inch glass pipe. A test section of 3/4-inch O.D. copper tubing was not evaluated in this study. Flow through each pipe test section was governed by proper control of valves on the respective lines. Pipe section F was used in calibrating the rotameters by allowing the circulating water to exit through this section into a weighing barrel instead of returning to the temperature bath.

Circulation of the water was accomplished through a 1-1/2-horsepower centrifugal pump, and the flow rate was read on the two rotameters, R. The by-pass shown on the feed line in Figure 2 was intended to regulate low flow rates, although it was not used in this investigation. Connection was made from the city water line for washing the system. The pressure drops across the test sections were measured by means of two 78-centimeter Meriam manometers, one containing mercury, the other containing Meriam red oil, Fluid No. 3, of specific gravity 2.95.

The maximum flow of 1150 gallons per hour was limited by the capacity of the pump. The minimum flow obtained was governed by the ability to read the flow rates on the rotameters. This was approximately 56 gallons per hour.



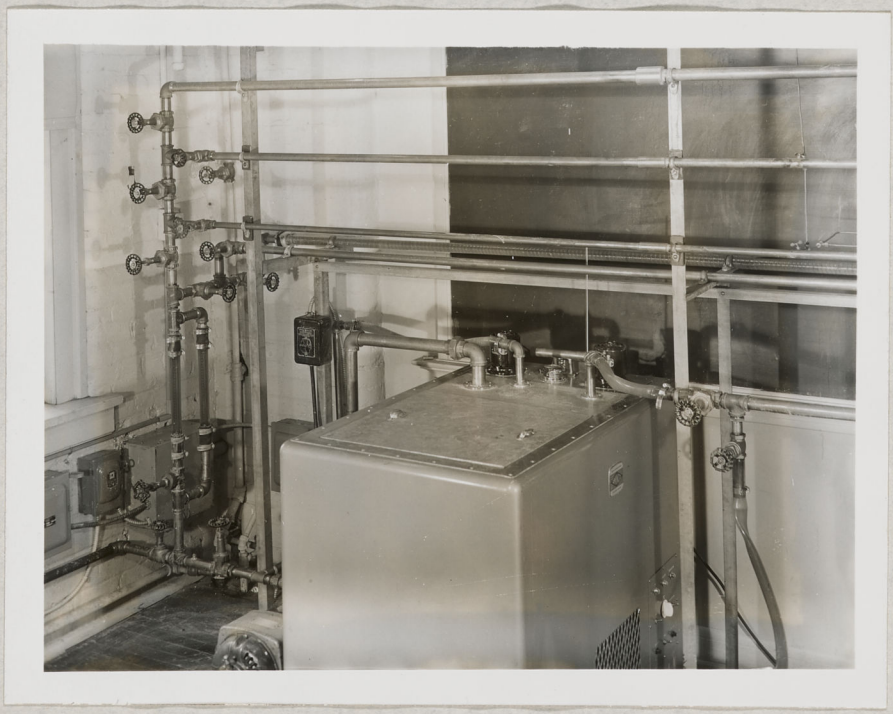


Figure 1. Photographs of Equipment

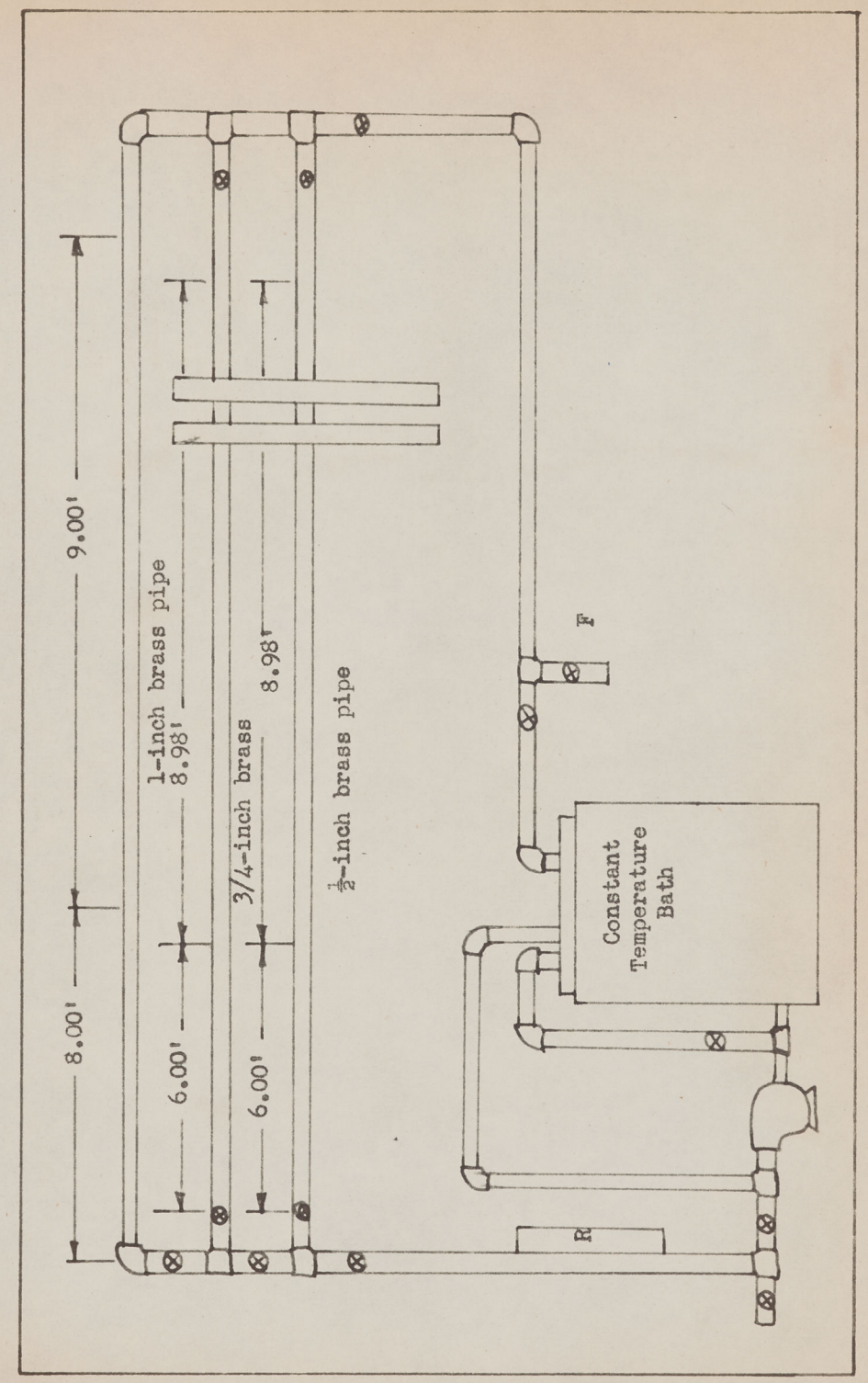


Figure 2. Front view of the pipe system

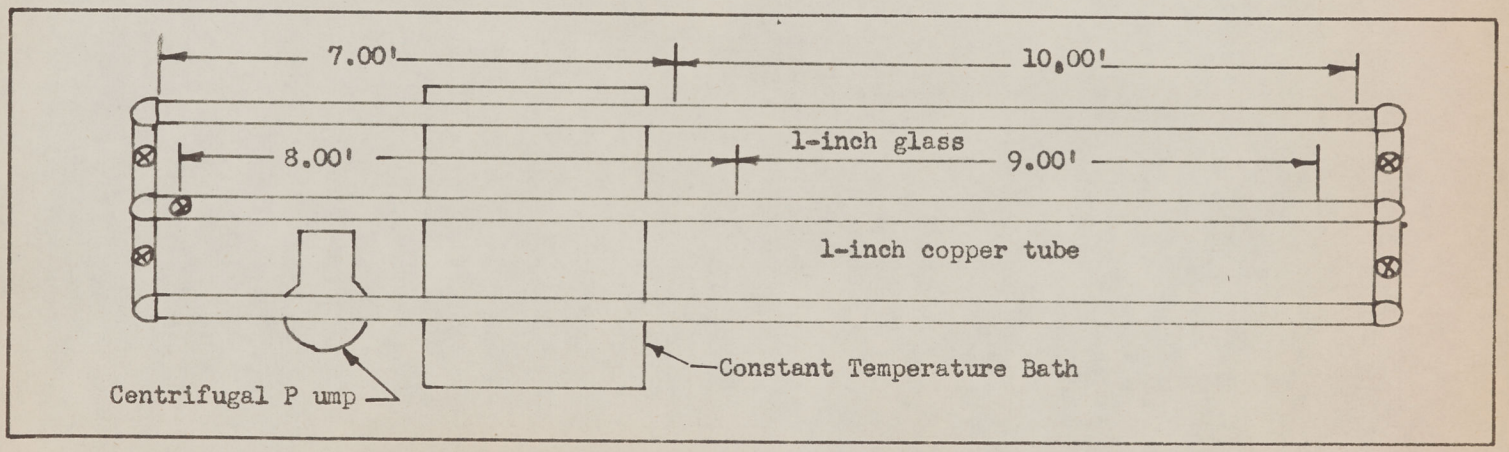


Figure 3. Top view of the pipe system

Table I is a tabulation of dimensions of the piping test sections, including upstream calming lengths. Pressure was transmitted through 3/16-inch O.D. copper tubing from the pressure taps to the manometers. Each pressure lead was equipped with an individual shut-off valve.

A 50-gallon constant temperature bath manufactured by the American Instrument Company was used as the water reservoir. This was provided with a bimetallic thermostat control and two 1/30-horsepower stirrers to maintain circulation in the bath itself.

Manometer readings were taken with a cathetometer manufactured by the Fred C. Henson Company, which provided readings to 0.01 millimeter from an arbitrary reference point.

Viscosity data were obtained using a Hoeppler falling-ball viscometer in conjunction with a separate temperature bath similar to the one used in the main apparatus. Density measurements were read directly from a Seederer-Kohlbusch, Inc. density balance.

TABLE I

SUMMARY OF PIPING DIMENSIONS

Nominal Pipe Size, Inches	Inside Diameter, Inches (3)	Test Section Length, Feet	Upstream Calming Length, Feet
1-inch brass	1.062	9.00	8.00
3/4-inch brass	0.822	8.98	6.00
1/2-inch brass	0.625	8.98	6.00
1-inch glass	1.000	10.00	7.00

CHAPTER IV

EXPERIMENTAL PROCEDURE

Before experimental operations could be begun on the equipment it was necessary to clean the system thoroughly due to the accumulated deposits of milling yellow dye. This was accomplished by circulating, at maximum flow rates, water heated to boiling by the constant temperature bath. Circulation was continued for several hours, after which the system was drained and fresh water introduced from the city water line. This cleaning procedure was repeated until visual inspection and density measurements indicated that no appreciable quantities of dye remained in the equipment. Following this, all pressure lead lines and associated valves were removed and cleaned. The manometer reservoirs and tubes were also disassembled and cleaned.

Calibration of the rotameters was accomplished by directing system flow into a tared weighing barrel for a known period of time, weighing the water collected, and computing the flow rate per unit time corresponding to a given rotameter reading. This procedure was repeated approximately twenty-five times for each of the three temperatures investigated.

Experimental measurements were made by starting the circulation of the system water which had been brought to the desired temperature by the bath, selecting the proper pipe by means of the available valves, opening the pressure transmitting lines, and reading the manometer. Additional accuracy in manometer readings was obtained by measuring the levels with a cathetometer. Considerable difficulty was encountered from air which

became trapped in the pressure leads, giving an erroneous manometer reading. This situation was corrected by keeping the pipes filled with water at all times, thereby preventing air from entering the system. Control of the flow rate was attained by partially closing the valves just downstream from the pump, and the valve immediately preceding the temperature bath.

CHAPTER V

PRESENTATION OF RESULTS

In Tables II through XIII, the calculated Fanning friction factor has been recorded along with its corresponding Reynolds number for each of the runs. Table XIV presents a summary of the measured viscosities and densities of the test water for each of the three operating temperatures.

Figures 4 through 6 show the experimental Fanning friction factor vs. Reynolds number relationships. Superimposed on these plots are lines representing literature values of this relationship for Newtonian fluids in smooth commercial brass piping (3).

TABLE II

CALCULATED RESULTS
1/2-INCH BRASS AT 25°C

Reynolds Number $x10^{-3}$	Fanning Friction Factor $x10^{3}$
5.01	14.0
12.84	7.2
20.26	6.2
27.86	5.7
35.46	5.4
43.11	5.2
50.53	5.4
58.10	5.0
66.15	4.8
71.81	4.8
79.27	4.6
86.22	4.8
92.72	4.8
90.40	4.8
83.50	4.7
77.42	4.8
70.00	4.8
60.73	4.7
53.78	5.1
46.36	5.2
39.40	5.3
31.40	5.1
22.62	5.9
16.22	6.5
8.71	13.1

TABLE III

CALCULATED RESULTS
3/4-INCH BRASS AT 25°C

Reynolds Number $x10^{-3}$	Fanning Friction Factor $x10^{3}$
6.57	14.4
12.53	12.1
18.31	7.1
23.73	6.0
29.14	5.8
35.29	5.6
40.09	5.2
45.80	4.9
51.60	4.8
57.20	4.6
61.80	4.6
67.53	4.7
69.36	4.6
64.49	4.7
57.98	5.1
53.05	4.7
47.76	4.8
44.17	5.1
37.90	5.7
35.40	5.6
27.50	5.9
22.57	6.3
16.18	7.3
10.53	12.4
5.29	19.9

TABLE IV

CALCULATED RESULTS
1-INCH BRASS AT 25°C

Reynolds Number $x10^{-3}$	Fanning Friction Factor $x10^{3}$
4.56	30.3
9.05	23.8
20.46	5.8
18.49	8.1
22.98	8.1
27.46	7.7
29.04	7.3
35.10	5.9
39.58	5.7
43.83	5.6
47.69	5.4
52.49	5.4
55.55	5.4
49.58	5.4
45.96	5.4
42.18	5.3
37.14	5.7
33.05	6.0
28.88	6.3
25.18	6.4
20.85	6.4
16.37	6.9
11.65	9.1
7.40	16.1
2.83	71.1

TABLE V

CALCULATED RESULTS
1-INCH GLASS AT 25°C

Reynolds Number $x10^{-3}$	Fanning Friction Factor $x10^{3}$
5.30	13.3
10.28	9.5
15.61	7.8
19.53	7.5
23.45	7.5
29.15	7.4
33.96	6.7
37.73	6.3
42.24	5.8
46.16	5.7
50.23	5.6
55.78	5.5
57.63	5.5
53.19	5.4
48.90	5.6
44.09	5.5
39.73	5.7
35.73	5.9
30.55	6.4
26.85	6.6
22.12	7.1
17.39	7.7
12.72	8.2
7.47	19.1
3.11	40.4

TABLE VI

CALCULATED RESULTS
1-INCH BRASS AT 10°C

Reynolds Number $x10^{-3}$	Fanning Friction Factor $x10^{3}$
3.76	32.2
7.08	13.5
10.40	10.8
13.80	9.6
17.07	9.3
20.45	7.9
21.76	7.8
24.90	6.8
28.25	6.2
30.74	6.0
33.06	5.9
37.16	7.2
40.43	6.0
38.71	5.8
35.32	6.0
32.52	6.2
28.72	6.4
26.64	6.5
23.25	7.1
20.40	7.4
17.12	7.5
13.50	7.5
10.10	10.7
7.08	12.3
3.69	15.1

TABLE VII

CALCULATED RESULTS
3/4-INCH BRASS AT 10°C

Reynolds Number $x10^{-3}$	Fanning Friction Factor $x10^{3}$
4.50	49.8
8.96	15.0
13.42	9.3
17.78	7.4
21.88	6.6
26.80	6.0
26.80	6.0
31.34	5.5
35.10	5.4
39.25	5.2
43.61	5.2
48.30	5.1
49.54	5.0
45.54	5.2
40.99	5.2
37.83	5.3
33.30	5.5
30.00	5.9
28.35	5.9
24.26	5.9
19.94	6.3
15.58	7.0
11.35	8.5
6.98	10.2
2.62	48.8

TABLE VIII

CALCULATED RESULTS
1/2-INCH BRASS AT 10°C

Reynolds Number $x10^{-3}$	Fanning Friction Factor $x10^{3}$
6.55	12.1
12.01	7.4
18.07	6.4
23.50	5.9
29.24	5.6
34.84	5.7
39.12	5.8
45.53	5.4
50.43	5.1
54.74	5.0
59.60	5.1
63.40	5.1
65.51	5.1
58.10	5.1
52.20	5.2
46.60	5.2
41.70	5.5
36.40	5.9
31.70	5.7
26.30	6.0
20.20	6.4
15.10	7.2
9.21	10.1
3.96	26.8

TABLE IX

CALCULATED RESULTS
1-INCH GLASS AT 10°C

Reynolds Number $x10^{-3}$	Fanning Friction Factor $x10^{3}$
3.80	78.2
7.38	22.9
11.10	12.8
14.60	9.7
18.43	7.8
21.72	7.9
25.86	7.0
29.13	6.5
33.28	6.1
36.30	6.0
39.52	5.9
42.9	5.9
38.2	6.0
34.3	6.1
31.7	6.2
25.6	7.6
24.8	7.1
19.7	7.5
16.6	7.9
12.6	9.1
9.0	12.5
5.53	22.5
2.35	85.4

TABLE X

CALCULATED RESULTS
1-INCH BRASS AT 40°C

Reynolds Number $x10^{-3}$	Fanning Friction Factor $x10^{3}$
6.39	18.1
16.9	6.6
21.9	6.3
27.4	6.2
32.4	6.5
35.1	6.5
38.5	6.1
43.6	5.8
47.9	5.5
52.5	5.2
57.6	5.2
63.3	5.1
59.7	5.2
55.3	5.2
50.3	5.2
46.7	5.3
41.0	5.6
36.4	5.9
30.0	5.9
24.2	6.3
19.3	6.3
14.4	7.9
9.0	11.8
3.5	46.7

TABLE XI

CALCULATED RESULTS
3/4-INCH BRASS AT 40°C

Reynolds Number $x10^{-3}$	Fanning Friction Factor $x10^{3}$
8.04	24.4
14.7	10.2
21.7	7.1
28.8	6.0
34.9	5.6
42.0	5.3
43.6	5.4
51.4	4.9
56.5	4.6
64.6	4.6
72.1	4.5
79.0	4.3
82.6	4.5
75.4	4.5
67.4	4.5
60.9	4.5
55.0	4.7
50.9	4.8
42.2	5.2
37.9	5.1
31.2	5.3
24.3	5.8
18.3	6.6
11.6	9.1
4.4	26.8

TABLE XII

CALCULATED RESULTS
1/2-INCH BRASS AT 40°C

Reynolds Number $x10^{-3}$	Fanning Friction Factor $x10^{3}$
5.69	22.4
14.8	8.0
23.9	6.2
33.1	5.4
42.2	5.2
51.1	5.1
59.6	5.1
64.0	5.0
69.0	4.8
79.0	4.6
85.6	4.5
92.8	4.6
103.0	4.6
107.0	4.7
96.6	4.6
88.9	4.6
81.7	4.6
71.2	4.7
54.4	6.9
45.6	5.1
38.3	5.2
27.4	5.6
19.2	6.5
10.9	9.1

TABLE XIII

CALCULATED RESULTS
1-INCH GLASS AT 40°C

Reynolds Number $x10^{-3}$	Fanning Friction Factor $x10^{3}$
6.79	34.6
12.2	14.6
17.9	9.4
23.3	7.8
29.1	6.9
35.1	6.5
38.4	6.1
43.8	5.7
49.9	5.5
55.9	5.4
57.8	5.3
65.6	5.3
60.3	5.3
56.9	5.3
48.5	5.5
43.5	5.6
38.7	6.0
28.5	6.4
22.6	7.1
17.6	7.6
9.34	13.4
3.88	49.7

TABLE XIV

SUMMARY OF DENSITIES AND VISCOSITIES

Temperature, °C	Density,* Pounds/ft^3	Viscosity,** Pounds/ft-SEC*10^4
10	62.59	9.327
25	62.43	7.029
40	62.21	5.881

*Determined on Seederer-Kohlbusch, Inc. balance.

**Determined with Hoeppler falling-ball viscometer.

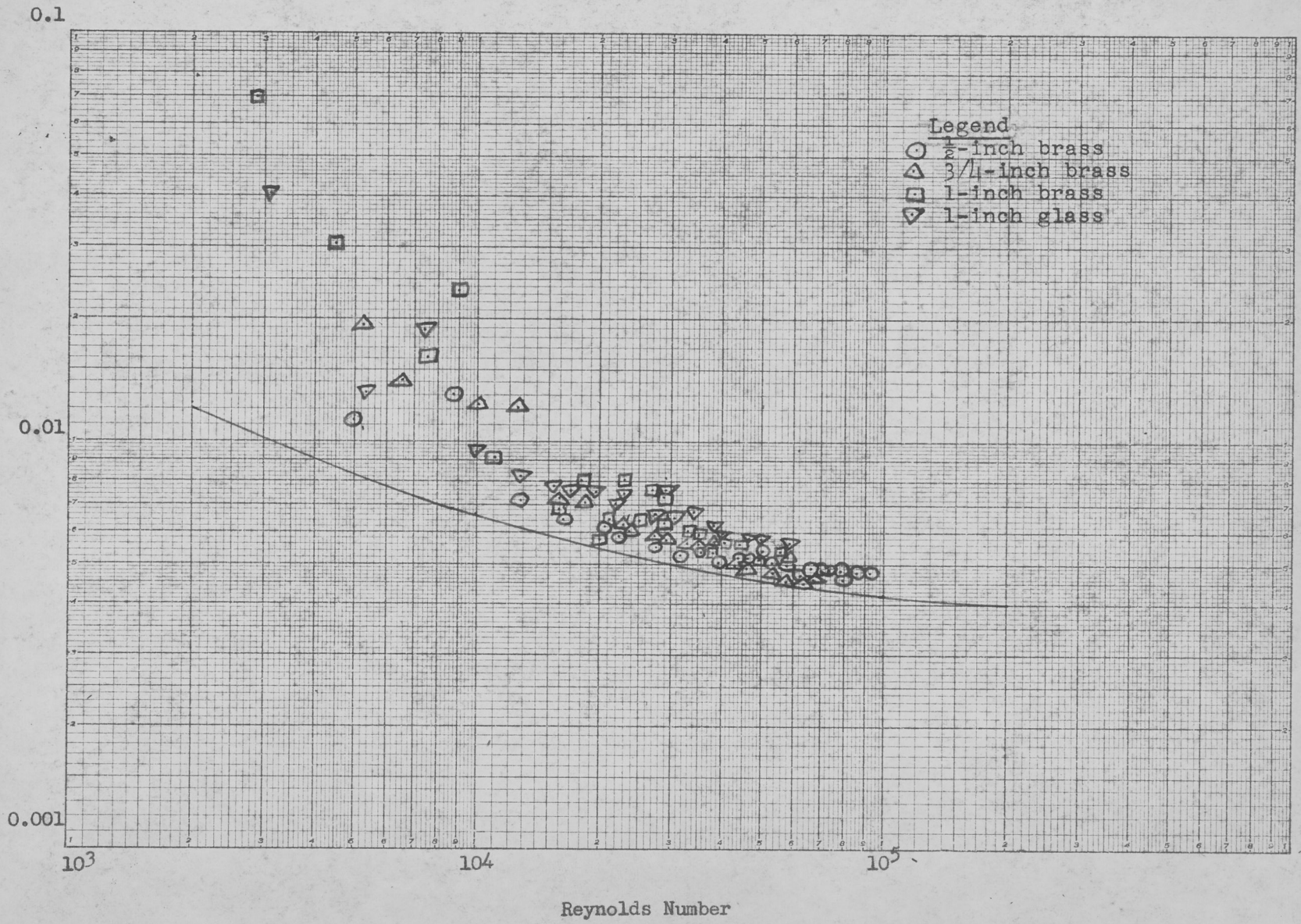


Figure 4. Fanning Friction Factor vs. Reynolds Number at 25°C

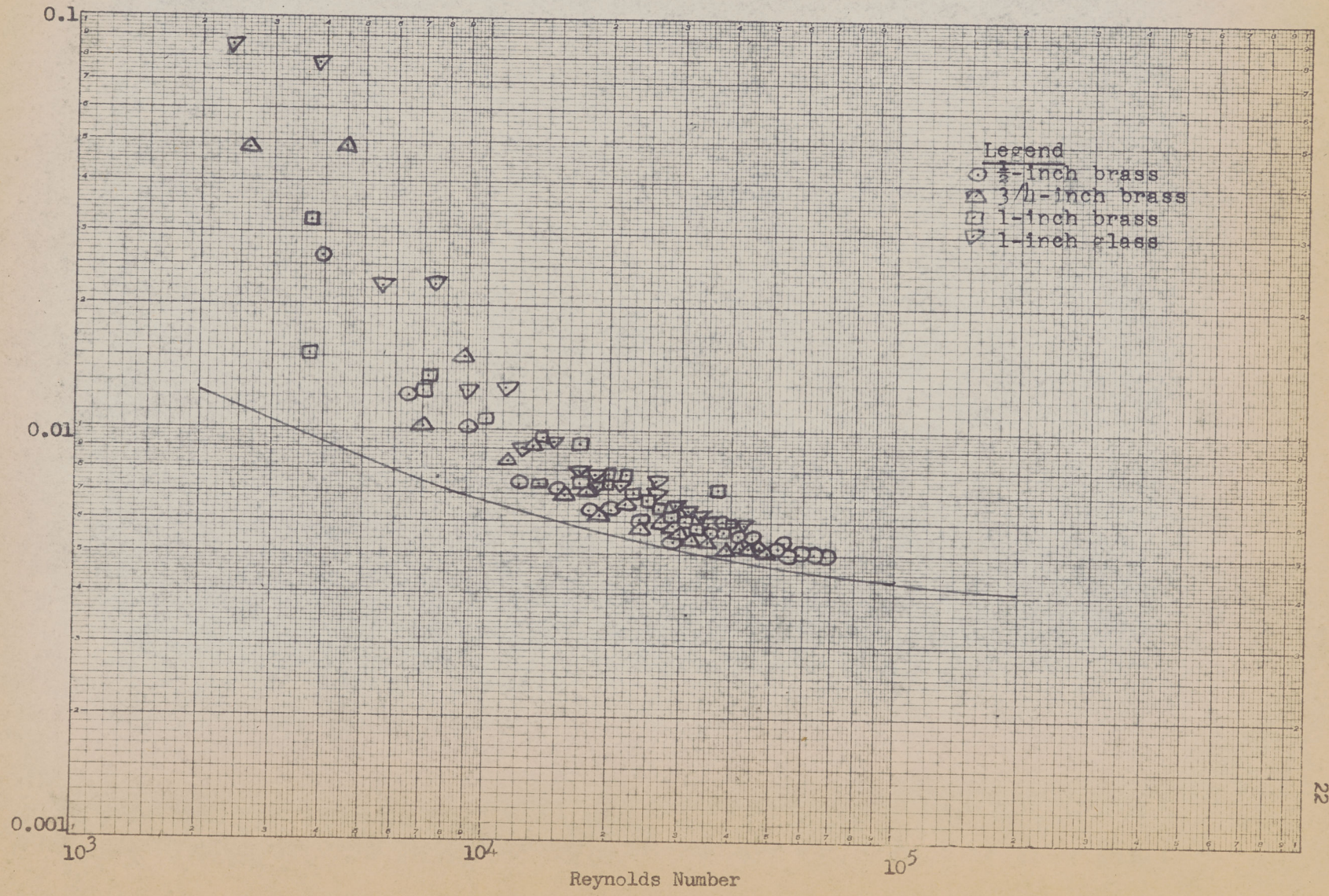


Figure 5. Fanning Friction Factor vs. Reynolds Number at 10°C

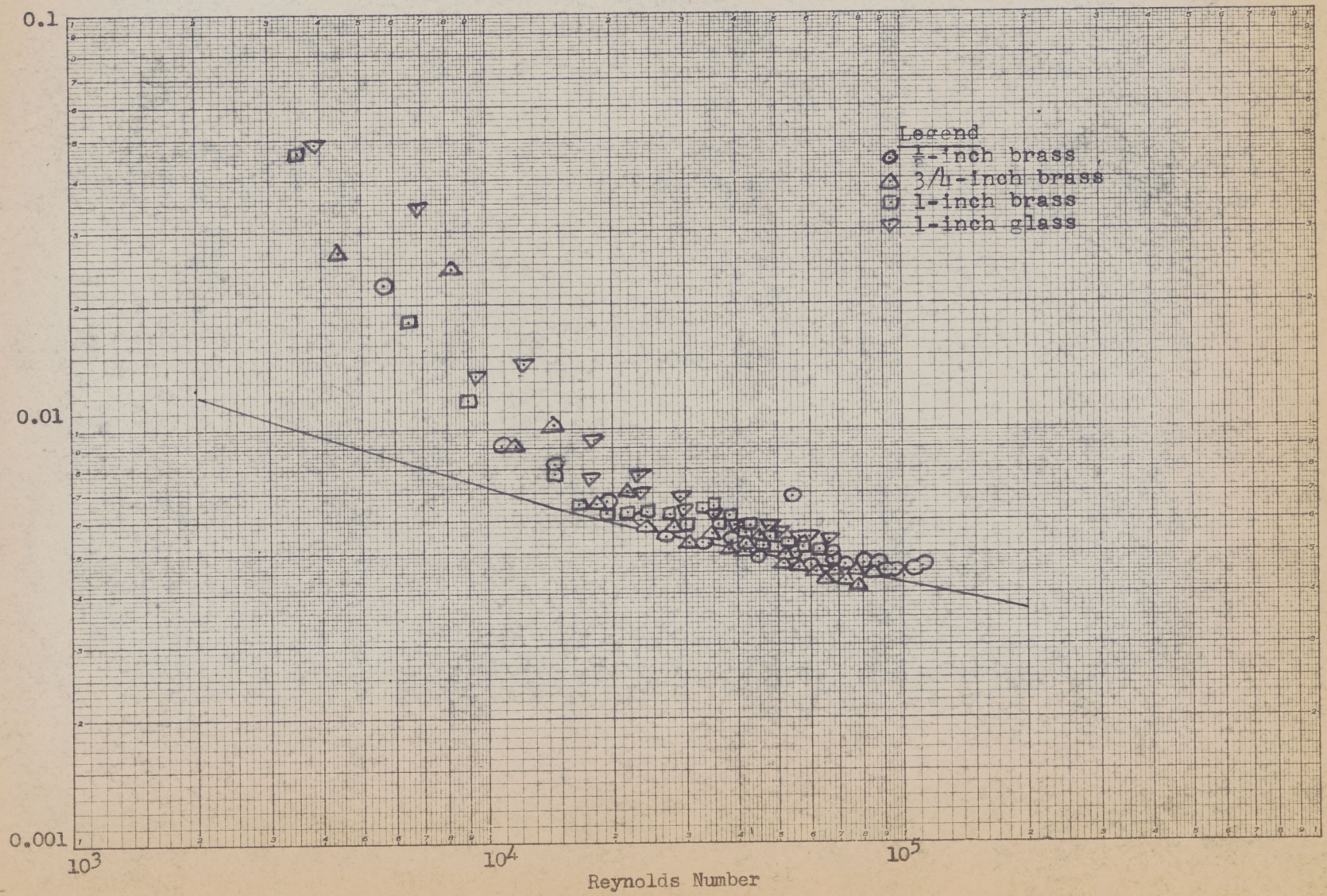


Figure 6. Fanning Friction Factor vs. Reynolds Number at 40^0C

CHAPTER VI

DISCUSSION OF RESULTS

The results generally tend to indicate that some roughness has been added to the inside walls of the pipes during use in previous experiments. This may be due to corrosion of the pipe walls by the milling yellow dye, or it might possibly be caused by remaining deposits of dye inside the test lengths. The results of the runs on the individual pipes seem to fall reasonably close together, and the limit of experimental error does not permit distinguishing one pipe roughness from another.

The correlation appears to account adequately for temperature effects, as no significant differences are observed between runs at different temperature.

However, a very disturbing effect is the sharp upward trend of the friction factors below Reynolds numbers of 15,000. This is in direct contradiction of previously reported data. Although flow and pressure drop measurements were rather uncertain in the low flow range, the consistently high, non-random trends of the data cannot be attributed to random errors in flow rate or pressure drop measurements.

Several reasons may account for the unexpected behavior. The short calming lengths preceding the test sections may possibly be charged with introducing error. Another possibility is the effect of impact pressures on the manometer lead taps. Highly turbulent areas of flow could produce an additional pressure effect upstream which might not be experienced at the downstream tap. Also, the installation of a

pressure tap in the pipe at an angle could cause an error due to impact pressures.

Maung Maung (1) investigated the flow of a Newtonian fluid through the apparatus, and results obtained in this investigation correspond to those produced in Maung's experiment. However, the minimum flows obtained by Maung are at Reynolds numbers of 10,000. Since the major portion of the unexpected behavior encountered during this experiment occurred below Reynolds number of 10,000, no comparisons may be made between results of Maung Maung and this investigation in this range.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

It may be concluded that:

(1) All pipes tested had roughness exceeding accepted values for new, clean, commercial brass pipe;

(2) Friction factors in the glass section tested did not vary noticeably from that of the brass tested;

(3) Friction factors showed positive deviations of up to 1000 per cent from recognized literature values at Reynolds numbers below 15,000.

It is recommended that:

(1) Further investigation of this nature be carried out, utilizing smaller capacity rotameters in order to obtain more accurate flow readings in the low flow range;

(2) The piping system be redesigned, installing longer calming lengths or straightening vanes as a possible remedy for the erratic flow;

(3) Piezometer rings be installed as pressure taps in order to reduce the effect of impact pressure.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. Maung, Maung, Frictional Behavior of A Non-Newtonian Fluid, M. S. Thesis, University of Tennessee, Knoxville (1957).

2. Badger, Walter L., and Julius T. Banchero, Introduction to Chemical Engineering, McGraw-Hill, New York, (1955).

3. Perry, John H., Ed., Chemical Engineers' Handbook, 3rd ed., McGraw-Hill, New York, (1950).

APPENDICIES

APPENDIX A

SAMPLE CALCULATIONS

Consider Run #12, 1-inch brass at 40°C.

1. Rotameter No. 1 reading = 237, Table XXIII.

2. Rotameter No. 2 reading = 243, Table XXIII.

3. Rotameter No. 1 flow = 19.0×10^{-3} ft^3/SEC, Figure 11.

4. Rotameter No. 2 flow = 22.6×10^{-3} ft^3/SEC, Figure 12.

5. Total flow, Item (3) plus Item (4) = 41.6×10^{-3} ft^3/SEC.

6. Velocity through pipe, Item (5)/inside area =

$$\frac{41.6 \times 10^{-3}}{.00616} = 6.75 \text{ ft/SEC.}$$

7. $(\text{Velocity})^2 = (\text{Item (6)})^2 = (6.75)^2 = 45.6$ ft^2/SEC^2.

8. Reynolds number, $\frac{D v \rho}{\mu}$ (Item (6)) =

$$\frac{(.0886)(62.21)}{.00058813} \times 6.75 = 63.3 \times 10^3.$$

9. Left manometer leg reading = 619.10 m.m. oil, Table XXIII.

10. Right manometer leg reading = 389.62 m.m. oil, Table XXIII.

11. Pressure loss, Item (9) - Item (10) =

$$619.10 - 389.62 = 229.5 \text{ m.m. oil}$$

12. Pressure loss, lbs./ft^2, const. x Item (11),

$$\Delta P = \Delta L_{oil} (\rho \text{ oil} - \rho \text{ water})(62.43)(.00328 \text{ ft/m.m.}) =$$

$$(2.95 - 1.00)(62.43)(.00328)(229.5) = 91.7 \frac{\text{lbs.}}{\text{ft}^2}$$

13. $\frac{\text{Item (12)}}{\text{Item (7)}} = \frac{91.7}{45.6} = 2.01 \frac{\text{lb-SEC}^2}{\text{ft}^4}$

14. Fanning friction factor, const. x Item (13),

$$f = \frac{(g_c)(\Delta P)(D)}{2U^2 L \rho} = \frac{(32.2)(.0886)}{(2)(9.00)(62.21)} \times \text{Item (13)} =$$

$$(.00255)(2.01) = 5.13 \times 10^{-3}$$

APPENDIX B

ROTAMETER CALIBRATION

Figures 7 through 12 contain the rotameter calibration for the three temperatures investigated. These curves were obtained by applying the "least squares" statistical method.

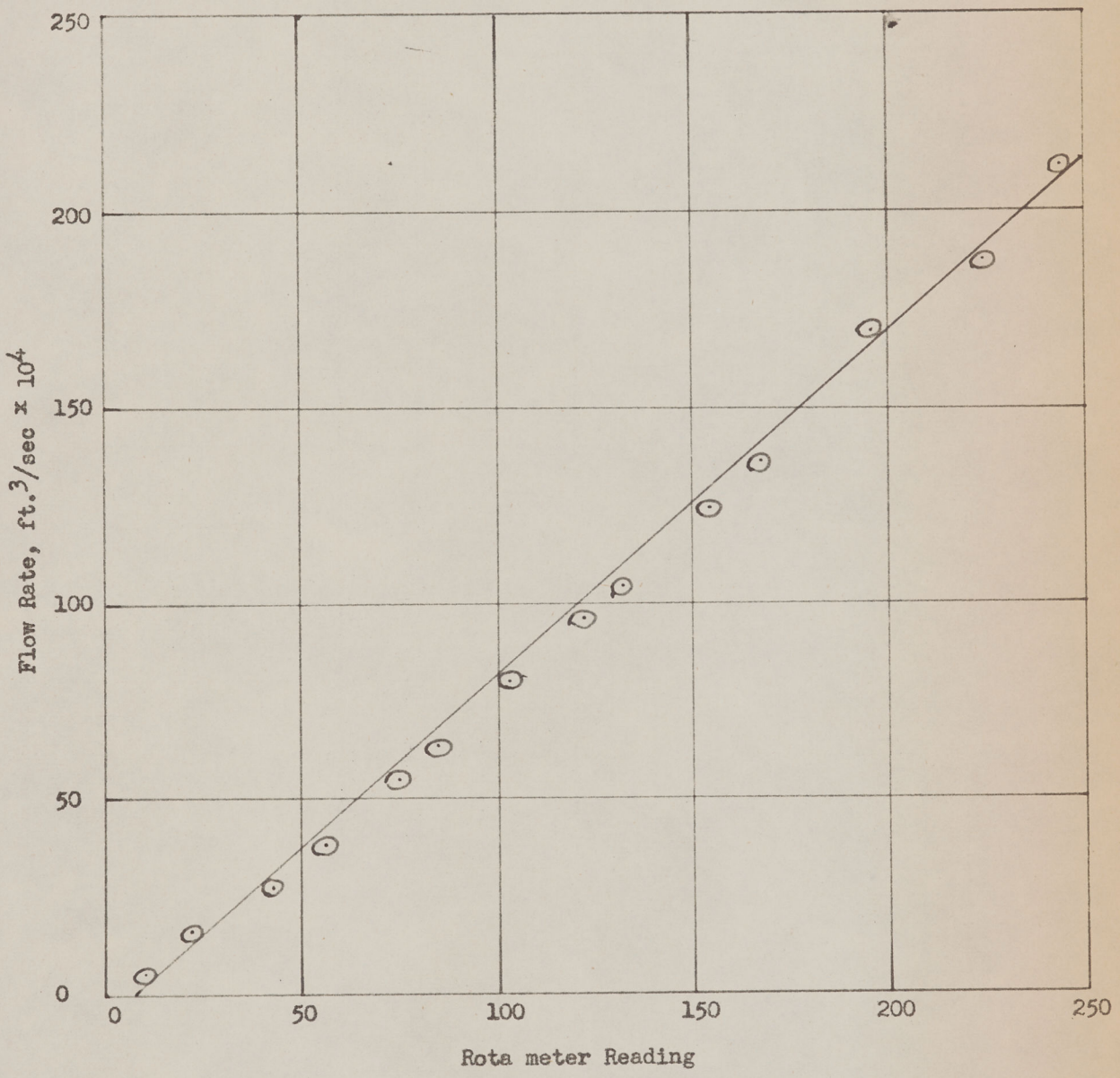


Figure 7. Rotameter calibration curve at 25°C - Rotameter No. 1

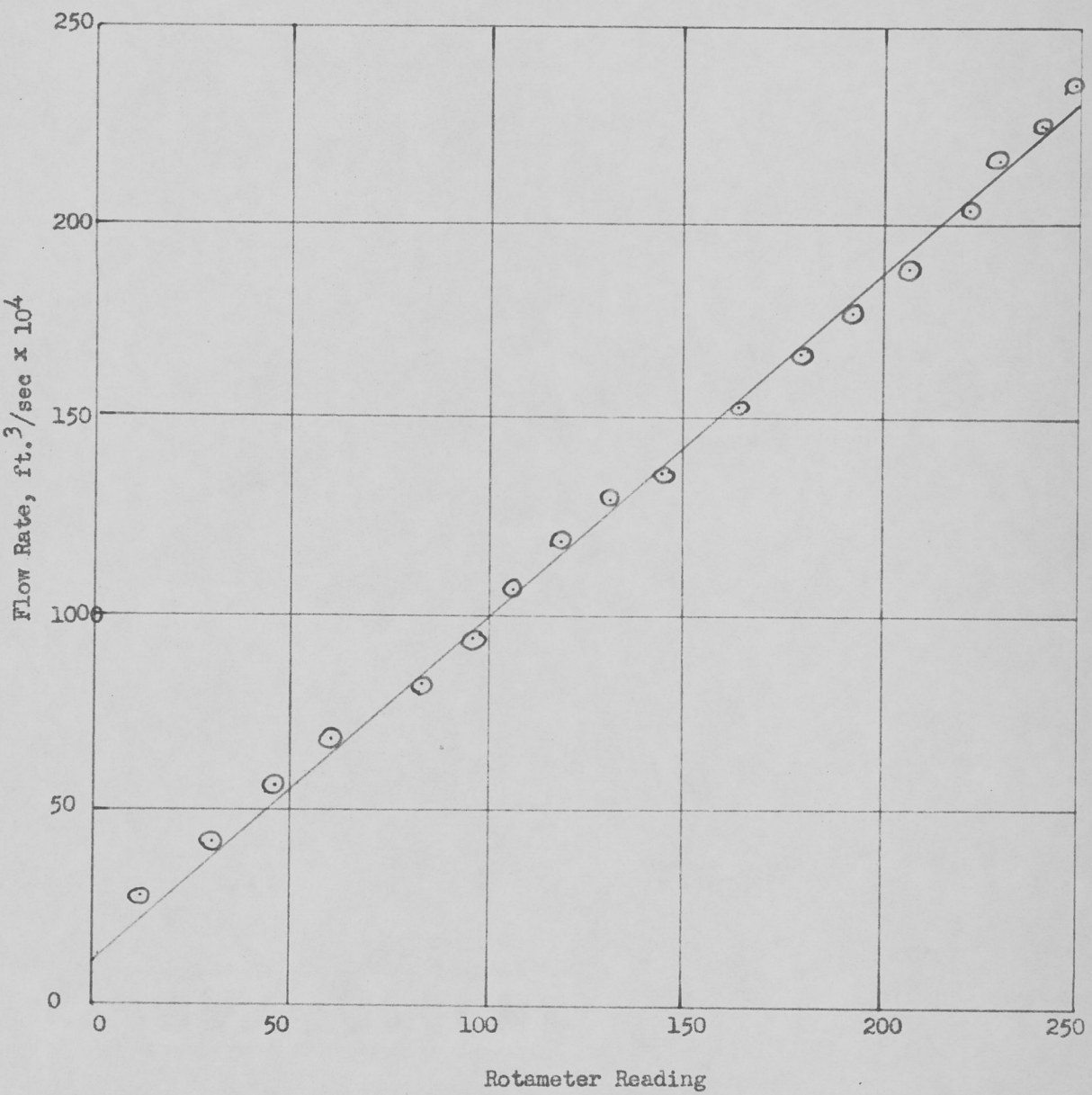


Figure 8. Rotameter calibration curve at 25°C - Rotameter No. 2

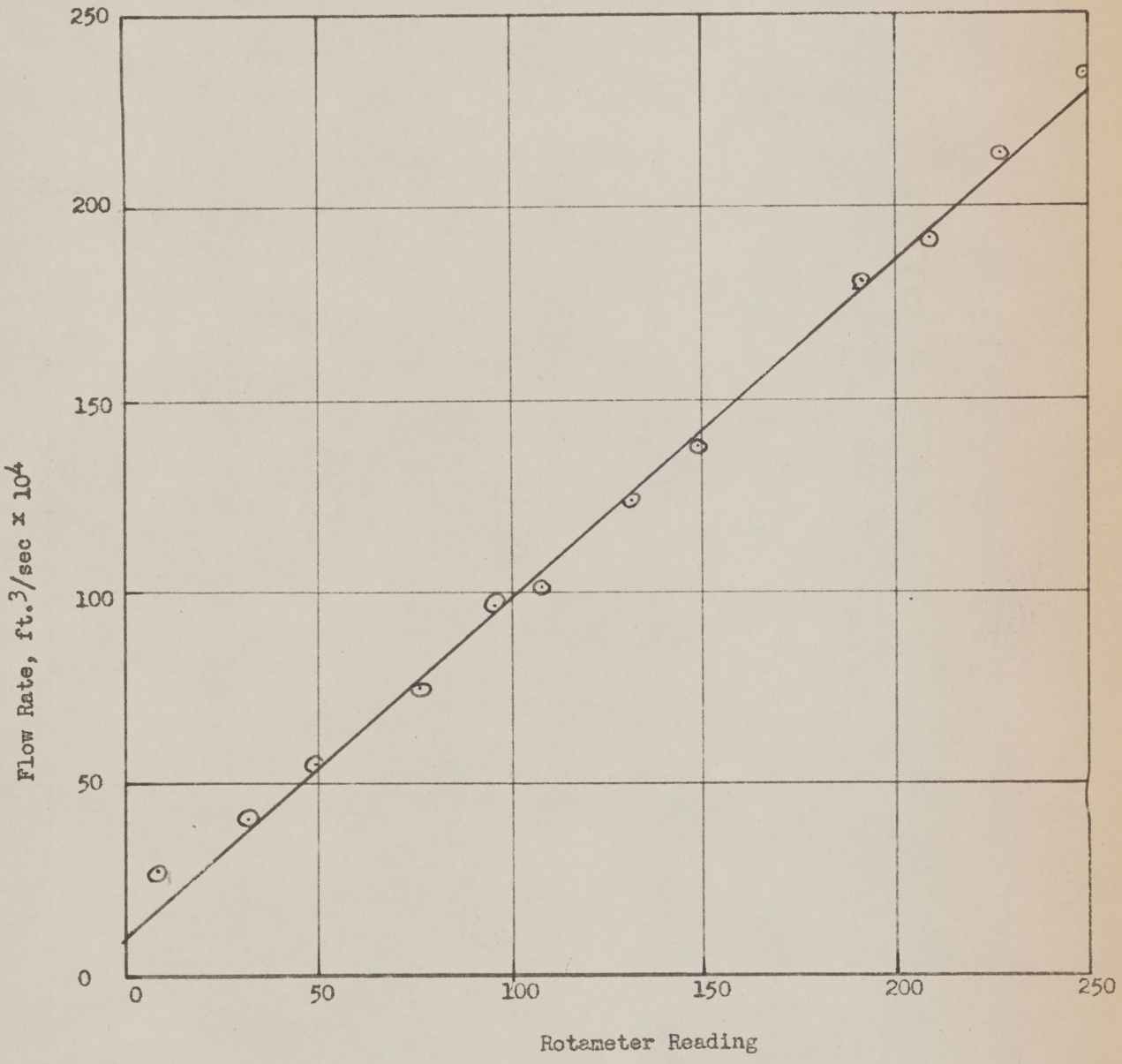


Figure 9. Rotameter calibration curve at 10^0 - Rotameter No.1

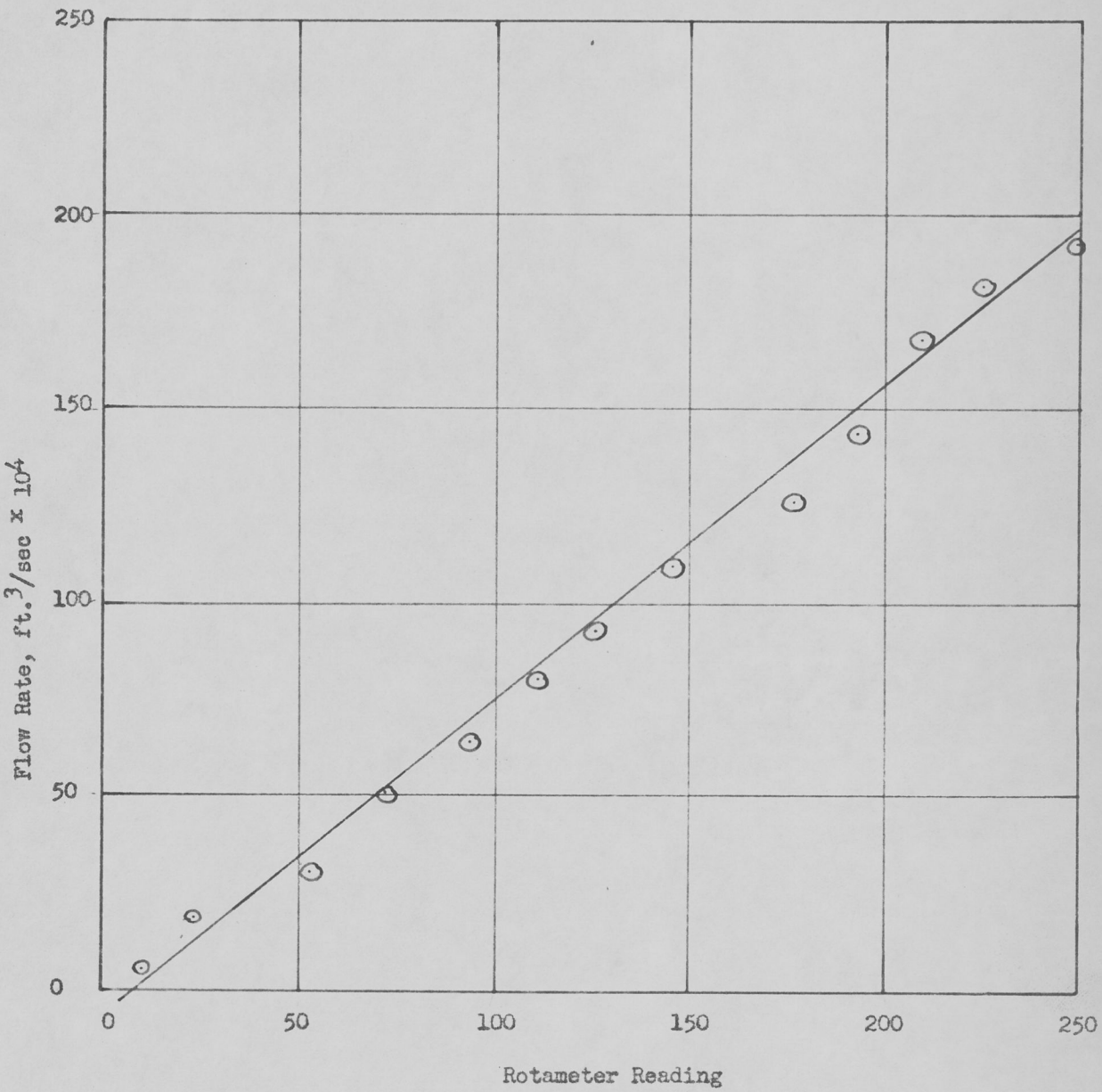


Figure 10. Rotameter calibration curve at 10°C - Rotameter No. 2

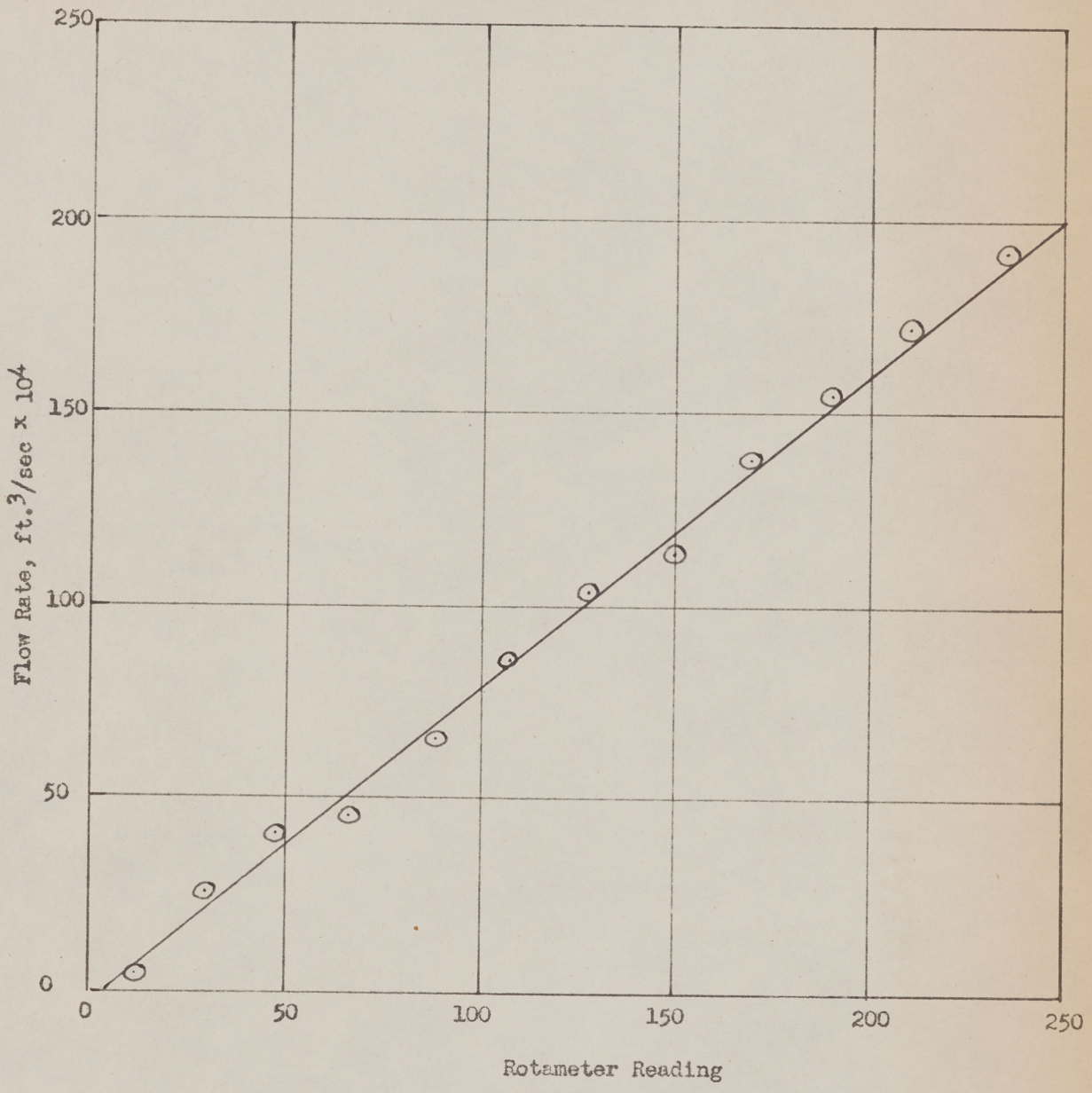


Figure 11. Rotameter Calibration curve at 40°C - Rotameter No. 1

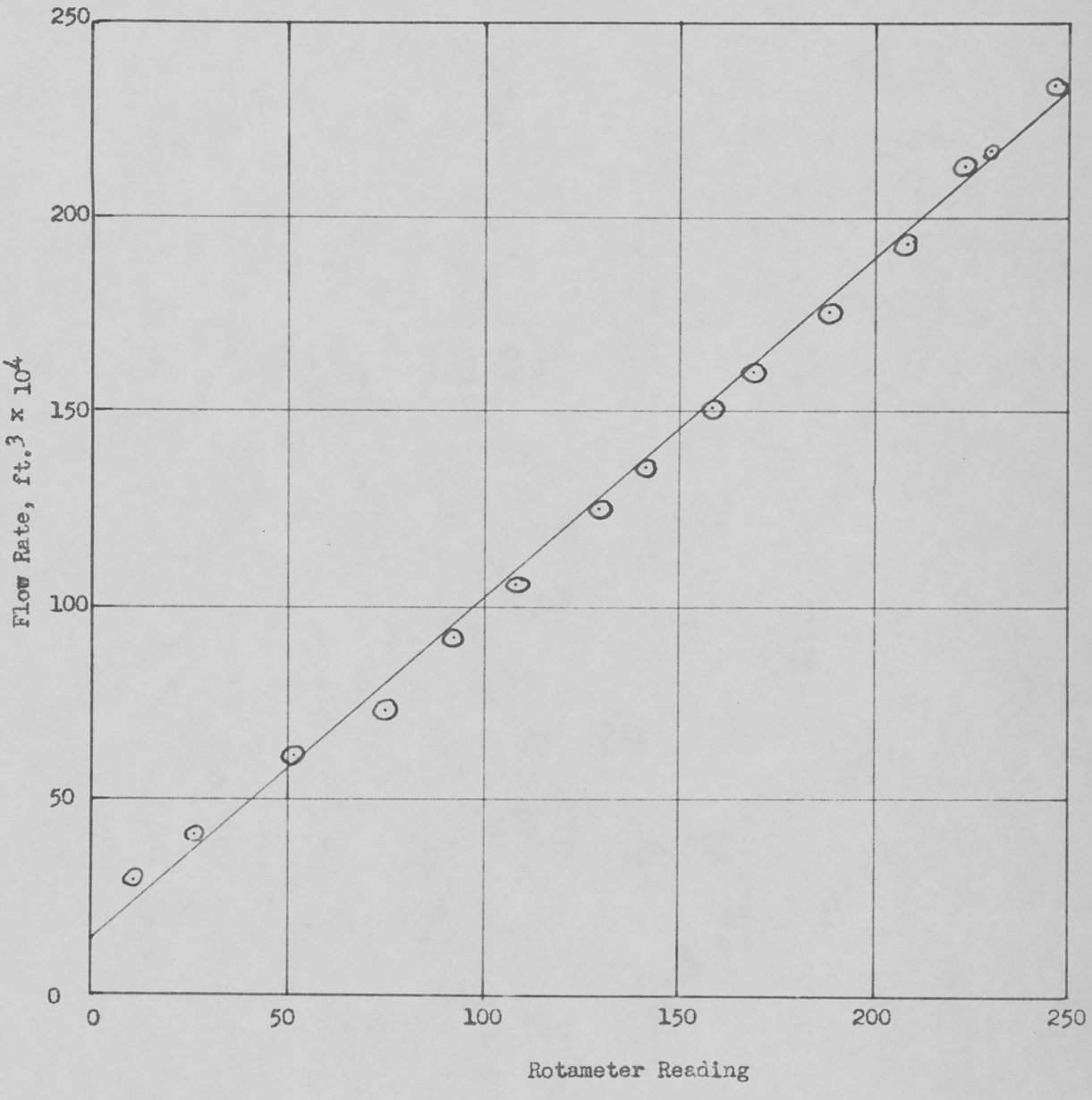


Figure 12. Rotameter calibration curve at 40°C - Rotameter No. 2

APPENDIX C

EXPERIMENTAL DATA

Contained in Tables XV through XXVI is the experimental data obtained throughout the evaluation. Both manometer legs were read in order to eliminate an error which might be produced due to a non-uniform manometer tube. Complete experimental data and calculations are contained in University of Tennessee Chemical Engineering notebook pages 23601 through 23628, deposited with the department at Knoxville.

TABLE XV

EXPERIMENTAL RESULTS - 1/2-INCH BRASS AT 25°C

Rotameter Readings No. 1	No. 2	Manometer Readings, m.m. Left Leg		Right Leg
	10	534.59	oil	507.33
	51	567.96		476.19
	90	620.88		424.72
	130	693.54		348.18
	170	783.37		258.42
	210	558.73	Hg	441.95
	250	584.69		417.00
50	245	604.00		398.62
97	244	628.37		375.26
125	247	651.75		355.37
163	249	680.33		328.51
214	238	719.80		290.47
247	242	754.57		254.54
242	236	743.86		269.00
223	215	701.25		308.75
160	243	674.93		330.27
120	243	644.44		359.68
73	235	607.06		395.78
30	241	591.40		413.15
	228	568.68		434.77
	191	548.08		451.36
	148	717.17	oil	311.62
	103	630.60		394.85
	68	582.24		449.54
	30	548.90		471.57

TABLE XVI

EXPERIMENTAL RESULTS - 3/4-INCH BRASS AT 25°C

Rotameter Readings No. 1	No. 2	Manometer Readings, m.m. Left Leg		Right Leg
	30	501.26	oil	479.81
	70	521.17		456.09
	110	530.17		448.32
	148	549.37		433.10
	187	575.54		405.88
	228	610.59		371.22
38	228	636.50		346.45
82	226	668.84		314.95
121	231	708.43		271.58
165	227	750.45		230.38
204	225	793.19		185.46
243	229	856.48		122.34
248	233	873.92		109.41
220	229	827.79		158.35
181	220	756.69		220.34
141	224	718.49		263.20
93	232	680.04		300.71
61	235	661.35		319.27
	250	631.56		349.76
	230	609.69		370.47
	175	567.76		413.70
	140	545.14		434.85
	96	522.25		456.64
	56	511.76		464.71
	20	498.79		479.64

TABLE XVII

EXPERIMENTAL RESULTS - 1-INCH BRASS AT 25°C

Rotameter Readings		Manometer Readings, m.m.	
No. 1	No. 2	Left Leg	Right Leg
	25	494.44 oil	484.40
	65	503.35	472.31
	105	508.36	469.52
	150	511.76	467.59
	190	522.31	454.28
	230	535.95	443.43
17	230	538.00	439.89
78	228	546.65	431.82
120	229	560.47	417.41
162	228	575.36	403.70
201	225	588.24	391.12
242	230	607.94	372.66
250	250	622.52	358.07
218	225	596.22	384.68
179	230	581.86	399.02
140	232	565.20	414.26
100	225	552.60	426.59
55	231	541.71	438.10
14	231	531.09	447.77
	210	521.78	456.56
	170	512.37	467.93
	130	504.51	475.18
	87	499.62	479.87
	50	482.05	496.03
	8	484.92	494.03

TABLE XVIII

EXPERIMENTAL RESULTS - 1-INCH GLASS AT 25°C

Rotameter Readings No. 1	Rotameter Readings No. 2	Manometer Readings, m.m. Left Leg	Manometer Readings, m.m. Right Leg
	28	485.54 oil	493.48
	70	499.84	478.42
	115	509.60	469.09
	148	519.68	458.47
	182	533.82	446.09
	230	556.28	422.68
45	230	572.32	407.05
78	231	585.60	395.45
120	230	601.06	378.73
160	225	620.90	361.41
198	224	640.78	339.39
240	231	673.98	308.23
247	240	683.97	298.67
221	227	655.18	327.22
180	230	631.66	348.56
142	225	606.83	377.93
100	227	586.09	395.58
62	228	570.36	409.55
17	227	553.00	426.71
	210	540.15	439.38
	170	526.39	452.90
	130	514.28	465.00
	91	503.28	475.12
	46	500.18	477.51
	9	494.37	485.91

TABLE XIX

EXPERIMENTAL RESULTS - 1-INCH BRASS AT 10°C

Rotameter Readings		Manometer Readings, m.m.		
No. 1	No. 2	Left Leg		Right Leg
	30	505.76	oil	493.00
	70	509.76		490.80
	110	515.14		482.54
	150	524.41		473.00
	190	537.69		461.48
	230	545.90		452.69
21	234	551.32		447.59
62	232	558.91		441.28
102	235	568.54		429.68
145	225	580.51		420.61
182	217	590.00		410.32
221	230	614.68		335.70
247	246	637.23		364.51
237	232	624.30		378.13
200	227	605.19		396.04
158	233	592.06		408.75
117	226	573.15		426.70
80	236	565.05		436.19
38	235	553.31		446.56
	228	542.73		456.80
	190	530.80		469.26
	147	518.80		480.34
	106	514.66		484.00
	70	508.31		491.04
	30	502.16		496.51

TABLE XX

EXPERIMENTAL RESULTS - 3/4-INCH BRASS AT 10°C

Rotameter Readings		Manometer Readings, m.m.		
No. 1	No. 2	Left Leg		Right Leg
	27	469.56	oil	530.64
	69	536.18		463.28
	110	550.14		449.14
	150	570.78		428.94
	188	596.10		405.80
	233	630.50		370.65
22	220	633.01		370.00
62	225	665.30		336.37
102	223	700.33		300.62
140	225	743.30		257.02
180	227	796.91		200.00
220	233	862.75		139.76
225	240	870.47		123.61
200	227	824.80		177.14
160	222	760.72		237.73
120	231	730.59		268.57
78	229	685.83		313.50
38	236	661.17		341.07
	248	646.90		357.62
	210	605.42		397.00
	170	575.18		424.80
	129	551.60		448.55
	90	532.12		465.94
	50	515.07		483.02
	10	509.31		489.00

TABLE XXI

EXPERIMENTAL RESULTS - 1/2-INCH BRASS AT 10°C

Rotameter Readings No. 1	No. 2	Manometer Readings, m.m. Left Leg		Right Leg
	32	535.61	oil	464.74
	70	573.55		427.86
	112	644.37		356.48
	150	722.64		275.29
	190	827.40		177.17
	230	398.38	Hg	251.08
40	230	418.32		230.64
80	238	444.85		206.62
120	233	465.75		187.81
162	225	489.00		167.81
200	224	523.59		134.60
212	238	549.82		111.33
242	225	566.80		97.00
181	230	512.20		148.05
140	228	478.15		177.27
98	228	448.77		206.26
60	230	427.84		223.83
18	231	407.57		241.77
	208	890.17	oil	106.75
	170	784.46		217.73
	127	679.02		321.39
	91	614.52		389.26
	50	559.25		442.25
	13	530.16		472.68

TABLE XXII

EXPERIMENTAL RESULTS - 1-INCH GLASS AT 10°C

Rotameter Readings		Manometer Readings, m.m.		
No. 1	No. 2	Left Leg		Right Leg
	28	524.73	oil	482.62
	70	528.08		481.54
	110	534.64		475.86
	150	543.74		466.26
	193	554.53		454.75
	230	575.28		435.92
60	227	593.56		417.37
102	225	610.15		402.38
143	233	634.52		378.83
183	230	654.02		359.24
220	230	677.33		333.23
245	240	707.76		303.90
208	228	671.60		342.65
160	228	640.66		373.17
118	239	623.05		389.23
80	227	600.38		414.00
38	237	588.08		425.00
	207	559.43		451.16
	172	547.14		465.90
	127	533.05		478.75
	87	524.59		486.79
	48	518.41		492.50
	12	515.16		497.19

TABLE XXIII

EXPERIMENTAL RESULTS - 1-INCH BRASS AT 40°C

Rotameter Readings No. 1	No. 2	Manometer Readings, m.m. Left Leg	Right Leg
	30	508.75 oil	500.49
	110	515.04	494.07
	148	521.78	488.00
	190	530.18	478.08
	228	542.49	466.84
21	232	548.38	458.57
50	231	554.70	453.88
90	233	565.84	442.12
129	228	573.30	433.43
168	226	584.18	422.65
213	223	600.16	407.72
237	243	619.10	389.62
227	226	606.31	401.00
190	227	591.91	415.37
147	229	576.00	430.00
111	236	567.02	439.00
72	230	555.67	449.90
28	235	546.36	459.30
	210	532.11	473.29
	166	523.19	481.96
	129	515.81	489.49
	92	511.61	493.30
	50	507.56	497.00
	7	505.38	499.00

TABLE XXIV

EXPERIMENTAL RESULTS - 3/4-INCH BRASS AT 40°C

Rotameter Readings		Manometer Readings, m.m.		
No. 1	No. 2	Left Leg		Right Leg
	29	521.75	oil	483.75
	68	529.17		475.52
	110	543.51		462.27
	151	562.26		443.00
	188	586.15		421.06
	229	616.58		390.11
18	227	627.79		379.83
60	232	661.00		345.78
102	222	682.72		323.64
147	227	732.89		271.49
195	227	786.41		219.69
231	234	827.82		178.34
249	239	877.79		129.47
210	231	807.18		196.55
164	228	746.18		256.55
127	223	704.29		299.70
87	227	673.72		331.94
52	235	653.28		352.22
10	225	615.45		390.41
	205	592.11		413.64
	165	564.79		440.00
	125	544.08		461.16
	89	529.24		475.86
	50	516.51		487.02
	6	507.94		495.79

TABLE XXV

EXPERIMENTAL RESULTS - 1/2-INCH BRASS AT 40°C

Rotameter Readings		Manometer Readings, m.m.		
No. 1	No. 2	Left Leg		Right Leg
	6	521.74	oil	482.22
	47	550.59		454.45
	88	599.96		406.29
	130	665.45		340.12
	171	756.67		245.75
	210	870.00		137.05
	248	404.29	Hg	248.34
42	233	414.83		239.81
61	236	424.42		228.58
103	240	450.53		205.71
143	233	471.83		190.37
183	226	499.03		165.81
220	236	537.78		126.32
230	247	562.05		107.91
201	227	513.43		150.73
158	233	484.89		178.67
123	235	459.76		200.23
80	227	429.18		225.31
	225	388.33		263.31
	186	793.73	oil	210.66
	153	704.50		293.31
	104	618.78		387.06
	67	567.41		437.50
	30	531.35		472.87

TABLE XXVI

EXPERIMENTAL RESULTS - 1-INCH GLASS AT 40°C

Rotameter Readings No. 1	No. 2	Manometer Readings, m.m. Left Leg		Right Leg
	30	514.54	oil	490.78
	68	518.25		486.78
	110	525.00		480.03
	148	534.29		471.70
	190	546.28		458.91
	233	562.33		443.89
40	222	569.23		435.77
80	223	584.18		420.18
120	230	606.09		401.26
155	240	628.67		377.59
188	222	635.04		371.39
228	240	673.46		333.72
202	227	645.42		359.65
160	242	630.18		375.04
117	222	599.88		405.46
77	223	582.23		423.78
36	228	568.90		434.76
	185	540.45		462.95
	144	528.48		474.23
	108	519.18		483.76
	49	510.36		492.94
	9	507.87		496.67

APPENDIX D

NOTATION

Symbol	Meaning
f	Fanning friction factor
Pf	Pressure loss due to friction
U	Mean flow velocity through the pipe section under investigation
ρ	Fluid density
L	Pipe length
D	Pipe diameter
gc	Force-mass conversion constant
N_{Re}	Reynolds number
μ	Viscosity of the fluid

APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by this approval the undersigned does not necessarily endorse or approve any statements made, opinion expressed, or conclusion drawn therein, but approves the thesis only for the purpose for which it is submitted.

Name John W. Prados

Title Assistant Professor

Date May 30, 1958