AN INVESTIGATION OF PRESSURE DROP THROUGH ROTATING PIPE

By

HOWARD HULEN FERRELL

Bachelor of Science

Oklahoma Agricultural and Mechanical College

Stillwater, Oklahoma

1951

Submitted to the faculty of the Graduate School of
the Oklahoma Agricultural and Mechanical College
in partial fulfillment of the requirements
for the degree of
MASTER OF SCIENCE
May, 1957

AN INVESTIGATION OF PRESSURE DROP THROUGH ROTATING PIPE

Thesis Approved:

J H Boggs
Thesis Adviser

Robert MacVicar
Dean of the Graduate School

ACKNOWLEDGEMENTS

The author is grateful to Stanolind Oil and Gas Company without whose financial assistance through the Stanolind Foundation Fellowship this work would not have been possible.

Indebtedness is acknowledged to the Chiksan Company for furnishing the special swivel joints and to the Moorlane Company for fabricating the meter-run.

The author appreciates the aid and support from Professor R. E. Venn and the mechanical engineering department. Indebtedness is acknowledged to Dr. J. H. Boggs, Mr. E. C. Fitch and Mr. B. S. Davenport who served as faculty advisors for this work and whose advice and technical assistance is appreciated.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

SYMBOLS AND ABBREVIATIONS

Symbols

$A_{1.407}$ $A_{1.005}$ $A_{0.603}$	Cross section area of orifice plates (ft^2) Subscript corresponds to diameter of orifice in inches
A_{pipe}	Cross section area of pipe (ft^2)
β	Ratio of orifice diameter to pipe diameter
BW gage	Birmingham wire gage
d	Diameter of pipe (inches)
$d_{1.407}$ $d_{1.005}$ $d_{0.603}$	Diameter of orifice plates (inches)
g	Acceleration of gravity (ft/sec^2)
h	Differential height of manometer column (ft H_2O)
h_m	Differential height of manometer column (inches manometer fluid)
K	Orifice constant
l	Length of rotating pipe (ft)
μ	Absolute viscosity lbm/ft sec
N_{Re}	Reynolds number (dimensionless)
Δp	Pressure loss of fluid over length of pipe (ft of H_2O)
ϕ	Function of
r	Radius of pipe (ft)
ρ	Density of fluid (lbm/ft^3)
Q	Flow rate of fluid (ft^3/sec)

$Q_{1.407}$ $Q_{1.005}$ $Q_{0.603}$	Flow rate of fluid through pipe when respective orifice plates are used. Subscripts refer to diameter orifice.
v	Velocity of fluid (ft/sec)
ω	Angular velocity (radians/sec)
T	Time (minutes)

Abbreviations

ave	Average
cfs	Cubic feet per second
diff	Difference
ft	Feet
gpm	Gallons per minute
hp	Horsepower
in	Inch
ind	Indicated
man	Manometer
min	Minutes
pres	Pressure
read	Reading
rpm	Revolutions per minute
sta	Static
tach	Chronograph tachometer
temp	Temperature

CHAPTER I

INTRODUCTION AND STATEMENT OF THE PROBLEM

Recent developments in petroleum drilling have enabled greater penetration depths than would have been thought possible a few years ago. With the greater depths of present day drilling have come increased problems of circulation. One of these problems is the tremendous power requirement of the circulation system. This means that an accurate prediction be made of this requirement. Much work on the detailed consideration of hydraulic losses has been done to analyze the effect of various types of drill stems and tool joints as well as the effect of bit nozzles. (1). Some work has also been done considering the losses due to the circulation fluid itself. However, a detail which has practically been overlooked in the consideration of hydraulic losses is the effect of pipe rotation.

Levy (2) noticed the effect of rotation on the pressure drop while he was studying heat transfer of gases in rotating diffusers. He obtained a reduction of the pressure loss through the rotating section, and attempted to explain the phenomena by defining a new coefficient of resistance to flow. Levy asserted that for otherwise similiar conditions, the coefficient of resistance to flow through rotating tubes would always be less than the coefficient for flow through stationary tubes. Besides Levy's recognition of the phenomena little work has been done to explain the effect of rotation on the flow characteristics.

The purpose of this work is to investigate the pressure loss characteristics of water in a rotating pipe.

CHAPTER II

ANALYSIS OF THE PROBLEM

The motion of a particle of fluid in a straight tube is governed by forces due to frictional and dynamic resistances. (3). In addition, if the tube is rotated, the particle is affected by centrifugal forces.

To determine the relation of pressure drop to the other variables affecting the flow, a dimensional study was made.

Results of Dimensional Study

	Variables	Dimension
r	Radius of pipe	L
Q	Flow rate of fluid	L^3T^{-1}
μ	Viscosity of fluid	$ML^{-1}T^{-1}$
l	Length of pipe	L
Δp	Pressure loss of fluid over length l	$ML^{-1}T^{-2}$
ρ	Density of fluid	ML^{-3}
ω	Angular velocity of pipe	T^{-1}

From Buckingham's theorem using (r, Q, μ) as a probasic triad, the following four dimensionless groups were obtained:

$$\frac{l}{r}, \quad \frac{r^3 \Delta p}{Q \mu}, \quad \frac{Q \rho}{r \mu}, \quad \frac{r^3 \omega}{Q}.$$

These groups can be operated on by dimensionless constants to place them in a more useful form for studying their physical significance. (4).

If $\frac{r^3 \Delta p}{Q}$ is multiplied by $\frac{\pi r}{8l}$, the result $\frac{\pi r^4 \Delta p}{8Ql\mu}$, can be recognized as Poiseuille's expression for laminar flow. The result $\frac{2Q\rho}{\pi r\mu}$ obtained by multiplying $\frac{2}{\pi}$ times $\frac{Q\rho}{r\mu}$ can be readily recognized as Reynolds number, If $\frac{r^3\omega}{Q}$ is multiplied by $\frac{Q\rho}{r\mu}$, an expression of the form angular momentum divided by viscosity, $\frac{r^2\omega\rho}{\mu}$, can be obtained.

Carrying out these operations gave the four dimensionless groups:

$$\frac{l}{r}, \quad \frac{\pi r^4 \Delta p}{8Ql\mu}, \quad \frac{2Q\rho}{\pi r\mu}, \quad \frac{r^2\omega\rho}{\mu}$$

From the dimensional study it was noted that the pressure loss could be expressed as:

$$\Delta p = \left(\frac{8Ql\mu}{\pi r^4}\right) \times \phi \left[N_{Re}, \frac{l}{r}, \frac{r^2\omega\rho}{\mu}\right] \tag{1}$$

CHAPTER III

EXPERIMENTAL APPARATUS

The essential part of the experimental apparatus was the test section. A 19-foot, 5-inch length of BW gage 11 seamless low carbon 2-inch tubing was used for this section. The tubing was secured by four Fafnir self-aligning bearings to a channel frame which was bolted to the floor.

In order to rotate the test section, a sheave was fastened to the tube with a tapered bushing. A 10 hp Varidrive drove the tubing with a twin "A" belt drive. The 7-inch pipe sheave was driven by a 4.8 inch drive sheave. This arrangement allowed a minimum angular speed of 275 rpm, and the apparatus was capable of a maximum speed of 2,400 rpm.

A tachometer was used to measure the angular velocity. To assure an accurate 2 to 1 tachometer drive, a 3 11/16-inch sheave was fastened to the tubing and a variable pitch 7 1/2 to 8-inch sheave was used on the tachometer shaft which was driven by a single "B" belt.

To force water through the system a 7 1/2 hp centrifugal pump with a 2 1/2-inch suction and a 2-inch discharge was used. This pump had a maximum capacity of 135 gpm at a head of 40 feet of water. In order to control the flow rate, a by-pass was put in the piping arrangement. Proper regulation of two valves, one on the by-pass and the other on the approach to the test section, allowed a wide range of flow rates through the rotating pipe. Fig. 1 shows the overall apparatus and piping arrangement.

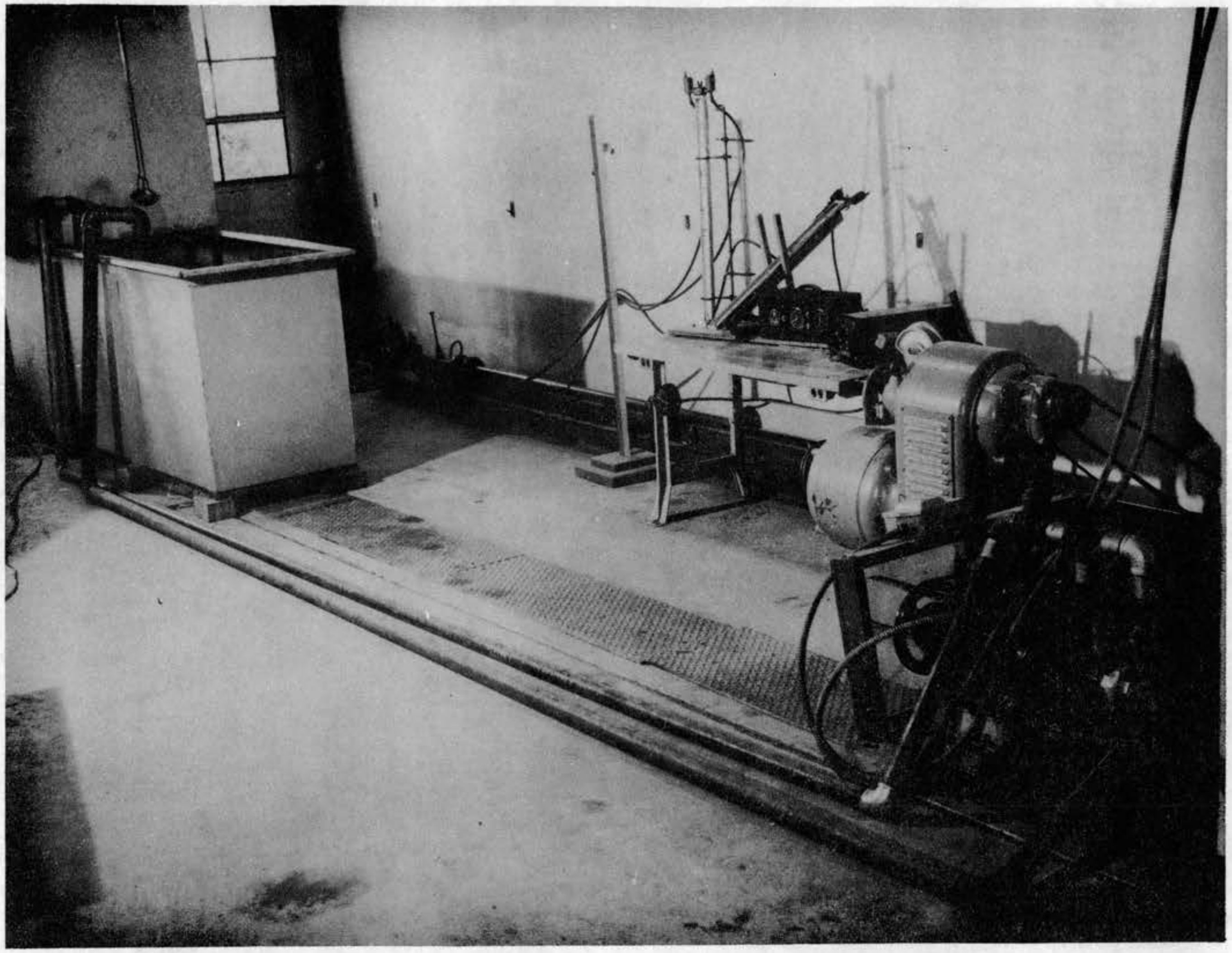

Figure 1. Experimental Apparatus.

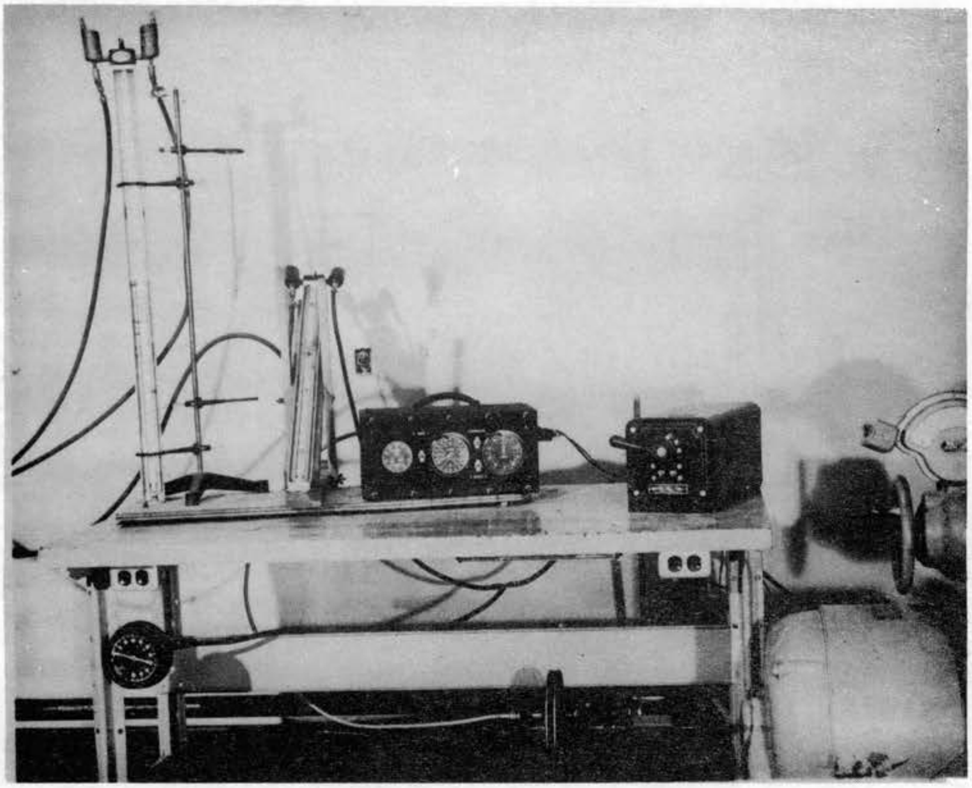

Figure 2. Instruments and Control.

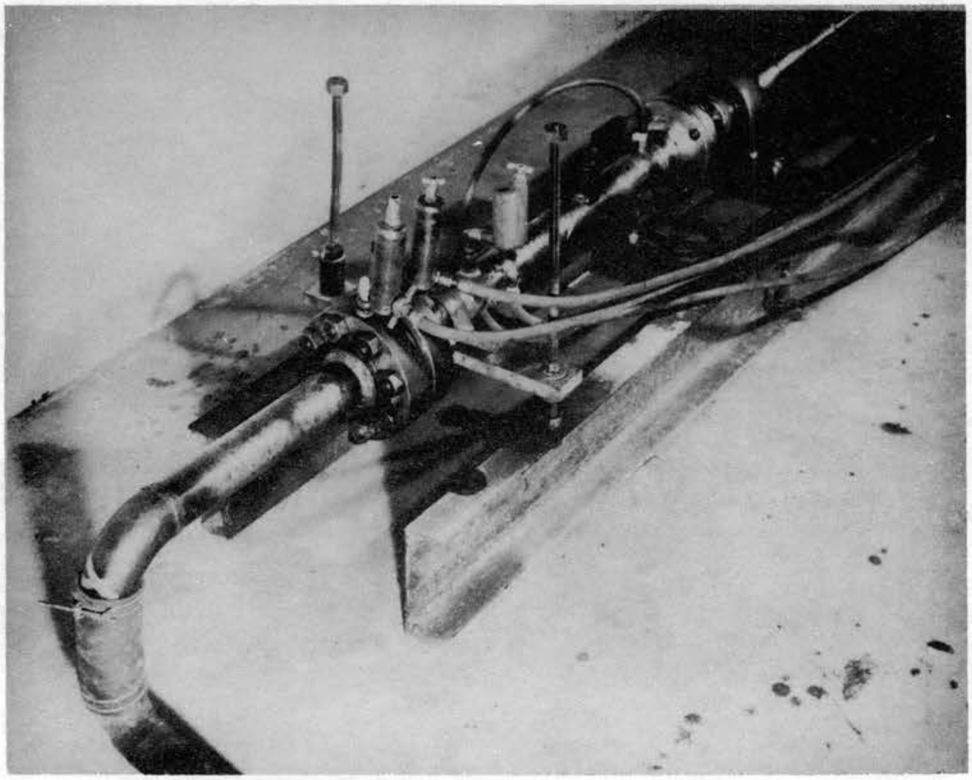

Figure 3. Discharge Section and Meter Run.

Special Chiksan high speed swivel joints were used to connect the stationary approach and discharge sections to the test section. In order to keep the weight off of the swivels and to minimize the effect of a slight misalignment as well as vibration, the approach and discharge sections were supported by spring hangers and were connected to the other piping by flexible connections, see Fig. 3.

The swivels were silver soldered to the tubing to facilitate good alignment. To reduce flow interference, the swivels were made with the same internal diameter as the tubing.

An orifice meter-run assembly was fabricated into the discharge section. The tapped flange, orifice plates, and straightening vanes were manufactured and assembled by the Moorelane Company in accordance with specifications by the American Gas Association. (5). There is no specification for the location of the orifice plate after a rotating pipe, so the orifice was located as prescribed for the situation in which two ells in perpendicular planes preceed the meter-run. The approach to the test section was a 25-inch length of straight tubing.

The differential static pressure across the test section was measured by an inclined manometer. The measuring fluid in this manometer was carbon tetrachloride for the flow rates up to 50 gpm, and mercury for the greater rates. The upstream pressure tap was placed in the stationary approach section 5 inches upstream of the swivel, and the downstream tap was placed between the straightening vanes and the orifice 5 inches upstream from the orifice. Fig. 2 shows the control panel with the manometer and tachometer.

In order to remove trapped air from the piping and manometer lines, an air pot with a stopcock was installed at each pipe tap as well as on each manometer, and the manometer lines were led from the taps to the manometer with a constant slope as prescribed by the American Society of Mechanical Engineers. (6).

CHAPTER IV

EXPERIMENTAL PROCEDURE

Information necessary to study the pressure loss characteristics of flow in a rotating pipe was obtained by making differential static pressure measurements across the test section which was rotated at various angular velocities and for various flow rates.

The data was recorded in a series of test runs which consisted of setting the selected flow rate by regulating the by-pass valve and the control valve and varying the angular velocity of the test section. With the valve settings remaining unchanged the angular velocity was varied with the Varidrive in increments of 200 rpm from 400 rpm to 1,800 rpm. Readings were also made at angular velocities of zero and 275 rpm.

With each new angular velocity, adequate time was given to allow the flow to stabilize before any recording was made. At each step three readings of each the orifice manometer and the pressure drop manometer were made over a two minute interval. The average of the readings was used in calculations. The rpm was recorded by the tachometer over the same two minute intervals.

The barometer was read at the beginning and end of each test run. Air and water temperatures were also noted at the beginning and end as well as at irregular intervals during the run. The air temperature was measured in the vicinity of the manometers and the water temperature was measured in the circulation tank.

Test runs were made for flow rates of 15, 25, 35, 50, 70, 90, and 120 gpm. Three orifice plates with diameters of 0.603, 1.005, and 1.417 inches were used to measure the seven flow rates. The small orifice plate was used for flow rates up to 35 gpm, while the 1.005 inch diameter orifice plate was used for intermediate flow rates.

The pressure drop manometer was inclined 53 degrees 7.8 minutes from the vertical during the lower flow rates when the manometer fluid was carbon tetrachloride, and 60 degrees from the vertical during the greater rates when mercury was the measuring fluid.

The flow was measured volumetrically in a tank to check the accuracy of the orifice measurement. The check was made at the 120 gpm flow rate, varying the angular velocity from 0 to 2,000 rpm in 400 rpm increments.

The presence of air in the system was recognized as a possible source of serious error; consequently, each air bleed was opened before and after each run and often at irregular intervals during the runs to assure that the presence of air did not affect the results.

CHAPTER V

OBSERVED DATA

Run 1

Barometer <u>29.35</u> <u>in.</u> <u>Hg</u> $\beta = .3$

Temp °F		Sta Pres Psi	RPM		Orifice Man. in. Hg		Pres Drop Man. in. CCl_4 X 3/5	
Air	Water		Ind.	Tach	Read.	Ave.	Read.	Ave.
90	86	2.5	0	0	6.50 6.40 6.50	6.50	4.81 4.82 4.84	4.83
			270	276.6	6.45 6.43 6.41	6.43	3.25 3.22 3.24	3.24
			400	420	6.30 6.28 6.28	6.29	3.22 3.22 3.22	3.22
			600	616	6.25 6.22 6.22	6.23	3.20 3.17 3.18	3.18
90	86.7	2.5	800	810.2	6.20 6.18 6.17	6.18	3.18 3.18 3.18	3.18
			1000	1004.3	6.13 6.11 6.08	6.11	3.14 3.12 3.10	3.12
			1200	1207	6.01 6.01 6.01	6.01	3.07 3.05 3.07	3.06
			1400	1408.5	6.00 6.01 6.00	6.00	3.33 3.32 3.32	3.32
			1600	1618.2	5.80 5.78 5.78	5.79	3.30 3.30 3.32	3.31

Run 1 (Continued)

					5.82		3.46	
90.5	87.5	2.5	1800	1839	5.93	5.85	3.48	3.46
					5.90		3.45	

Run 2

Barometer 29.35 in. Hg $\beta = .3$

Temp °F		Sta Pres Psi	RPM		Orifice Man. in. Hg		Pres Drop Man. in. CCl_4	
Air	Water		Ind.	Tach	Read.	Ave.	Read.	Ave.
90	82	9.5	0	0	21.00 21.05 21.05	21.02	7.50 7.52 7.53	7.52
			270	278	21.00 21.05 21.05	21.03	5.50 5.50 5.50	5.50
			400	423	21.00 21.00 21.03	21.01	5.05 5.05 5.07	5.06
			600	610.5	20.95 20.90 20.90	20.92	4.95 4.95 4.95	4.95
	82.3		800	794	20.9 20.85 20.85	20.88	4.88 4.88 4.90	4.89
			1000	1012	20.90 20.85 20.83	20.86	4.87 4.87 4.85	4.86
91.5			1200	1204	20.95 20.95 21.00	20.97	4.78 4.75 4.77	4.76
	82.7		1400	1412	20.95 20.90 21.00	20.97	5.02 5.07 5.15	5.08
			1600	1616.5	20.95 20.95 20.92	20.94	5.23 5.25 5.65	5.24
91.5	82.3	9.5	1800	1837.6	20.95 20.90 20.90	20.92	5.25 5.23 5.27	5.25

Run 3

Barometer <u>29.29</u> <u>in.</u> <u>Hg</u> $\beta = .3$

Temp °F		Sta Pres Psi	RPM		Orifice Man. in. Hg		Pres Drop Man. in. CCl_4	
Air	Water		Ind.	Tach	Read.	Ave.	Read.	Ave.
					31.70		11.33	
91.7	82.7	14	0	0	31.75	31.72	11.30	11.31
					31.72		11.30	
					31.70		9.10	
			270	275.8	31.70	31.72	9.12	9.11
					31.75		9.10	
					31.80		8.00	
			400	420.6	31.80	31.80	8.08	8.04
					31.80		8.05	
					31.75		7.60	
			600	617.8	31.75	31.75	7.60	7.60
					31.75		7.60	
					31.80		7.45	
92	83.3		800	795	31.75	31.77	7.50	7.48
					31.80		7.48	
					31.80		7.50	
			1000	1011.2	31.72	31.79	7.50	7.49
					31.75		7.48	
					31.80		7.34	
			1200	1207.9	31.75	31.77	7.35	7.35
					31.75		7.35	
					31.75		7.42	
			1400	1410.5	31.75	31.78	7.50	7.46
					31.85		7.47	
					31.85		7.52	
			1600	1621.5	31.75	31.78	7.52	7.53
					31.75		7.55	
					31.75		7.70	
92	83.8	14	1800	1832	31.80	31.77	7.75	7.72
					31.75		7.72	

Run 4

Barometer 29.35 in. Hg. $\beta = .5$

Temp °F		Sta Pres Psi	RPM		Orifice Man. in. Hg		Pres Drop Man. in. CCl_4	
Air	Water		Ind.	Tach	Read.	Ave.	Read.	Ave.
					8.42		24.72	
93	91.5	2.5	0	0	8.40	8.40	24.70	24.71
					8.38		24.70	
					8.40		22.05	
			270	277	8.44	8.42	22.05	22.04
					8.42		22.03	
					8.40		20.45	
			400	419.8	8.45	8.42	20.45	20.45
					8.42		20.45	
					8.45		18.40	
			600	613.1	8.40	8.42	18.30	18.35
					8.40		18.35	
					8.38		17.00	
			800	810.6	8.33	8.35	17.15	17.12
					8.35		17.20	
					8.38		16.92	
			1000	1011	8.40	8.40	16.95	16.92
					8.42		16.90	
					8.42		16.60	
96	92		1200	1206.3	8.50	8.45	16.55	16.58
					8.44		16.58	
					8.42		16.45	
			1400	1416	8.42	8.43	16.45	16.44
					8.45		16.43	
					8.40		16.48	
			1600	1633.2	8.38	8.40	16.45	16.47
					8.42		16.47	
					8.40		16.50	
96	92	2.5	1800	1826	8.38	8.39	16.55	16.55
					8.40		16.57	
					8.40		16.70	
			2000	1963.6	8.40	8.39	16.72	16.70
					8.38		16.67	

Run 5

Barometer 29.43 in. Hg.　　　　$\beta = .5$

Temp °F		Sta Pres Psi	RPM		Orifice Man. in. Hg		Pres Drop Man. in. Hg. X 1/2	
Air	Water	10	Ind.	Tach	Read.	Ave.	Read.	Ave.
93	82.5		0	0	20.08	20.08	6.25	6.25
					20.10		6.25	
					20.10		6.25	
			270	277.5	20.13	20.14	5.83	5.84
					20.16		5.85	
					20.15		5.83	
			400	414.8	20.18	20.16	5.75	5.75
					20.16		5.75	
					20.17		5.75	
			600	626	20.27	20.26	5.37	5.36
					20.28		5.37	
					20.25		5.35	
93	83		800	807.8	20.32	20.32	5.10	5.10
					20.32		5.10	
					20.35		5.09	
			1000	1011	20.35	20.38	4.90	4.91
					20.40		4.90	
					20.40		4.92	
			1200	1204.2	20.35	20.33	4.70	4.71
					20.33		4.72	
					20.30		4.69	
			1400	1407.2	20.30	20.28	4.67	4.66
					20.25		4.66	
					20.28		4.65	
			1600	1625.1	20.28	20.27	4.65	4.61
					20.25		4.61	
					20.28		4.60	
			1800	1830	20.22	20.23	4.53	4.54
					20.22		4.55	
					20.24		4.53	
92.8	83.7	10	2000	1993.5	20.22	20.25	4.55	4.54
					20.25		4.55	
					20.28		4.53	

Run 6

Barometer <u>29.35</u> <u>in.</u> <u>Hg</u> $\beta = .5$

Temp °F		Sta Pres Psi	RPM		Orifice Man. in. Hg		Pres Drop Man. in. Hg. X 1/2	
Air	Water		Ind.	Tach	Read.	Ave.	Read.	Ave.
82	86.5	14	0	0	30.95	30.93	8.65	8.65
					30.90		8.65	
					30.95		8.65	
			270	276.5	31.10	31.12	8.22	8.21
					31.10		8.20	
					31.15		8.20	
			400	418	31.18	31.19	7.92	7.93
					31.18		7.95	
					31.20		7.95	
			600	619.8	31.35	31.35	7.50	7.51
					31.40		7.53	
					31.30		7.50	
81.7	86.3	14	800	814	30.70	30.71	6.97	6.98
					30.70		6.97	
					30.72		7.02	
			1000	1010.2	30.80	30.83	6.85	6.91
					30.85		6.92	
					30.85		6.95	
			1200	1209	30.80	30.82	6.67	6.70
					30.85		6.70	
					30.80		6.73	
			1400	1414	30.80	30.81	6.70	6.69
					30.83		6.68	
					30.75		6.70	
			1600	1625	30.90	30.84	6.68	6.66
					30.88		6.67	
					30.75		6.70	
82	86.7	14	1800	1814	31.00	30.99	6.70	6.67
					31.00		6.68	
					30.97		6.67	

Run 7

Barometer 29.395 in. Hg $\beta = .7$

Temp °F		Sta Pres Psi	RPM		Orifice Man. in. Hg		Pres Drop Man. in. Hg. X 1/2	
Air	Water		Ind.	Tach	Read.	Ave.	Read.	Ave.
92	81.5	16.5	0	0	15.20 15.18 15.21	15.20	21.42 21.43 21.41	21.42
			270	275	15.27 15.25 15.28	15.27	20.95 20.97 20.97	20.97
			400	409	15.35 15.35 15.32	15.34	20.30 20.35 20.32	20.34
			600	614.7	15.47 15.47 15.45	15.46	19.52 19.52 19.52	19.52
			800	812	15.45 15.47 15.48	15.47	18.95 18.95 18.93	18.95
			1000	998.5	15.59 15.56 15.58	15.58	18.30 18.32 18.31	18.31
92.5	82.3		1200	1204	15.60 15.61 15.60	15.60	17.70 17.72 17.75	17.72
			1400	1409	15.58 15.62 15.63	15.61	17.33 17.33 17.30	17.32
			1600	1628.7	15.74 15.74 15.71	15.73	17.03 17.03 17.07	17.04
			1800	1833	15.73 15.73 15.78	15.74	16.78 16.77 16.77	16.77
			2000	2038	15.73 15.75 15.77	15.75	16.40 16.42 16.42	16.41

Run 7 (Continued)

					15.85		16.40	
			2200	2237.5	15.82	15.83	16.38	16.39
					15.82		16.40	
					15.83		16.40	
92.7	82	16.5	2400	2431	15.82	15.82	16.38	16.39
					15.81		16.40	

Run 8

Barometer <u>29.24 in. Hg</u> $\beta = .7$

Temp. °F		RPM		Orifice in. Hg		Rise in Tank		Time
Air	Water	Ind.	Tach.	Read.	Ave.	ft.	in.	Min.
96.7	86.7	0	0	14.98 14.96 14.98	14.97	1	2	1.230
		400	432.3	15.20 15.22 15.23	15.22	1	2	1.218
		800	818	15.24 15.23 15.22	15.23	1	2	1.222
		1200	1210.8	15.70 15.69 15.70	15.70	1	2	1.197
		1600	1624.1	15.83 15.80 15.78	15.80	1	2	1.193
97	87.2	2000	2051	15.92 15.90 15.93	15.92	1	2	1.189

CHAPTER VI

CALCULATED DATA

Run 1

RPM	h ft. H_2O	$\sqrt{h}$	Q cfs	v ft/sec	N_{Re}	Δp ft. H_2O
0	6.82	2.611	0.025	1.136	22,250	0.142
277	6.75	2.598	0.025	1.136	22,250	0.095
420	6.60	2.567	0.025	1.136	22,250	0.095
616	6.54	2.557	0.025	1.136	22,250	0.094
810	6.49	2.548	0.025	1.136	22,250	0.094
1004	6.42	2.534	0.025	1.136	22,250	0.091
1207	6.31	2.512	0.024	1.091	21,370	0.090
1408	6.30	2.512	0.024	1.091	21,370	0.098
1618	6.08	2.463	0.024	1.091	21,370	0.098
1839	6.14	2.478	0.024	1.091	21,370	0.102

Run 2

RPM	h ft. H_2O	$\sqrt{h}$	Q cfs	v ft/sec	N_{Re}	Δ p ft. H_2O
0	22.071	4.698	0.046	2.08	40,739	0.368
278	22.071	4.698	0.046	2.08	40,739	0.269
423	22.071	4.698	0.046	2.08	40,739	0.248
611	21.966	4.687	0.045	2.04	39,956	0.241
754	21.924	4.682	0.045	2.04	39,956	0.240
1012	21.923	4.682	0.045	2.04	39,956	0.238
1204	22.018	4.692	0.045	2.04	39,956	0.235
1412	22.018	4.692	0.045	2.04	39,956	0.249
1617	21.987	4.689	0.045	2.04	39,956	0.257
1838	21.966	4.687	0.045	2.04	39,956	0.258

Run 3

RPM	h ft. H_2O	$\sqrt{h}$	Q cfs	v ft/sec	N_{Re}	Δ p ft. H_2O
0	33.306	5.771	0.056	2.55	49,945	0.554
270	33.306	5.771	0.056	2.55	49,945	0.446
461	33.390	5.779	0.056	2.55	49,945	0.394
618	33.337	5.774	0.056	2.55	49,945	0.372
795	33.357	5.775	0.056	2.55	49,945	0.367
1011	33.379	5.778	0.056	2.55	49,945	0.368
1208	33.357	5.775	0.056	2.55	49,945	0.360
1411	33.369	5.777	0.056	2.55	49,945	0.376
1622	33.369	5.777	0.056	2.55	49,945	0.369
1832	33.357	5.775	0.056	2.55	49,945	0.377

Run 4

RPM	h ft. H_2O	$\sqrt{h}$	Q cfs	v ft/sec	N_{Re}	Δ p ft. H_2O
0	8.820	2.970	0.082	3.73	73,046	1.311
277	8.841	2.974	0.083	3.77	73,829	1.129
420	8.841	2.974	0.083	3.77	73,829	1.002
613	8.841	2.974	0.083	3.77	73,829	0.899
817	8.767	2.961	0.082	3.73	73,046	0.835
1011	8.820	2.970	0.082	3.73	73,046	0.829
1206	8.873	2.979	0.084	3.82	74,810	0.812
1416	8.851	2.975	0.083	3.77	73,829	0.806
1633	8.820	2.970	0.082	3.73	73,046	0.807
1826	8.810	2.968	0.082	3.73	73,046	0.811
1963	8.810	2.968	0.082	3.73	73,046	0.818

Run 5

RPM	h ft. H_2O	$\sqrt{h}$	Q cfs	v ft/sec	N_{Re}	Δ p ft. H_2O
0	21.095	4.593	0.127	5.77	113,013	3.282
278	21.147	4.599	0.127	5.77	113,013	3.066
404	21.168	4.594	0.127	5.77	113,013	3.019
626	21.273	4.612	0.128	5.82	113,987	2.814
808	21.347	4.608	0.128	5.82	113,987	2.677
1011	21.399	4.612	0.128	5.82	113,987	2.578
1204	21.347	4.608	0.128	5.82	113,987	2.473
1407	21.294	4.602	0.128	5.82	113,987	2.447
1625	21.284	4.601	0.128	5.82	113,987	2.421
1830	21.242	4.596	0.127	5.77	113,013	2.384
1993	21.263	4.599	0.127	5.77	113,013	2.384

Run 6

RPM	h ft. H_2O	$\sqrt{h}$	Q cfs	v ft/sec	N_{Re}	Δ p ft. H_2O
0	32.477	5.699	0.157	7.136	139,826	4.542
277	32.676	5.716	0.158	7.181	140,630	4.311
418	32.750	5.723	0.158	7.181	140,630	4.169
620	32.918	5.738	0.158	7.181	140,630	3.944
814	32.246	5.679	0.157	7.136	139,826	3.665
1010	32.372	5.690	0.157	7.136	139,826	3.628
1209	31.393	5.692	0.157	7.136	139,826	3.534
1414	32.351	5.688	0.157	7.136	139,826	3.513
1625	32.382	5.691	0.157	7.136	139,826	3.497
1814	32.540	5.704	0.157	7.136	139,826	3.502

Run 7

RPM	h ft. H_2O	$\sqrt{h}$	Q cfs	v ft/sec	N_{Re}	Δ p ft. H_2O
0	15.960	3.995	0.242	11.00	215,449	11.246
275	16.034	4.004	0.243	11.05	216,429	11.004
409	16.108	4.014	0.243	11.05	216,429	10.679
615	16.232	4.029	0.244	11.17	217,996	10.248
812	16.274	4.034	0.245	11.13	217,996	9.949
999	16.359	4.045	0.245	11.13	217,996	9.613
1204	16.380	4.047	0.245	11.13	217,996	9.303
1409	16.391	4.049	0.245	11.13	217,996	9.093
1629	16.506	4.053	0.245	11.13	217,996	8.946
1833	16.527	4.065	0.246	11.18	218,975	8.804
2038	16.538	4.067	0.246	11.18	218,975	8.615
2238	16.622	4.077	0.247	11.23	219,954	8.605

Run 7 (Continued)

2431	16.611	4.076	0.247	11.23	219,954	8,605

CALCULATED DATA FOR CONSTANT RPM

0 RPM

Δp ft. H_2O	Q cfs	$\frac{\Delta p}{Q}$	$\frac{\Delta p \pi r^4}{8Ql\mu}$	N_{Re}
0.142	0.025	5.680	0.6332	22,250
0.368	0.046	8.000	0.8940	40,739
0.554	0.056	9.890	1.1040	49,945
1.311	0.082	15.990	2.4087	73,046
3.282	0.127	25.840	2.8857	113,013
4.542	0.157	28.930	3.2347	139,826
11.246	0.242	46.471	5.1899	215,449

277 RPM

Δp ft. H_2O	Q cfs	$\frac{\Delta p}{Q}$	$\frac{\Delta p \pi r^4}{8Ql\mu}$	N_{Re}
0.095	0.025	3.800	0.4246	22,250
0.269	0.046	5.848	0.6518	40,739
0.464	0.056	8.286	0.9250	49,945
1.129	0.083	13.603	1.5210	73,829
3.066	0.127	24.142	2.6943	113,013
4.311	0.158	27.285	3.0481	140,630
11.004	0.243	45.284	5.0595	216,429

418 RPM

Δp ft. H_2O	Q cfs	$\frac{\Delta p}{Q}$	$\frac{\Delta p \pi r^4}{8Ql\mu}$	N_{Re}
0.095	0.025	3.800	0.4246	22,250
0.248	0.046	5.390	0.6022	40,739
0.394	0.056	7.040	0.7984	49,945
1.002	0.082	12.070	1.3471	73,829
3.019	0.127	23.770	2.6570	113,013
4.169	0.157	26.390	2.9488	140,630
10.679	0.242	44.320	4.9540	216,429

617 RPM

Δp ft. H_2O	Q cfs	$\frac{\Delta p}{Q}$	$\frac{\Delta p \pi r^4}{8Ql\mu}$	N_{Re}
0.094	0.025	3.760	0.4203	22,250
0.241	0.045	5.355	0.5985	39,956
0.372	0.056	6.643	0.7388	49,945
0.899	0.083	10.831	1.2106	73,829
2.814	0.128	21.894	2.4460	113,987
2.944	0.158	24.962	3.0978	140,630
10.248	0.244	42.000	4.6932	217,996

808 RPM

Δp ft. H_2O	Q cfs	$\frac{\Delta p}{Q}$	$\frac{\Delta p \pi r^4}{8Ql\mu}$	N_{Re}
0.094	0.025	3.760	0.4203	22,250
0.240	0.045	5.333	0.5960	39,956
0.367	0.056	6.554	0.7325	49,945
0.835	0.082	10.183	1.1361	73,046
2.631	0.128	20.555	2.2970	113,987
3.665	0.157	23.344	2.6074	139,826
9.949	0.245	40.608	4.5380	217,996

1010 RPM

Δp ft. H_2O	Q cfs	$\frac{\Delta p}{Q}$	$\frac{\Delta p \pi r^4}{8Ql\mu}$	N_{Re}
0.091	0.025	3.640	0.4097	22,250
0.238	0.045	5.288	0.5898	39,956
0.367	0.056	6.554	0.7325	49,945
0.829	0.082	10.109	1.1299	73,046
2.578	0.128	20.405	2.2783	113,987
3.591	0.157	22.866	2.5515	139,826
9.613	0.245	39.196	4.3766	217,996

1206 RPM

Δp ft. H_2O	Q cfs	$\frac{\Delta p}{Q}$	$\frac{\Delta p \pi r^4}{8Ql\mu}$	N_{Re}
0.090	0.024	3.750	0.4221	21,370
0.235	0.045	5.220	0.5836	39,560
0.360	0.056	6.430	0.7201	49,945
0.812	0.084	9.660	1.0802	74,810
2.473	0.128	19.320	2.1604	113,987
3.534	0.157	22.510	2.5142	139,826
9.303	0.245	39.970	4.4511	217,996

1411 RPM

Δp ft. H_2O	Q cfs	$\frac{\Delta p}{Q}$	$\frac{\Delta p \pi r^4}{8Ql\mu}$	N_{Re}
0.098	0.024	4.083	0.4532	21,370
0.249	0.045	5.533	0.6183	39,956
0.376	0.056	6.714	0.7512	49,945
0.806	0.083	9.718	1.0864	73,829
2.447	0.128	19.118	2.1356	113,987
3.513	0.157	22.331	2.4956	139,826
9.093	0.245	37.114	4.1469	217,996

1623 RPM

Δp ft. H_2O	Q cfs	$\frac{\Delta p}{Q}$	$\frac{\Delta p \pi r^4}{8Ql\mu}$	N_{Re}
0.098	0.024	4.083	0.4532	21,370
0.257	0.045	5.711	0.6394	39,956
0.369	0.056	6.509	0.7388	49,945
0.807	0.082	9.842	1.0988	73,046
2.421	0.128	18.941	2.1169	113,987
3.497	0.157	22.274	2.4894	139,826
8.946	0.245	36.514	4.0787	217,996

1831 RPM

Δp ft. H_2O	Q cfs	$\frac{\Delta p}{Q}$	$\frac{\Delta p \pi r^4}{8Ql\mu}$	N_{Re}
0.102	0.024	4.250	0.4749	21,370
0.258	0.045	5.730	0.6394	39,956
0.377	0.056	6.730	0.7512	49,945
0.811	0.082	9.890	1.0554	73,046
2.384	0.127	18.770	2.0983	113,013
3.502	0.157	22.300	2.4894	139,826
8.804	0.246	35.790	3.9980	218,975

SAMPLE CALCULATIONS

The flow rate was calculated from the basic orifice equation:

$$Q = AK\sqrt{2gh}$$

$$h = \frac{h_m}{12} \; \frac{\rho_{Hg\ air\ temp} - \rho_{H_2O\ air\ temp}}{\rho_{H_2O\ flow\ temp}}$$

$$= \frac{844.11 - 62.08}{12 \times 62.16} h_m$$

$$h = (1.05\ h_m)\ \text{ft}\ H_2O$$

$$A = 0.00545\ D^2\ \text{ft}^2$$

$$A_{pipe} = 0.022\ \text{ft}^2$$

$$A_{.603} = 0.00198\ \text{ft}^2$$

$$A_{1.005} = 0.00550\ \text{ft}^2$$

$$A_{1.407} = 0.0179\ \text{ft}^2$$

then

$$Q_{.603} = 0.0160\ K\ \sqrt{h}\ \text{cfs}$$

$$Q_{1.005} = 0.0441\ K\ \sqrt{h}\ \text{cfs}$$

$$Q_{1.407} = 0.0866\ K\ \sqrt{h}\ \text{cfs}$$

The orifice coefficient K is dependent only on the size pipe, the β value and N_{Re}. N_{Re} was assumed and the corresponding K value was read from the table. (6). Using the data from the maximum flow rate with the 1.407 inch diameter orifice to illustrate, the procedure is shown below:

$h_m = 15.20$ in Hg

$h = 1.05 \times 15.20 \quad 15.96$ ft H_2O

$A = 0.01079\ ft^2$

$N_{Re} = 220{,}000$ (assumed)

$K = 0.7009$ (interpolated from table)

$Q = 0.0866 \times 0.7009\ \sqrt{15.96} = 0.242\ ft^3/sec$

$$V = \frac{.242}{.022} = 11\ ft/sec$$

$$N_{Re} = \frac{VD\rho}{\mu}$$

$$\frac{D\rho}{\mu} = \frac{\frac{2.010}{12} \times 62.16}{.53 \times 10^{-3}} = 19586.3$$

$$N_{Re} = 11 \times 19586.3 = 215{,}449$$

This value is sufficiently close to the assumed value.

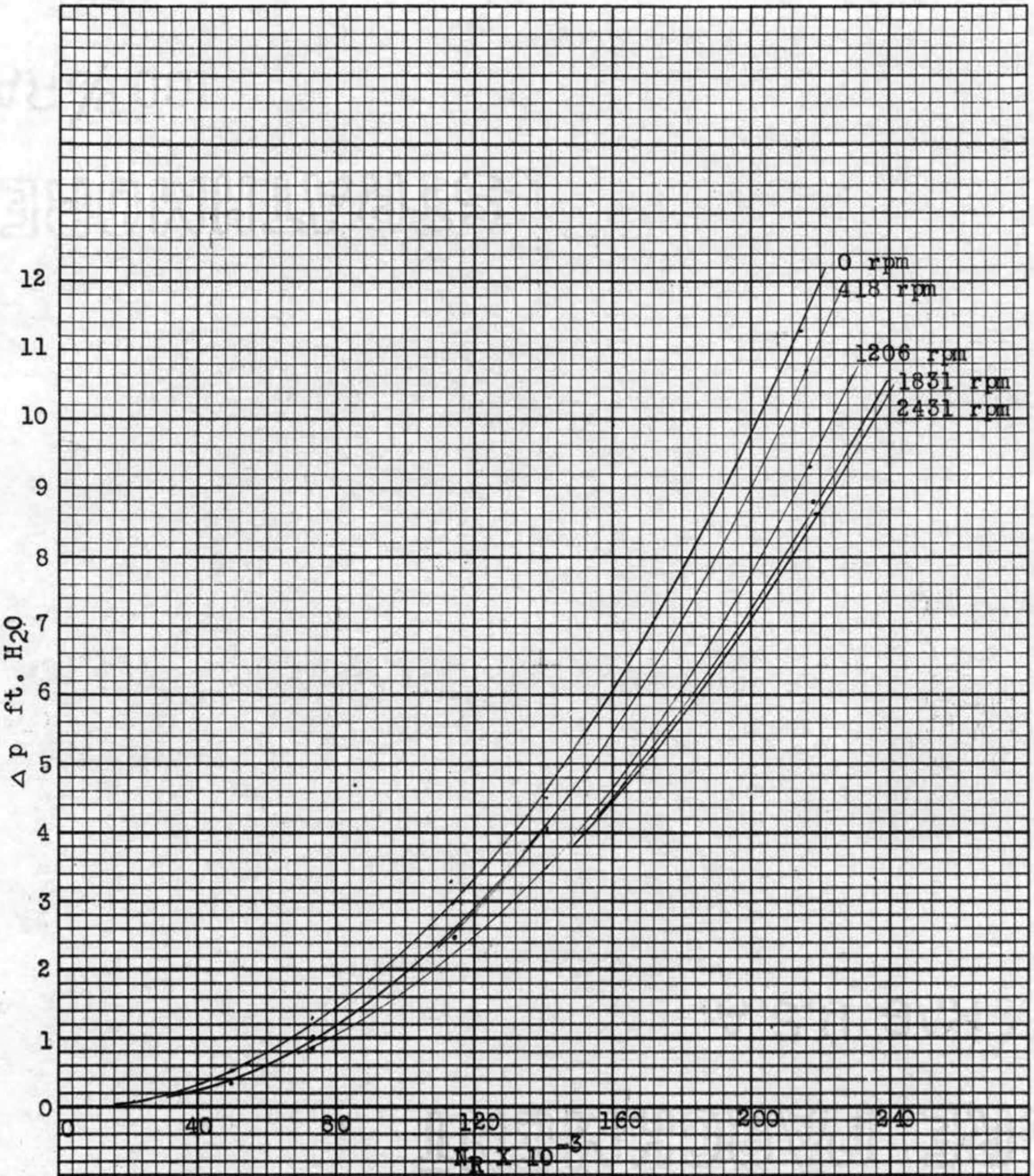

Fig. 4

Pressure Drop vs. Reynolds Number for Constant R. P. M.

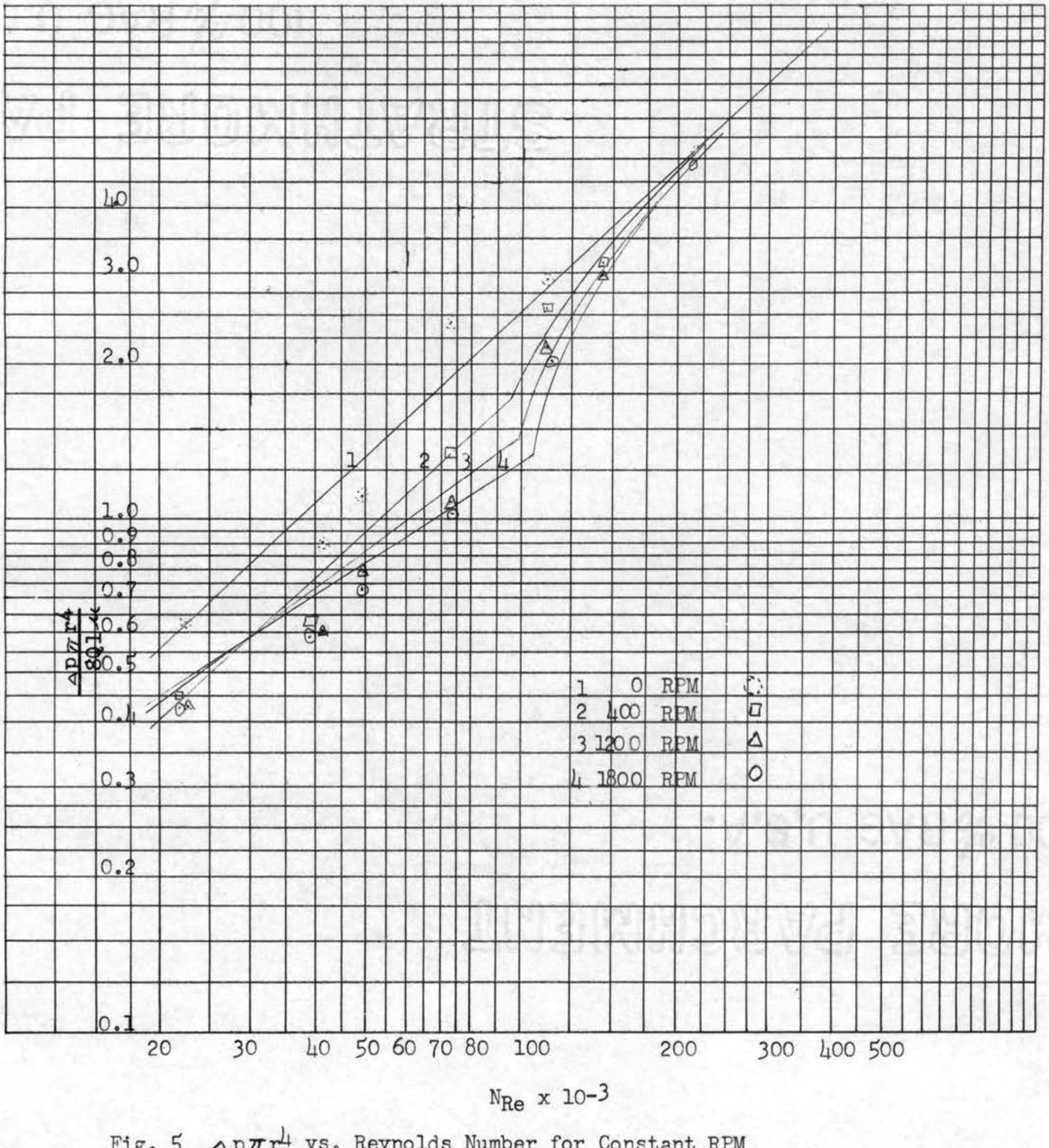

Fig. 5 $\frac{\Delta p \pi r^4}{8Ql\mu}$ vs. Reynolds Number for Constant RPM

TABLE I

Pressure Drop for Average Reynold's Numbers at Various Average Angular Velocities

Pressure Drop (Δp Ft Water)

N_{Re} / RPM	21,898	40,188	49,945	73,218	113,544	140,087	218,080
0	0.142	0.368	0.554	1.311	3.282	4.542	11.246
277	0.095	0.269	0.446	1.129	3.066	4.311	11.004
418	0.055	0.248	0.394	1.002	3.019	4.169	10.679
617	0.094	0.241	0.372	0.899	2.814	4.944	10.248
808	0.094	0.240	0.367	0.835	2.631	3.665	9.949
1010	0.091	0.238	0.368	0.829	2.578	3.628	9.613
1206	0.090	0.235	0.360	0.812	2.473	3.534	9.303
1411	0.098	0.249	0.376	0.806	2.447	3.513	9.093
1623	0.098	0.257	0.369	0.807	2.421	3.497	8.946
1831	0.102	0.258	0.377	0.811	2.384	3.502	8.804
1998				0.818	2.384		8.615
2238							8.605
2431							8.605

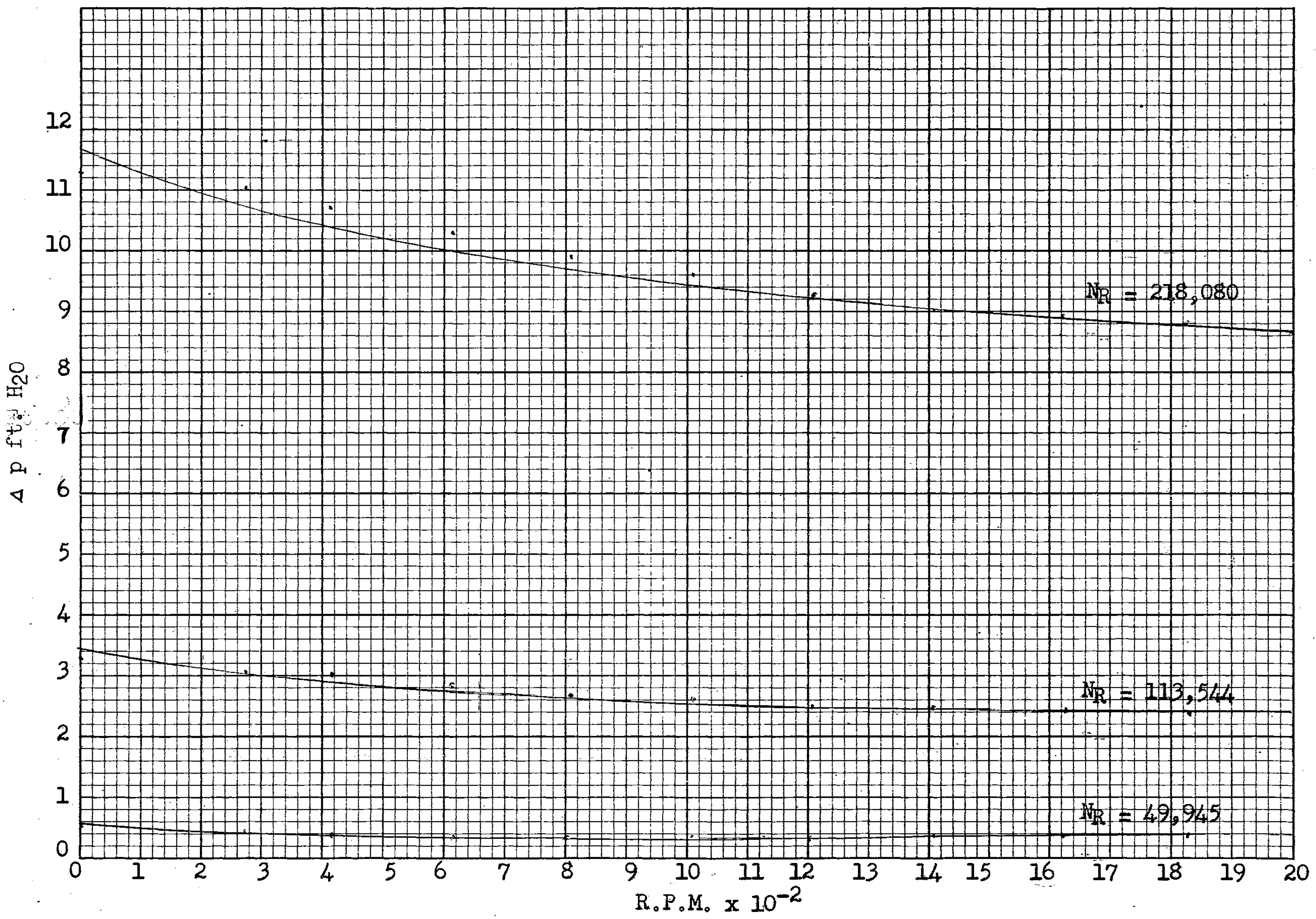

Fig. 6 Pressure Drop vs. Angular Velocity for Constant Reynolds Numbers

CHAPTER VII

INTERPRETATION AND DISCUSSION OF RESULTS

The result of the dimensional study, Eq. (1), shows the relation of pressure drop over the length of pipe to the other variables.

$$\Delta p = \left(\frac{8Ql\mu}{r^4\pi}\right) \times \phi\left[N_{Re}, \frac{l}{r}, \frac{\omega r^2\rho}{\mu}\right] \qquad (1)$$

Breaking the equation down it is noted that the pressure drop for the rotating tube is expressed as Poiseuille's pressure drop for laminar flow times a function of Reynolds number, ratio of length to radius, and the ratio of angular momentum to viscosity. (7). Since l, r, and μ are constant for a given tube and fluid Eq. (1) shows that the pressure loss is proportional to the flow rate times a function of Reynolds number and angular momentum.

Fig. 4 shows that the pressure loss decreases as the rotational speed increases. The curve taken at 400 rpm is almost parallel to the curve taken at zero rpm but is displaced to the right. As the angular velocity was increased above 400 rpm, the slopes of the lines of constant angular velocity decreased to a minimum at 1,800 rpm.

Fig. 5 is a plot of $\frac{\Delta p \pi r^4}{8Ql\mu}$ vs N_{Re} for constant rpm on log-log coordinates. On this plot the zero rpm line is a straight line. The lines representing less than 400 rpm are parallel to it, but displaced to the right. The slopes of lines representing constant angular velocities greater than 400 rpm decrease to a minimum value at 1,800 rpm as the angular velocity increases.

All of the constant angular velocity curves make a sharp break close to values of Reynolds number equal to 100,000 and approach the stationary pipe flow condition asymptotically.

Fig. 6 is a graphical representation of Table I, showing that the pressure loss reduction reaches a minimum between 1,200 rpm and 2,000 rpm, depending on the flow rate. Above the angular velocity at which the minimum values occured, the slope of the pressure drop curves increased slowly as the rpm increased.

The curves shown in this work have the same general shape as other investigation curves which represent similiar conditions. (1), (2).

Eq. (1), and Figs. 4, 5, and 6 imply that when a proper balance of dynamic and centrifugal forces exist a reduction of pressure loss is achieved. The term $\frac{r^2 \omega \rho}{\mu}$ from Eq. (1) is a function of the amount of work the fluid may absorb. The rotational work absorbed by the fluid tends to stabilize or restrict the random motion of the water particles. For flow rates corresponding to Reynolds number greater than 100,000 the dynamic forces overcome the rotational effect and the pressure drop approaches the value for the stationary pipe condition. For flow rates corresponding to Reynolds number less than 30,000 the centrifugal forces are greater than are needed to stabilize the flow and the flow rate is retarded.

From this study it would appear that the pressure drop varies from values produced by streamline flow as the lower limit to values produced by pure turbulent flow as the upper limit. When streamline flow exists the value of

$$\phi \left[N_R, \ \frac{1}{r}, \ \frac{r^2 \omega \rho}{\mu} \right] \text{ is equal to unity,}$$

and the constant angular velocity lines would plot as straight horizontal lines on a log-log coordinate plot.

Close observation of Table I and Fig. 6, reveals that for all flow rates at least half of the pressure drop reduction occurred by 600 rpm. Even for the maximum flow rate corresponding to a Reynolds number of 218,000, 5/6 of the total reduction occured by 1,200 rpm. These observations become important when considering this work in light of actual oil well drilling where the rotary speed is limited, depending on various conditions.

Since the use of the orifice in a flow with swirl was not in accord with best practice it was necessary to determine if the rotation affected the accuracy of the flow measurement. A volumetric check was made by recording the time for the fluid level to rise a given amount in a tank. The quantity of flow is equal to the product of the time for water to rise in the tank and the square root of the orifice manometer reading multiplied by a constant. Table II shows that the product of time and the square root of the orifice reading was constant for various angular velocities using the largest orifice plate at the maximum flow rates. The rotation did not affect the flow measurement for this condition and since the smaller orifice plates exercise a greater damping effect on flow disturbance, it was concluded that the rotation did not affect any of the flow measurements.

In order to compare the data, all flow calculations were made for average environmental conditions during the experiment. Thus flow rates are for atmospheric pressure of 29.35 inches of mercury, a temperature of 90°F and the flowing temperature of 86°F. An average value of angular velocity was used to plot the constant rpm lines of Figs. 4 and 5. Also an average value of Reynolds number was used to tabulate the constant

TABLE II

Effect of Rotation on Orifice Accuracy

RPM	T	h_m	$\sqrt{h_m}$	$T\sqrt{h_m}$
0	1.230	14.97	3.869	4.758
432	1.218	15.22	3.901	4.745
818	1.222	15.23	3.905	4.772
1210	1.197	15.70	3.962	4.744
1624	1.193	15.80	3.975	4.742
2051	1.189	15.92	3.991	4.744

N_{Re} values of Table I.

It is believed that possibly the source of the greatest error is the presence of air within the system. Air would be separated by the pipe rotation. If the air became separated, two phase flow might exist and the resulting reading of pressure drop would be much too high. It is recommended that future tests be conducted in a closed system. Since facilities were not available for a closed system, every effort was made to eliminate the air. As shown in Figs. 2 and 3, air bleeds were installed at each pipe tap as well as on each manometer. Care was taken to assure that there was no leakage around the pump impeller or at any place in the piping; also the discharges into the tank were kept well under water. The water was circulated through the system several times prior to the test to allow the air to be removed.

The largest standard deviation from the mean for any data was 1.25% and the largest residual from the mean was 1.30%. Considering these errors and the errors due to averaging and rounding, the data of this experiment can be reproduced within ± 4%.

This work was an original investigation into the effect of rotation on fluid flow. More experimental and theoretical work is needed before this study can be directly applied to petroleum drilling. However, it is believed that the results presented in this work can be extrapolated by dimensionless methods (see Appendix) to lend an insight as to what might be expected in a field situation. The values obtained by extrapolating the observed data of the 2 1/4 inch tubing to the 5 1/2 inch drill pipe using the relations of the Appendix is shown in Fig. 7.

Fig. 7 reveals that for 5 1/2 inch drill pipe the stabilizing effect should extend to a value of Reynolds number equal to 200,000, and that the maximum pressure loss reduction should occur at 450 rpm with a

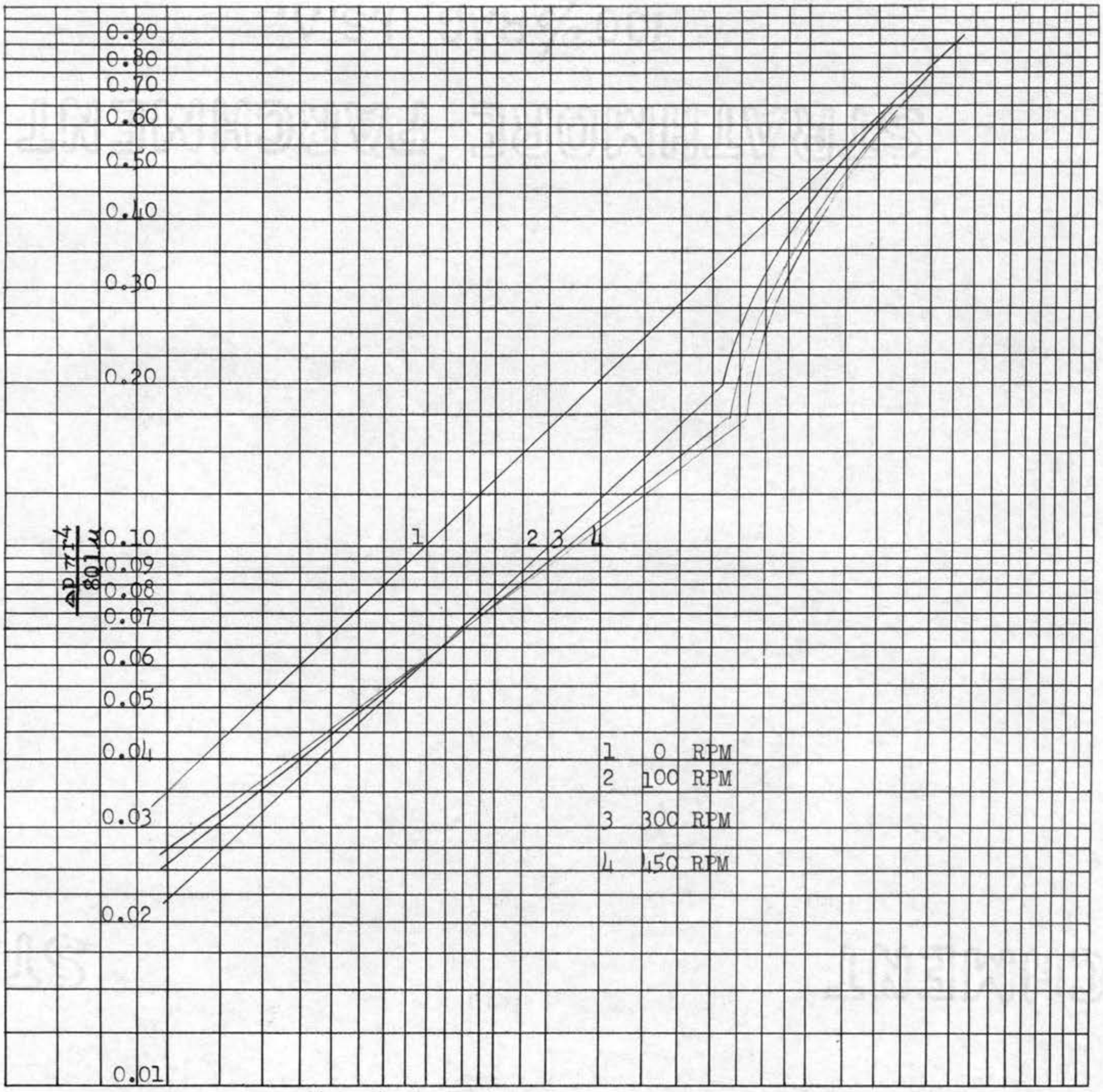

Fig. 7 $\frac{\Delta p \pi r^4}{8Ql\mu}$ vs. Reynolds Number for Constant RPM for Drill Pipe significant reduction occuring above 100 rpm.

Since the power to turn the rotary table is small compared to the power required to maintain circulation, these observations indicate that if the rotary speed were increased above 100 rpm a net power saving could be achieved.

BIBLIOGRAPHY

Literature Cited

(1) Anonymous, *Hydraulics in Rotary Drilling,* Bulletin No. 1-A. Houston: Hughes Tool Company, April 1954.

(2) Levy, F., "Flow Phenomena in Revolving Tubes" *Forschemzsonbeiten auf den Sebietc des Ingenieurwessens,* number 322, pp 8-45, 1929.

(3) Richardson, E. F., *Dynamics of a Real Fluid,* London: Edward Arnold and Co., 1950.

(4) Focken, C. M., *Dimensional Methods and Their Application,* London: Edward Arnold and Co., 1953.

(5) Anonymous, *Orifice Metering of Natural Gas,* Measurement Committee Report No. 3, New York: American Gas Association, April 1955.

(6) Anonymous, *Fluid Meters Their Theory and Application,* Fourth Edition. New York: American Society of Mechanical Engineers, 1937.

(7) Green, Henry, *Industrial Rheology and Rheological Structures.* New York: John Wiley and Sons, Inc., 1959.

Other References

Bakhmeteff, Boris V., *The Mechanics of Turbulent Flow.* Princeton, New Jersey: Princeton University Press, 1936.

Bakhmeteff, Boris V. and Allen, William, "Mechanisms of Energy Loss in Fluid Friction", *American Society of Civil Engineers Proceedings,* Vol. 71, pp 129-166, February 1945.

Binder, R. C., *Fluid Mechanics,* Second Edition. New York: Prentice-Hall, Inc., 1949.

Karman, Th. V., "Some Aspects of Turbulence Problem", *Mechanical Engineering,* Vol. 57 pp. 407-412, July 1935.

Pai, S. L. "Turbulent Flow in Circular Pipes", *Franklin Institute Journal,* Vol. 256, pp. 337-352, October, 1953.

Perkins, C. L., "Stability of the Laminer Parabolic Flow of a Viscous Fluid Between Parallel Fixed Walls", Physical Review, Vol. 74, pp. 191-199, July, 1948.

Rouse, Hunter, "Modern Conception of the Mechanics of Turbulence", Society of Civil Engineering Proceedings, Vol. 62, pp. 21-63, January, 1936.

Storran, J. A. and Zychlin, H., "Flow Through Whirling Tubes", Journal of Society of Chemical Industry, Vol. 69, pp. 379-384, December, 1950.

Vennard, John K., Elementary Fluid Mechanics, Second Edition, New York: John Wiley & Sons, Inc., 1947.

APPENDIX

Using the constants derived in this study, a comparative analysis between Acme 5 1/2 inch streamline drill pipe and 2 1/4 inch tubing yield the following relations:

$\frac{1}{r}$ drill pipe $=$ $\frac{1}{r}$ tubing

(l) drill pipe $=$ $2(l)$ tubing

$\frac{\omega r^2 \rho}{\mu}$ drill pipe $=$ $\frac{\omega r^2 \rho}{\mu}$ tubing

(ω) drill pipe $=$ $1/4(\omega)$ tubing

N_{Re} drill pipe $=$ N_{Re} tubing

Q drill pipe $2Q$ tubing

V drill pipe $=$ $2V$ tubing

$$\frac{\Delta p}{Q} \text{ drill pipe} = \frac{8 \times 2l_{tubing}\, \mu}{(2r_{tubing})^4\, \pi}$$

$$= \frac{1\, l_{tubing}\, \mu}{(r_{tubing})^4\, \pi}$$

$$\frac{\Delta p}{Q} \text{ tubing} = \frac{8\, l\, \mu}{r^4 \pi}$$

$$\frac{\Delta p\, \pi\, r^4}{8Ql\mu} \text{ drill pipe} = 1/8\, \frac{\Delta p \pi r^4}{8Ql\mu} \text{ tubing}$$

VITA

Howard Hulen Ferrell

Candidate for the Degree of

Master of Science

Thesis: AN INVESTIGATION OF PRESSURE DROP THROUGH ROTATING PIPE

Major Field: Mechanical Engineering

Biographical:

Personal data: Born in Shreveport Louisiana, April 11, 1929, the son of Bun O. and Eva Cotton Ferrell.

Education: Attended grade school in Houston, Texas; graduated from Lamar High School, Houston, Texas in 1947; received the Bachelor of Science degree from Oklahoma Agricultural and Mechanical College, with a major in Mechanical Engineering, in August, 1951; completed requirements for the Master of Science degree in Septmember, 1956.

Professional experience: In August, 1951 employed by Stanolind Oil and Gas Company as Engineer in Training; entered United States Navy in May, 1952, and rose to the rank of Lieutenant Junior Grade before separation in September, 1955.

Honorary Organizations: Member Pi Tau Sigma (national honorary mechanical engineering fraternity)