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A STUDY OF WATER FLOW IN NON-WETTED TEFLON TUBES

By

SAMI I. ATALLAH

A STUDY OF
WATER FLOW IN NON-WETTED
TEFLON TUBES

by

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A THESIS

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June 1, 1954
(Date)

Louis Maus Jr.
Professor in Charge

Alan S Foust
Head of the Department

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ABSTRACT

This report presents the results of an investigation on the flow of water in non-wetted teflon tubes. Three teflon tubes of nominal diameters 3/8", 3/4" and 1 1/4" were used. The pressure drop across a certain length of each was found and the friction factor calculated at different flow rates. Upon comparing the friction factors obtained in this investigation with published data for smooth wetted tubes at the same Reynolds numbers, it was found that the friction factors in the case of non-wetted tubes were higher than those of wetted tubes. The values approached those of wetted tubes as the diameter became larger. The high values of friction factors under non-wetted conditions were attributed to the entrainment of air bubbles in the liquid stream which tend to increase the roughness of the tube and reduce its effective diameter.

An effort was made to explain some of the anomalies found in heat transfer from molten metals under wetting and non-wetting conditions using some of the observations noted above.

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INTRODUCTION

Development and Purpose of Investigation

During the past decade, chemical engineering research workers found a comparatively new line of interest. Non-wetted surfaces have attracted their attentions primarily in the field of drop-wise condensation and more recently in the field of heat transfer to molten metals.

This project was originally concerned with drop-wise condensation. It was thought that an exploratory study of fluid flow might reveal a difference between the characteristics of flow in wetted and non-wetted tubes.

Water-teflon system was chosen for this investigation because of the following reasons :

1. The expense of materials required for the construction of such a system is much less than a system for molten metals or mercury.
2. Easiness of construction and handling.
3. Water hardly wets teflon since the contact angle between the two is 108°.(Ref. 3)

It was desired to compare the Fanning friction factors obtained by pressure drop measurements across the non-wetted teflon tube with the published data on friction factors at the same Reynolds numbers for wetted metallic and glass tubes.

THEORETICAL BACKGROUND

A great deal of theoretical and experimental work has been devoted to the flow of fluids in pipes. Yet, it seems that most of this work has been confined to the flow of fluids which wet the walls of the carrying pipe.

The equations governing the flow of wetting liquids in circular pipes have been well established. A fluid moving at a sufficiently small Reynolds number such that it flows in paths parallel to the walls of the tube is said to be in laminar motion. Hagen and Poiseuille developed the following equation for laminar flow:

$$f = \frac{16}{Re}$$

where

$$f = \frac{\pi^2 \rho \, g_c D^5 \Delta P}{32 \, L \, w^2} \quad \text{(Fanning friction factor)}$$

$$Re = \frac{V D \rho}{\mu} \quad \text{(Reynolds dimensionless number)}$$

ρ = density of fluid.

g_c = conversion factor.

D = diameter of the pipe.

ΔP = pressure drop across the pipe.

L = pipe length.

w = weight flow rate.

V = linear velocity.

μ = the viscosity of the fluid.

At higher Reynolds numbers, where the fluid flows in an irregular manner in the tube, the Hagen - Poiseuille equation was found not to apply. Several authors collected all published experimental data for the turbulent region and thus developed equations relating f and Re.

$$f = .00140 + \frac{.125}{Re^{.32}} \quad \ldots\ldots\ldots\ldots \text{ Koo (Ref. 6)}$$

$$\frac{1}{\sqrt{f}} = 4.0 \log_{10} Re\sqrt{f} - 0.40 \quad \ldots\ldots \text{ von Karman (Ref.12)}$$

The early work done on fluids non-wetting the sides of the tube was conducted primarily to study the theory of slip and for viscosity determinations.

Poiseuille (Ref. 8) studied the flow of mercury in capillary tubes. He found that the rate of flow of mercury depended on the diameter of the tube, while for water and ether the flow varied as the square of the diameter. He also noticed that the data for mercury was scattered and irregular and he attributed that to non-wetting and to the possible separation between the mercury and glass tube by a layer of entrained air or foreign liquid.

Warburg (Ref. 13) and Whetham (Ref. 14) could not detect any slip of water on silvered glass or mercury on glass respectively.

Jul Hartmann (Ref. 5) conducted experiments in order to compare the flow of water and mercury flowing in steel and glass tubes. He obtained higher friction factors for mercury at high Reynolds numbers (>30000). His data was more scattered for mercury than water, and these effects were more pronounced in tubes of smaller diameters. He found also that the mercury values became less scattered and approached the normal values when the tubes were cleaned, polished and smoothed. He gave the following explanation for these irregularities:

> "I hold the opinion that this is due to the mercury not wetting the wall of the tube. On account of this property the flow in the neighbourhood of the wall will, undoubtedly, largely depend on the adhesion to the wall, and said adhesion is certainly a poorly defined quality, unless particular and well-nigh impracticable precautions are taken. The want of definiteness of the flow with mercury is well known to me from numerous experiments with jet-holes of various shapes."

The most recent work on slip was conducted by Tolstoi (Ref.10) who did some theoretical and experimental (Ref. 11) studies on the flow of mercury in very thin glass capillaries. He found that slip could be considerable in very thin tubes however, for practical purposes, slip could be neglected, which is in agreement with Goldstein's conclusions. (Ref. 4).

During the past few years, considerable work has been done on heat transfer to molten metals. Studies under wetting and non-wetting conditions revealed great irregularities between the results of different workers. A non-wetted surface was found to offer a greater resistance to heat transfer (and a greater electrical resistance) than a wetted surface. The three theories offered to explain these facts were presented and discussed by Messrs. Macdonald and Quittenton (Ref. 7) however they will be summerized below:

1. The surface gas and oxide film theory: in which a very thin layer of chemisorbed and adsorbed gas layers are formed on the surface as well as a possible metal oxide layer, all of which contribute towards increasing heat transfer resistance. Macdonald and Quittenton discarded this theory because the required thickness of such layers was beyond general expectation.
2. The gas entrainment theory: It was found by several investigators that the presence of small quantities of entrained gas in the liquid metal increased the resistance to heat transfer. Macdonald and Quittenton adopted this theory as the best possible explanation stating further that:

   > "The presence of small amounts of gas bubbles in the common heat transfer liquids such as water does not ordinarily affect their heat transfer properties in turbulent flow to any great extent, since such liquids depend wholly on convective or eddy transfer of heat. In metallic liquids however, a significant portion of the heat transferred by both electron and molecular conduction, which would be inhibited by intervening gas bubbles."

3. The local detachment theory: In their recent work at the University of Tennessee, Stromquist and his associates (Refs. 9 & 1) found that the erratic heat transfer data sometimes observed in non-wetted systems was due to random local detachments of the liquid from the tube wall.

They also found that these detachments were a function of the pressure head within the fluid. In a more recent report, however, Boarts et al (Ref. 2) showed that these detachments were actually due to entrained gas. It was also found that mercury had the ability of entraining large amounts of air especially when splashing or a vortex occurs in the mercury reservoir.

The last two theories are of particular importance in this investigation. Although the theories of entrained gas and local detachment were forwarded primarily to explain the irregularities in heat transfer to non-wetting molten metals, they could also be applied to other fluids which do not wet the wall of the conducting pipe. It could be easily seen that if such bubbles are present in the fluid, the bubbles will try to float by the force of buoyancy. If the fluid is moving at a sufficiently low flow rate, the bubbles will tend to float towards the upper surface of the tube and will stay there until the driving force of the moving liquid overcomes the friction force between the bubbles and the surface. The presence of these bubbles not only will hinder the flow because of increased roughness, but will also reduce the effective diameter of the tube.

****

DESCRIPTION OF APPARATUS

A diagram of the flow system is shown in Figure 1. The apparatus used in this ivestigation consisted of an elevated reservoir which received water from a ground reservoir by means of a pump. The over-head tank was allowed to maintain a constant head of about 15 ft. by means of an overflow pipe. Water was allowed to flow down from the over-head reservoir through the tested tube. This consisted of two parts: a calming section of 50 diameters length and the test section. A gate valve placed at the outlet of the test section was used to regulate the flow, which in turn was measured by a Fisher and Porter rotameter. The arrangement as shown in Figure (1) insured that the water filled the tested tube.

A water-over-carbon tetrachloride manometer was attached to the pressure taps. The pressure taps are shown with the bleeding setup in Figure (2).

In drilling pressure tap holes through the tested tubes, care was taken to remove drill shavings and dents inside the tube to prevent any undue turbulence.

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FIGURE (1)

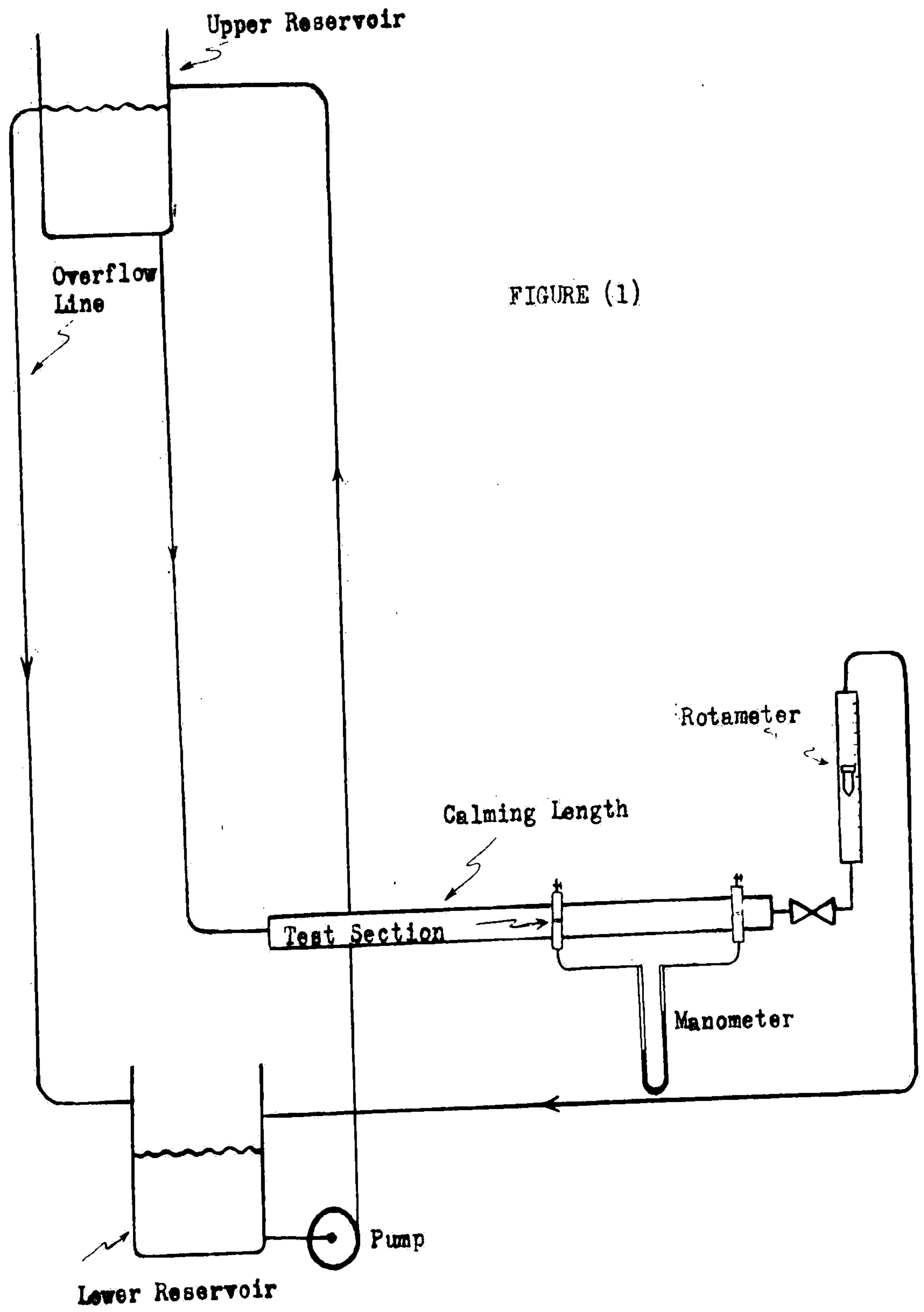

Figure 1. Flow Diagram of Apparatus

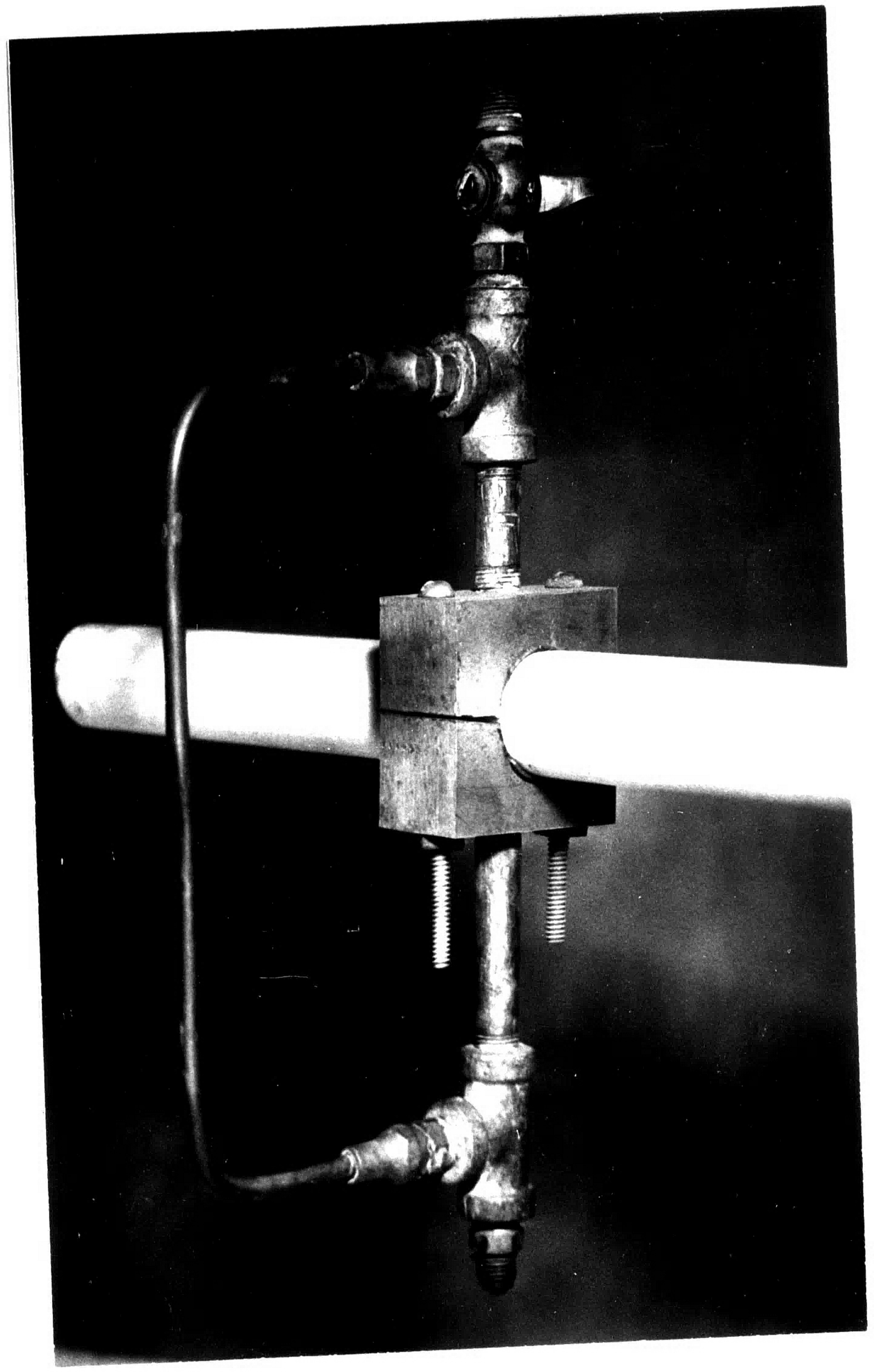

Figure 2. Pressure taps and bleeding setup.

TABLE I

DIMENSIONS OF TUBES

(All lengths in inches)

	I	II	III	IV
Material	Teflon	Teflon	Teflon	Copper
Total length	71	72	96	85
Calming length	20	34	60	30
Tested length	48	32	30	48
Actual I.D.	0.372"	0.721"	1.228"	0.522
Nominal I.D.	3/8"	3/4"	1 1/4"	***
Nominal O.D.	1/2	1	1 11/16	**
Actual O.D	0.516	1.032	1.723	

Note: Teflon tubes were obtained from Ethylene Corp.

****

CALIBRATION OF INSTRUMENTS

The rotameter used in this experiment to measure the flow rate was calibrated with two home-made floats. A calibration chart is shown in Figure 7 .

The temperature of water was measured from time to time and was found to be about 25°C and was practically constant during the runs.

****

EXPERIMENTAL PROCEDURE

The overhead reservoir was first filled with water and allowed to overflow in order to maintain a constant head of about 15 ft. of water. Water was then allowed to flow through the tested tube by opening the gate valve to the desired flow rate. After bleeding the manometer taps the manometer and rotameter readings were recorded. This procedure was used for tubes I, II and IV. However in the case of the large tube, the flow was not high enough to obtain any readings on the manometer. The tube was then connected directly to the main city water line and the flow was regulated with a valve at the inlet because the pressure was very high and in some instants broke the teflon-iron pipe connections. The city line was also used to obtain high flow rates on tube II.

At certain points of the experiments, the gate valve in the apparatus was transferred to the inlet of the tested tube, thus reducing the head to about 3 ft. which is the height of the attached rotameter and its connections.

In all cases, readings were taken at random. The experimental data is listed in the appendix in the same order it was taken and the calculated results are listed correspondingly.

The tubes were cleaned from time to time.

TABLE II

CALCULATED RESULTS

The following are the calculated values for the Reynolds number and the friction factor with the corresponding values of flow rate and pressure drop in inches of carbon tetrachloride under water, for the teflon tube of 3/8" nominal I.D.

Flow rate lb./min.	Pressure drop in inches	Reynolds No.	Friction factor
9.8	22.35	11180	.0114
9.2	20.10	10500	.0116
8.5	17.45	9700	.0118
7.55	14.40	8600	.0123
7.5	13.92	8550	.0121
7.2	13.22	8200	.0123
6.5	11.02	7400	.0127
5.9	9.55	6720	.0134
5.25	7.65	6000	.0135
4.5	5.92	5130	.0142
3.95	4.47	4500	.0139
9.5	21.00	10800	.0114
8.8	19.58	10000	.0117
8.2	16.05	9350	.0116
7.55	14.15	8600	.0121
6.85	12.08	7800	.0125
6.25	10.28	7120	.0128
5.5	8.25	6260	.0133
4.85	6.71	5530	.0139
4.25	5.35	4850	.0145
3.2	3.23	3650	.0154
2.97	2.77	3380	.0153
3.85	4.40	4380	.0145
4.6	5.98	5250	.0138
5.95	9.28	6780	.0128
7.25	13.11	8250	.0122
8.5	17.19	9700	.0116
9.8	22.25	11180	.0113
9.85	22.35	11230	.0112
10.45	24.36	11800	.0108
2.32	1.50	2642	.0136
2.63	2.22	3000	.0157
3.03	2.76	3450	.0146

TABLE II (Contd.)

Flow rate lb./min.	Pressure drop in inches	Reynolds number	Friction factor
3.6	3.75	4100	.0141
4.2	5.09	4790	.0140
4.85	6.63	5530	.0137
5.6	8.29	6380	.0129
6.25	10.15	7120	.0126
6.85	12.10	7800	.0125
7.55	14.19	8600	.0121
8.20	16.46	9350	.0119
8.85	19.03	10100	.0119
9.5	21.33	10800	.0115
10.2	23.90	11600	.0113
10.4	24.56	11850	.0110
1.25	.61	1425	.0190
1.63	.82	1850	.0152
2.0	1.00	2280	.0122
2.43	1.60	2760	.0132
2.63	2.20	3000	.0156
3.2	3.20	3650	.0152
4.6	6.05	5250	.0139
4.6	5.93	5250	.0137
3.85	4.50	4390	.0148
3.25	3.33	3700	.0154
2.63	2.18	3000	.0155
1.98	1.02	2260	.0127
1.25	.60	1425	.0188
1.77	.88	2020	.0137
1.55	.74	1770	.0151
2.2	1.19	2510	.0120
2.55	1.95	2910	.0147
8.55	17.48	9750	.0116
1.25	.54	1425	.0168
1.91	1.05	2180	.0140
2.63	2.20	3000	.0156
3.9	4.58	4450	.0146
5.2	7.65	5930	.0138
5.25	7.75	5990	.0137
6.65	11.65	7580	.0128
8.0	15.89	9100	.0121
9.25	20.62	10550	.0118
9.8	23.21	11180	.0118
9.95	23.58	11350	.0116

****

TABLE II A

CALCULATED RESULTS

The following are the calculated values for the Reynolds number and the friction factor for the teflon tube of 3/8" nominal I.D. with the gate valve at the inlet.

Flow rate lb./min.	Pressure drop in inches	Reynolds number	Friction factor
2.54	1.91	2920	.0145
3.18	3.15	3650	.0152
3.85	4.55	4410	.0150
4.50	5.69	5150	.0137
5.35	7.81	6150	.0133
6.35	10.51	7280	.0127
7.55	13.76	8650	.0118
9.20	19.85	10500	.0115
9.80	22.45	11200	.0114
1.70	.90	1950	.0152
1.32	.68	1510	.0191
2.32	1.40	2660	.0127
2.70	2.26	3100	.0158
2.50	1.90	2870	.0149
8.85	19.04	10100	.0119
5.30	7.90	6080	.0137
9.55	22.28	10900	.0119
3.10	3.10	3550	.0158

****

FIGURE (3)

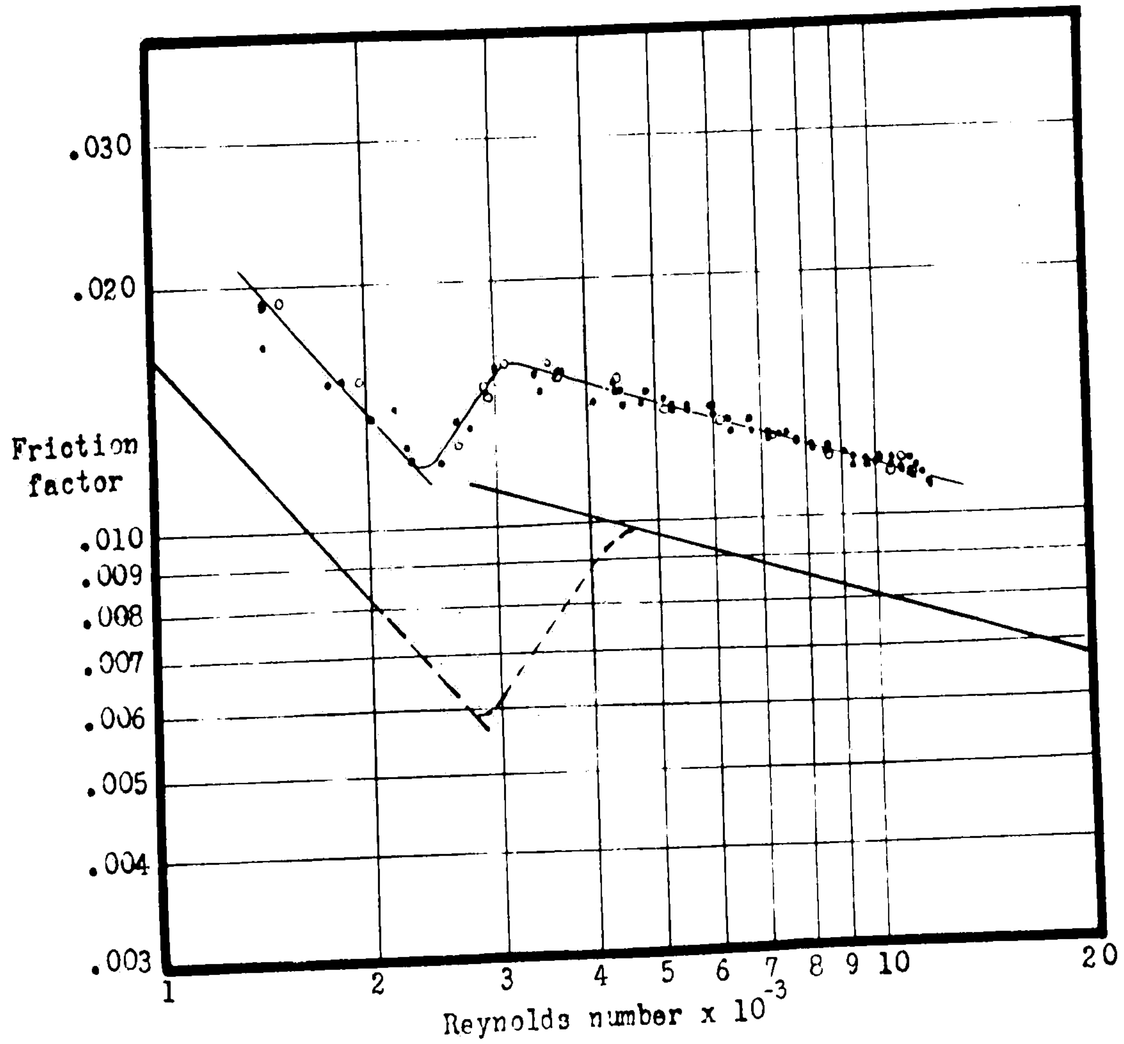

Figure 3. Friction factor Vs. Reynolds number for the teflon tube of nominal 3/8" I.D.

Legend: • with valve at outlet.

○ with valve at inlet.

TABLE III

CALCULATED RESULTS

The following are the calculated values of the Reynolds number and the friction factor for the teflon tube of 3/4" nominal I.D. with the gate valve at the outlet of the tube.

Flow rate lb./min.	Pressure drop in inches	Reynolds number	Friction factor
5.3	.18	3600	.0130
12.85	.89	7500	.0110
9.1	.51	5320	.0125
7.3	.32	4275	.0122
13.5	.99	7900	.0111
17.3	1.36	10100	.0092
15.75	1.18	9200	.0097
11.35	.78	6650	.0123
8.35	.43	4900	.0125
13.1	.91	7670	.0108
4.8	.19	2820	.0167
12.75	.88	7470	.0110
9.0	.50	5270	.0125
16.25	1.30	9500	.0100
16.55	1.33	9700	.0099
6.0	.24	3520	.0135
17.25	1.49	10100	.0102
11.2	.75	6550	.0121
3.9	.12	2290	.0160
10.85	.60	6350	.0104
15.25	1.22	8920	.0106
8.2	.42	4800	.0127
14.75	1.11	8650	.0104
11.3	.71	6620	.0113
8.25	.42	4850	.0125
4.65	.16	2730	.0151
10.2	.59	5970	.0115
5.65	.23	3310	.0146
18.	1.77	10500	.0111
17.4	1.58	10200	.0107
16.75	1.40	9800	.0102
16.0	1.30	9360	.0104
15.5	1.24	9080	.0105
15.1	1.18	8850	.0105
14.3	1.10	8380	.0109

TABLE III (Contd.)

Flow rate lb./min.	Pressure drop in inches	Reynolds number	Friction factor
13.25	.98	7760	.0113
11.85	.80	7000	.0114
10.0	.58	5850	.0120
8.6	.42	5050	.0116
7.5	.32	4400	.0118
6.5	.24	3800	.0116
5.25	.18	3080	.0133
4.85	.20	2840	.0173
5.8	.24	3400	.0145
7.3	.34	4275	.0129
7.95	.40	4650	.0129
9.25	.50	5410	.0119
10.45	.60	6110	.0112
12.15	.80	7110	.0111
13.6	1.00	7950	.0111
15.5	1.20	9050	.0102
17.3	1.42	10100	.0096
16.3	1.32	9550	.0101
15.6	1.22	9130	.0102
13.4	.93	7840	.0111
11.8	.78	6910	.0114
10.55	.62	6160	.0114
9.5	.55	5550	.0126
8.5	.40	4970	.0113
7.75	.35	4540	.0122
5.85	.22	3430	.0131
10.2	.62	5980	.0121
11.45	.79	6700	.0122
12.5	.91	7350	.0119
14.0	1.09	8200	.0113
15.25	1.28	9200	.0105
16.75	1.41	9800	.0102
17.15	1.49	10000	.0103
17.85	1.74	10450	.0111
16.0	1.28	9350	.0102
13.95	1.06	8150	.0111
12.75	.97	7460	.0121
10.75	.73	6280	.0128
9.5	.59	5560	.0133
7.8	.42	4570	.0140
6.25	.30	3660	.0156
5.2	.22	3040	.0166
11.5	.80	6720	.0123
17.05	1.44	9950	.0101
7.2	.36	4210	.0141

TABLE III (Contd.)

Flow rate lb./min.	Pressure drop in inches	Reynolds number	Friction factor
9.25	.52	5410	.0124
11.5	.75	6720	.0115
14.8	1.14	8650	.0106
17.55	1.56	10300	.0103
20.25	2.00	11900	.0099
22.1	2.34	12950	.0097
6.75	.30	3960	.0134
19.8	1.90	11600	.0098
9.25	.52	5410	.0130
19.5	1.82	11420	.0097
10.75	.69	6300	.0121
12.9	.91	7540	.0111
19.4	1.33	11400	.0101
17.1	1.44	10000	.0100
14.8	1.11	8650	.0103
23.6	2.66	13880	.0101
8.3	.40	4850	.0118
11.8	.78	6890	.0114
23.5	2.52	13750	.0093
7.2	.32	4230	.0125
14.6	1.10	8550	.0105
18.55	1.70	10880	.0101
13.2	.99	7620	.0116
15.5	1.24	9050	.0105
12.0	.82	7000	.0116
19.2	1.76	11200	.0097
15.9	1.28	9300	.0103
10.2	.66	5960	.0129
21.75	2.20	12720	.0094
23.8	2.60	13940	.0093
19.3	1.78	11310	.0097
23.7	2.58	13900	.0093

****

TABLE III A

CALCULATED RESULTS

The following are the calculated values of the Reynolds number and friction factor for the teflon tube of 3/4" nominal I.D. at high flow rates using city water line with a gate valve at the inlet.

Flow rate lb./min.	Pressure drop in inches	Reynolds number	Friction factor
65.0	17.02	38100	.00816
81.0	23.37	47500	.00724
73.0	19.95	42800	.00760
61.0	14.48	35700	.00790
56.0	12.15	32800	.00785
51.0	10.26	29900	.00800
44.0	8.10	25800	.00850
39.2	6.13	23000	.00810
36.5	6.09	21400	.00927
32.0	4.50	18750	.00890
46.0	8.78	27000	.00842

****

TABLE III B

CALCULATED RESULTS

The following are the calculated values of the Reynolds number and friction factor for the teflon tube of 3/4" nominal I.D. when the gate valve was moved to the inlet of the tube thus reducing the head to app.3 ft. It should be noted that the manometer was unsteady.

Flow rate lb./min.	Pressure drop in inches	Reynolds number	Friction factor
14.75	1.31	8650	.0122
15.6	1.44	9150	.0120
11.9	.99	6970	.0142
13.6	1.40	7950	.0154
7.75	.52	4550	.0176
8.9	.64	5210	.0164
10.8	.84	6330	.0146
12.1	1.02	7100	.0141
7.9	.55	4630	.0179
7.1	.38	4150	.0153
5.25	.26	3080	.0192
20.2	2.76	11800	.0137
17.4	2.36	10200	.0158
16.2	1.57	9500	.0121
15.25	1.71	8940	.0149
14.75	1.36	8640	.0127
13.85	1.46	8110	.0154
12.85	1.38	7540	.0170
12.8	1.13	7500	.0140
12.45	1.22	7300	.0160
11.5	.96	6750	.0147
10.0	.79	5860	.0160
9.85	.75	5760	.0157
8.4	.52	4930	.0150
6.8	.41	3980	.0180

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FIGURE (4)

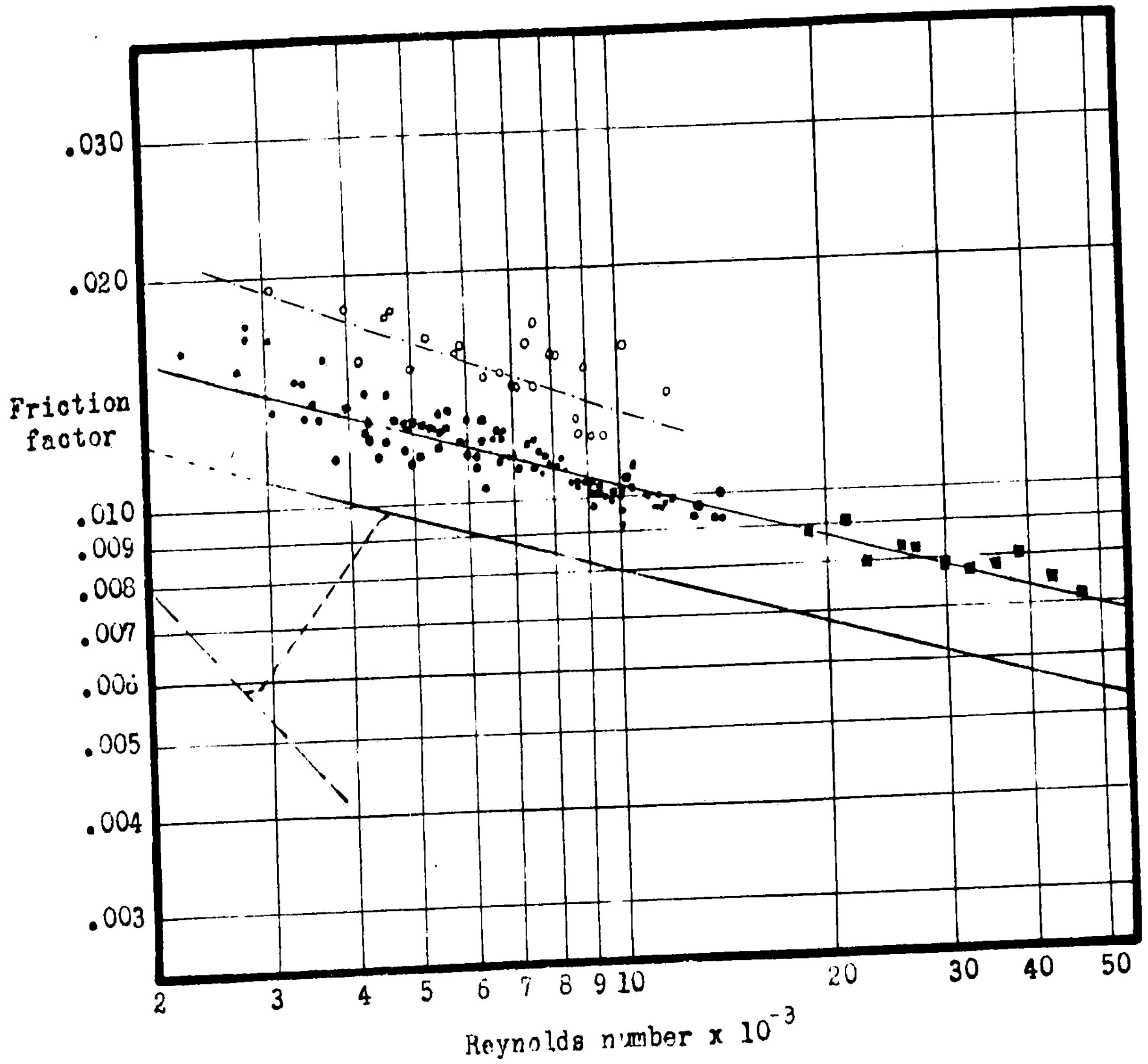

Figure 4. Friction factor vs. Reynolds number for the teflon tube of nominal 3/4" I.D.

Legend: —●— with valve at outlet using apparatus.

—·—○—· with valve at inlet using apparatus.

—■— with valve at inlet using main city water line of high pressure.

TABLE IV

CALCULATED RESULTS

The following are the calculated values of the Reynolds number and friction factor for the teflon tube of 1 1/4" nominal I.D. using city water line with a gate valve at the entrance to the tube. At higher flow rates the teflon-iron pipe connections came apart.

Flow rate lb./min.	Pressure drop in inches	Reynolds number	Friction factor
43.3	.49	14900	.00805
53.5	.71	18400	.00760
67.0	1.05	23000	.00580
72.0	1.13	24800	.00566
75.0	1.23	25800	.00695
64.0	.93	22000	.00731
48.0	.53	16500	.00705
48.5	.55	16700	.00722
58.0	.75	20000	.00590
72.0	1.11	24800	.00662
84.5	1.48	29100	.00634

****

TABLE V

CALCULATED RESULTS

The following are the calculated values of the Reynolds number and the friction factor for the copper tube of 0.522" I.D. with the gate valve at the outlet.

Flow rate lb./min.	Pressure drop in inches	Reynolds number	Friction factor
7.55	2.00	6150	.0094
16.75	7.80	13650	.0074
3.35	0.52	2730	.0124
4.6	0.90	3750	.0114
5.85	1.38	4760	.0107
9.75	3.24	7950	.0091
14.0	5.84	11400	.0080
15.12	6.55	12350	.0077
16.55	7.72	13500	.0075
12.25	4.72	10000	.0084
9.1	2.83	7400	.0092
7.12	1.82	5800	.0096
5.2	1.09	4250	.0108
3.25	0.42	2650	.0106
2.0	0.21	1630	.0141
17.3	8.62	11100	.0077

****

FIGURE (5)

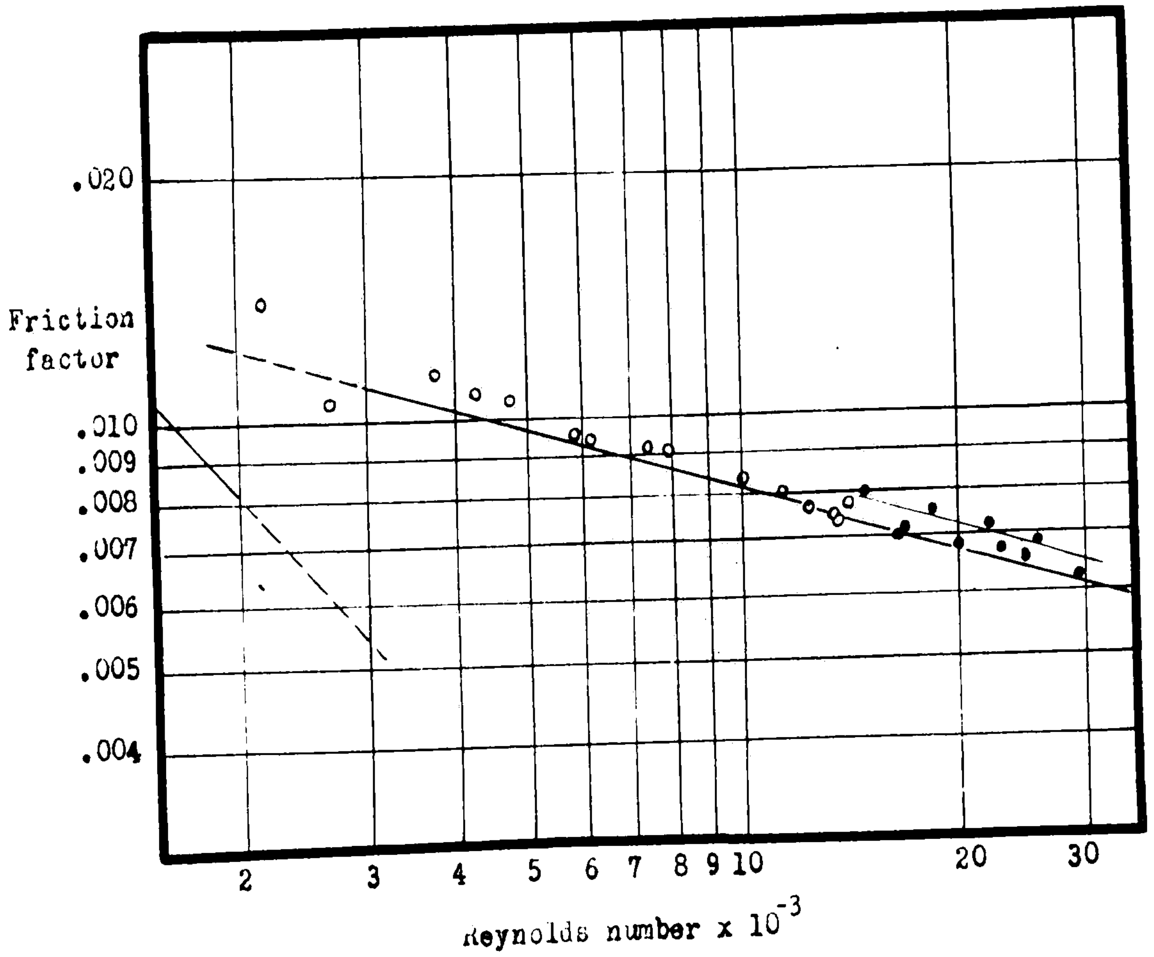

Figure 5. Friction factor vs. Reynolds number for the copper tube and for the teflon tube of nominal 1 1/4" I.D. compared with published data.
Legend: ○ Copper tube using apparatus.
-●- Teflon tube using main city water line with valve at inlet.

DISCUSSION OF RESULTS

The calculated results of this investigation are presented in Tables II to V. They are also presented graphically in Figs. 3, 4 and 5, where the Fanning friction factor was plotted against the Reynolds number for each tube and compared with the established relationships for the flow of fluids in smooth wetted metallic and glass tubes.

It could be easily seen that the friction factors for the water-teflon system were considerably higher than the accepted normal values which were approached by the results of the copper tube. The copper tube was used to check the accuracy of the apparatus.

It could also be seen that the ratio of the experimental friction factors to the normal friction factors decreased with the increase in diameter of the teflon tube.

Diameter		Ratio of friction factors
0.372	(laminar flow)	1.70
0.372	(turbulent flow)	1.45
0.721	" "	1.31
1.228	" "	1.06

The ratio of the friction factors seems to approach 1 for larger diameters.

Another important observation is that when the valve was moved to the inlet, thus reducing the pressure within the liquid from 15 to 3 ft. the friction factor was increased in the case of 3/4" nominal I.D. teflon tube but not in the case of 3/8" tube. It should also be noted that the results were more scattered at low pressure head.

Earlier in this report, the factors affecting the flow of a non-wetting fluid were discussed. Slip could be immediately discarded as a reason for the anomalies displayed in the results of this investigation. Slip should increase the velocity of flow and not decrease it,as was the case in this investigation, Furthermore, the magnitude of slip velocity is so small that it could not be possibly detected.

The presence of a chemisorbed or an adsorbed gas layer or an oxide film could also be disregarded in the case of teflon. The inertness of teflon and its hydrophobic properties do not allow any oxide formation, dirt accumulation or any gas adsorption (which in any case, is too small to have any effect on friction factors).

The entrainment of air seems to be the most plausible explanation for the results in this experiment. The arrangement of the upper reservoir was such that splashing definitely occurred and a vortex could have been formed. When the pressure head was reduced by moving the valve to the inlet, the flow became unsteady and at high flow rates, surges of air bubbles were seen carried by the water stream in the rotameter. As it was mentioned earlier, these bubbles tend to float by the force of buoyancy. When they reach the upper surface of the tube they may remain attached to the wall, unless the velocity of the liquid is high enough to overcome the friction between the bubble and the wall and thus sweep it with its current. The presence of these bubbles could be easily demonstrated in the laboratory by attaching a Tygon tube to the water tap and allowing the water to flow horizontally in the tube. By loosening the connection between the tube and the tap, air will leak in the water stream. If the flow rate is sufficiently small, the air bubbles will be seen clinging to the upper surface of the tube. Upon increasing the rate of flow the bubbles are swept with the flowing water.

Another factor of equal importance is the possible presence of extrusion cavities in the wall of the tube. A non-wetting liquid will possibly form a free surface which may seal the air in the cavity. This could also be of prime importance in heat transfer, coupled with the fact that this free surface layer of liquid may have different properties i.e. viscosity,from the rest of the liquid.

A hypothetical sketch of the flow of a non-wetting liquid in a tube is shown in Fig. 6.

FIGURE (6)

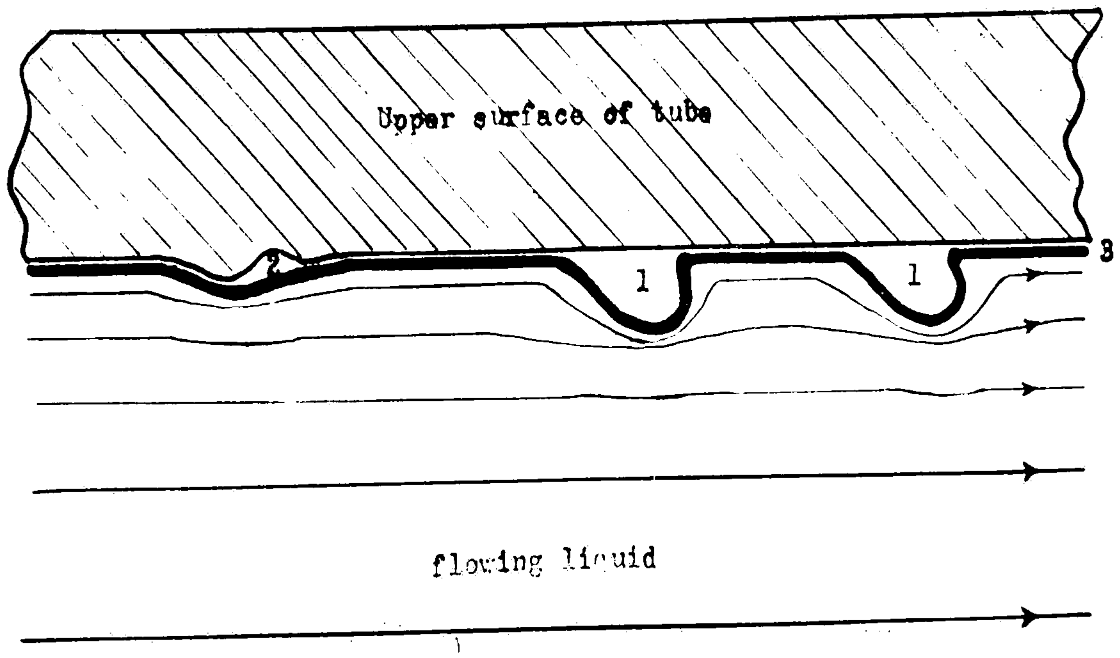

Figure 6. A hypothetical sketch for the flow of a non-wetting liquid in a tube.

Legend

1. Air bubbles attached to the upper surface of the tube which hinder the flow of the liquid by increasing the roughness and by decreasing the effective diameter.
2. Sealed air within an extrusion cavity. Had the liquid wet the tube, it would have displaced the air in the cavity and in the form of bubbles.
3. A multimolecular layer formed due to surface tension within the liquid. This layer is of unknown properties.

CONCLUSIONS

1. This investigation showed that it was possible to obtain higher friction factors during non-wetted flow in smooth pipes than would normally be expected from smooth wetted pipes.
2. Under non-wetted conditions, friction factors approached the expected values for wetted flow as the diameter of the tube was increased.
3. The high values obtained for friction factors under non-wetted conditions were attributed to the entrainment of air bubbles in the liquid stream. These bubbles tended to attach themselves to the upper surface of the tube thus increasing the roughness factor and reducing the effective diameter of the tube.
4. Entrained gas bubbles and the possible sealing of gas (or air) in cavities in the wall of the tubes which are not wetted by the flowing liquid could explain the large anomalies found in heat transfer from molten metals under wetting and non-wetting conditions.
5. It is recommended that further work be done in order to verify the results of this investigation. A study of flow at small Reynolds numbers is necessary. It is recommended that further work be done on the flow in orifices under non-wetting conditions.

APPENDIX

FIGURE (7)

CALIBRATION OF ROTAMETER

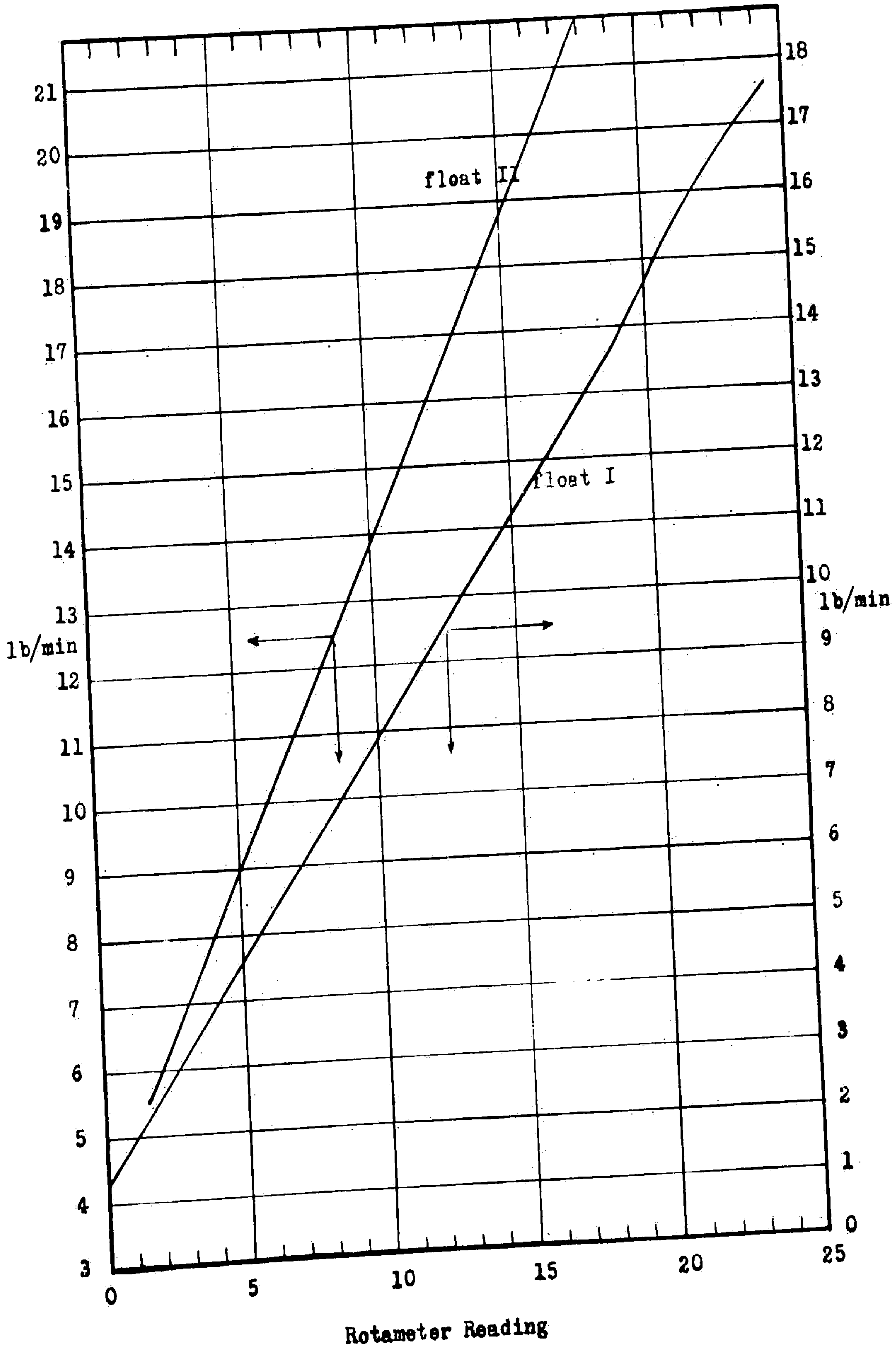

TABLE VI

EXPERIMENTAL DATA

The following is the experimental data taken for the teflon tube of nominal 3/8" I.D. with gate valve at outlet.

Date	Rotameter Rdg.	Manometer Rdgs.	
March 9	13.0	11.15	11.20
	12.0	10.00	10.10
	11.0	8.70	8.75
	9.6	7.20	7.20
	9.45	6.92	7.00
	8.9	6.60	6.62
	8.0	5.50	5.52
	7.0	4.75	4.80
	6.0	3.80	3.85
	4.9	2.92	3.00
	4.0	2.22	2.25
March 10	12.5	10.40	10.60
	11.5	9.20	9.38
	10.5	7.96	8.09
	9.5	7.00	7.15
	8.5	5.98	6.10
	7.5	5.09	5.19
	6.4	4.04	4.21
	5.45	3.25	3.46
	4.5	2.57	2.79
	2.9	1.50	1.73
	2.5	1.27	1.50
	3.9	2.15	2.25
	5.0	2.90	3.08
	7.0	4.58	4.70
	3.05	6.50	6.61
	11.0	8.50	8.69
	13.0	11.00	11.25
	13.1	11.05	11.30
	13.9	12.02	12.34
	1.4	0.70	0.80
	2.0	1.02	1.20
March 12	2.6	1.38	1.38
	3.5	1.81	1.94
	4.4	2.49	2.60
	5.5	3.23	3.40
	6.5	4.09	4.20
	7.5	5.02	5.13
	8.5	6.00	6.10
	9.5	7.02	7.17
	10.5	8.12	8.32

TABLE VI (Contd.)

Date	Rotameter Rdg.	Manometer Rdgs.	
March 12	11.0	8.30	8.17
	11.65	9.62	9.41
	12.5	10.80	10.53
	13.5	11.80	12.10
	13.8	12.44	12.12
March 15	0.0	.30	.31
	0.5	.41	.41
	1.0	.50	.50
	1.58	.80	.80
	2.0	1.10	1.10
	2.9	1.60	1.60
	5.0	3.03	3.02
March 16	5.0	3.01	2.92
	3.9	2.30	2.20
	3.0	1.70	1.63
	2.0	1.04	1.14
	0.98	.57	.45
	0.0	.25	.35
	0.7	.40	.48
	0.4	.43	.31
	1.25	.63	.56
	1.85	1.02	.93
	11.1	8.70	8.78
March 24	0.0	.27	.27
	0.9	1.03	1.02
	2.0	1.10	1.10
	4.0	2.29	2.29
	5.95	3.83	3.82
	6.0	3.88	3.87
	8.15	5.83	5.82
	10.2	7.95	7.94
	12.1	10.31	10.31
	13.0	11.61	11.60
	13.2	11.79	11.79

****

TABLE VI A

EXPERIMENTAL DATA

The following is the experimental data taken for the teflon tube of 3/8" nominal I.D. with valve at the inlet.

Date	Rotameter Rdg. I	Manometer Rdgs.	
March 16	1.80	1.00	.91
	2.87	1.60	1.55
	3.90	2.30	2.25
	4.87	2.85	2.84
	6.20	3.91	3.90
	7.70	5.26	5.25
	9.50	6.90	6.86
	12.00	10.00	9.85
	13.00	11.30	11.15
	.60	.50	.40
	.10	.39	.29
	1.40	.75	.65
	2.10	1.17	1.09
March 17	1.70	1.00	.90
	11.70	9.54	9.50
	6.20	4.00	3.90
	12.70	11.16	11.12
	2.70	1.60	1.50

****

TABLE VII

EXPERIMENTAL DATA

The following is the experimental data taken for the teflon tube of nominal 3/4" I.D. with the gate valve at the outlet.

Date	Rotameter Rdg. I	Manometer Rdgs.	
Feb. 10	6.1	.06	.12
	17.7	.40	.49
	11.9	.20	.31
	9.2	.11	.21
	18.6	.48	.51
	23.9	.61	.75
	21.4	.57	.64
	15.4	.38	.40
	10.8	.18	.25
	17.9	.40	.51
	5.4	.07	.12
	17.3	.40	.48
	11.8	.20	.30
	22.0	.62	.68
	22.6	.63	.70
	7.1	.11	.13
Feb. 11	23.7	.71	.78
	15.1	.35	.40
	4.0	.02	.10
	14.5	.29	.31
	20.7	.60	.62
	10.5	.20	.22
Feb. 12	20.1	.52	.59
	14.8	.32	.39
	10.6	.19	.23
	5.1	.05	.11
	13.5	.28	.31
	6.6	.10	.13
Feb. 15	25.1	.89	.88
	24.0	.79	.79
	22.8	.70	.70
	21.7	.65	.65
	21.0	.62	.62
	20.5	.59	.59
	19.5	.55	.55
	18.2	.49	.49
	16.1	.40	.40
	13.3	.29	.29
	11.2	.21	.21

TABLE VII(Contd.)

Date	Rotameter Rdg. I	Manometer Rdgs.	
Feb. 15	9.5	.16	.16
	8.0	.12	.12
	6.0	.09	.09
Feb. 16	5.5	.10	.10
	6.8	.12	.12
	9.1	.17	.17
	10.15	.20	.20
	12.1	.25	.25
	13.5	.30	.30
	16.3	.40	.40
	18.7	.50	.50
	21.0	.60	.60
	23.9	.71	.71
	22.1	.66	.66
	21.1	.61	.61
	18.4	.49	.49
	16.0	.39	.39
	14.1	.31	.31
	12.5	.28	.28
	11.0	.20	.20
	9.8	.18	.18
	6.9	.11	.11
Feb. 23	13.5	.31	.31
	15.4	.40	.39
	17.0	.45	.46
	19.2	.55	.54
	21.4	.65	.63
	22.3	.70	.71
	23.5	.75	.74
	24.9	.88	.86
	21.5	.65	.63
	19.1	.53	.53
	17.4	.47	.50
	14.4	.35	.38
	12.5	.29	.30
	10.0	.20	.22
	7.5	.12	.18
	5.9	.10	.12
	15.5	.39	.41
	23.1	.72	.72
	Rotameter Rdg. II		
Feb. 24 (Float II in rotameter)	3.5	.18	.18
	5.6	.26	.26
	7.8	.37	.38
	11.2	.57	.57
	13.9	.78	.78
	16.5	1.00	1.00
	18.3	1.17	1.17

TABLE VII (Contd.)

Date	Rotameter Rdg. II	Manometer Rdgs.	
Feb. 25	3.1	.11	.19
	16.1	1.00	.90
	5.6	.22	.30
	15.0	.87	.95
	7.1	.38	.31
	9.2	.49	.42
	15.8	.90	.98
	13.4	.69	.75
	11.2	.51	.60
	19.9	1.33	1.33
	4.6	.20	.20
	8.2	.39	.39
	19.7	1.26	1.26
	3.5	.16	.16
	10.9	.55	.55
	14.9	.85	.85
	9.5	.49	.50
	11.8	.62	.62
	8.3	.41	.41
	15.5	.88	.88
	12.25	.64	.64
	6.55	.33	.33
	18.0	1.10	1.10
	20.0	1.30	1.30
	15.7	.89	.89
	19.9	1.29	1.29

****

TABLE VIIA

EXPERIMENTAL DATA

The following is the experimental data taken for the teflon tube of 3/4" nominal I.D. at high flow rates using city water line with gate valve at inlet.

Date	Flow rate (lb./min.)	Manometer rdgs.	
May 17	65.0	8.40	8.60
	81.0	11.70	11.67
	73.0	10.00	9.95
	61.0	7.33	7.15
	56.0	6.10	6.15
	51.0	4.98	5.28
	44.0	4.20	3.90
	39.2	3.00	3.13
	36.5	2.87	3.22
	32.0	2.07	2.43
	46.0	4.21	4.57

****

TABLE VIIB

EXPERIMENTAL DATA

The following is the experimental data taken for the teflon tube of 3/4" nominal I.D. with the gate valve at the inlet. Manometer readings were unsteady.

Date	Rotameter Rdg. I	Manometer Rdgs.	
Feb. 12	20.1	.80	.51
	21.2	.88	.56
	16.2	.49	.50
	18.7	.70	.70
	9.8	.23	.29
	11.7	.30	.34
	14.5	.40	.44
	16.3	.50	.52
	10.1	.25	.30
	7.8	.18	.20
	6.0	.10	.16
	20.2 lb./min.	1.38	1.38
Feb. 15	24.0	1.16	1.20
	21.9	.76	.81
	20.6	.81	.90
	20.0	.66	.70
	19.0	.70	.76
	17.6	.68	.70
	17.5	.52	.61
	16.9	.58	.64
	15.5	.45	.51
	13.3	.35	.44
	13.1	.34	.41
	10.8	.22	.30
	8.4	.16	.25

****

TABLE VIII

EXPERIMENTAL DATA

The following is the experimental data taken for the teflon tube of 1 1/4" nominal I.D. using city water line with a gate valve at the entrance to the tube. Flow was measured directly.

Date	Flow rate lb./min.	Manometer Rdgs.	
May 18	43.3	.38	.11
	53.5	.48	.23
	67.0	.60	.40
	72.0	.61	.54
	75.0	.68	.60
	64.0	.48	.50
	42.0	.30	.23
May 20	47.5	.17	.38
	58.0	.30	.46
	72.0	.63	.48
	84.5	.69	.79

****

TABLE IX

EXPERIMENTAL DATA

The following is the experimental data taken for a copper tube of 0.522" I.D. with the valve at the outlet.

Date	Rotameter Rdg. I	Manometer Rdgs.	
April 12	9.5	1.00	1.00
	22.8	3.90	3.90
	3.2	.26	.26
	5.0	.45	.45
	6.85	.69	.69
	13.0	1.62	1.62
	19.2	2.92	2.92
April 20	20.5	3.35	3.20
	22.6	3.98	3.74
	16.6	2.45	2.27
	11.9	1.50	1.33
	8.8	1.00	.82
	5.9	.60	.49
	3.0	.31	.11
	1.0	.20	.01
	23.95	4.40	4.22

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SAMPLE CALCULATIONS

The following is a sample calculation for the first item in Table II.

Calculation of the Reynolds number:

$$Re = \frac{D V \rho}{\mu}$$

V = velocity in ft./sec.

D = diameter of tube in ft.

ρ = density of water in lbs./cu.ft.

μ = viscosity of water in British units.

Experimental data gives the flow rate as 9.8 lb./min. Also the pressure drop is 22.35 inches of carbon tetrachloride under water. The diameter is .372 inches. The viscosity of water at 25°C is 0.896 centipoises. The density of water is 62.25 lbs./cu.ft.

$$V = \frac{9.8}{60 \times 62.25} \times \frac{4}{(0.031)^2 \pi} = 3.48 \text{ ft./sec.}$$

$$D = \frac{0.372}{12} = 0.031 \text{ ft.}$$

$$\mu = 0.896 \text{ centipoises} = 0.896 \times 6.72 \times 10^{-4} \text{ lb./ft.sec.}$$

$$Re = \frac{0.031 \times 3.48 \times 62.25}{0.896 \times 6.72 \times 10^{-4}} = 11180$$

Calculation of the friction factor:

$$f = \frac{\pi^2 \rho g_c D^5 \Delta P}{32 L w^2}$$

$$\Delta P = \frac{22.35''}{12}(1.595 - 1.00) \times 62.25 = 69 \text{ lb. force/sq.ft.}$$

$$g_c = 32.174$$

$$w = 9.8/60 = 0.167 \text{ lb./sec.}$$

$L = 4$ ft.

$$f = \frac{(3.14)^2 \text{ x } 62.25 \text{ x } 32.174 \text{ x } (0.031)^5 \text{ x } 69}{32 \text{ x } 4 \text{ x } 0.167}$$

$$= 0.0114$$

****

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