6-30-1956

Liquid-gas flow in venturi meter and sharp edged orifice

Frank John Chwalek
New Jersey Institute of Technology

LIQUID-GAS FLOW IN VENTURI METER
AND SHARP EDGED ORIFICE

BY

FRANK J. CHWALEK

A THESIS
SUBMITTED TO THE FACULTY OF
THE DEPARTMENT OF CHEMICAL ENGINEERING
OF
NEWARK COLLEGE OF ENGINEERING

IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

OF

MASTER OF SCIENCE
IN CHEMICAL ENGINEERING

NEWARK, NEW JERSEY

1956

ABSTRACT

The results of a study of pressure drops across a 5/32 inch throat venturi meter and a 5/32 inch thin plate sharp-edged orifice for the horizontal cocurrent, flow of the air-water two-phase two-fluid system in a 3/4 inch pipe under essentially isothermal conditions, are presented. This is the first critical study of two phase flow in a Venturi meter and in a 5/32" orifice.

Flows of water of 0.1 to 1.7 gallons per minute with air rates in range of 0.00022 lbs/sec. to 0.0092 lbs/sec. of air mixed in were studied. All flows were turbulent when judged with the conventional Reynolds number criteria. It was found that two phase two fluid flow in this region was not steady but fluctuated.

Predicted pressure drops calculated with the Chenoweth-Martin Correlation (1) gave results which were 50% to 150% too high for the orifice. An improved correlation is presented which gives predicted pressure drops to within 15% of the actual results for 85% of the data calculated, for both the orifice and the Venturi.

It is shown that temperature has important influence on single phase water flow in venturi, a 10% increase in pressure drop being observed with temperature rise in tap water from 10°C to 40°C.

(1) Ref. 10

APPROVAL OF THESIS

FOR

DEPARTMENT OF CHEMICAL ENGINEERING

NEWARK COLLEGE OF ENGINEERING

BY

FACULTY COMMITTEE

APPROVED: ______________________

____

____

NEWARK, NEW JERSEY

JUNE 1956

PREFACE

This thesis is the result of interest developed through two phase two fluid flow studies at the Newark College of Engineering Advanced Unit Operations Laboratory.

Work done by Martinelli (2), and simplified by Bergelin (3) indicated that an empirical method for estimating liquid-gas mixture pressure drops in a Horizontal pipe line system was possible.

It was decided to study the problem, using a controlled and well established medium for flow measure and pressure drop. The venturi meter and orifice were selected as this media.

Alves (4) re-studied the work of Martinelli and presented an inconclusive pressure drop study across for a return bend and a tee, with openings in a vertical plane.

Chenoweth and Martin (5) proposed an improved correlation encompassing valves, fittings and an orifice, using standard friction coefficients for the fittings.

Their data were published during the preliminary investigations on this thesis.

(2) Ref. 5 (3) Ref. 4 (4) Ref. 11 (5) Ref. 10

The apparatus for this thesis was designed, constructed and operated by the Writer at the Newark College of Engineering.

The writer wishes to thank Professor G.C. Keeffe for his guidance in this project and Mr. Furmadge of the Operations Laboratory for his assistance in the construction of the apparatus.

TABLE OF CONTENTS

FIGURES

LIST OF TABLES

INTRODUCTION

This thesis was undertaken to study the isothermal flow of a two-phase two-fluid system across a venturi and an orifice, with the purpose of developing a correlation to predict more accurately actual pressure drops.

Air and water were selected as the fluids to be studied. Nitrogen and carbon dioxide were considered for study but these were not pursued; it was felt that the molecular weight of Nitrogen and its physical characteristic were close enough to that of air to not make its study significant. Data, to date, on the air-water system gives reproducibility to only 50%. Carbon dioxide posed a solubility problem which would remove the study from the realm of "mixtures".

Equipment was installed to permit any liquid to be used, especially to study effects of surface tension, but the work was beyond the scope of this thesis.

Martinelli (2) originally proposed an empirical correlation for the estimation of pressure drops for a two-fluid two-phase mixture in a Horizontal pipe and his results were presented by Bergelin (3) as "more usable" data. His correlation gave reproducibility of +28% and -50% in Horizontal $1\frac{1}{2}$" pipe when the overall average pressures were low, that is in the neighborhood of 18 PSIA. The use of his method involves the calculation of a parameter X which involves the

(2) Ref. 5 (3) Ref. 4

ratio of the pressure drop of the liquid to that of the gas, each pressure drop being calculated as if the fluid were flowing alone in the system. These pressure drops are calculated by the standard Reynolds number & Fanning Equation theory but are modified by factors which are obtained from empirical data obtained by Martinelli. These factors are dependent of flow characteristics of the fluids and are determined by a study of the Reynolds Numbers of the individual fluids. The two phase pressure drop is determined from parameter ϕ which is obtained from a plot of ϕ vs. X.

Experiments in this laboratory indicate the above correlation for air-water flow in $\frac{1}{2}$" pipe agrees within the limits of experimental accuracy as noted.

Alves (4) in 1954 presented his work on 1" pipe which bore out the results as obtained by Martinelli.

The standard return bend and side flow through a "Tee" are discussed briefly for the above fittings, published values of pressure drops expressed as equivalent lengths of pipe, hold for two phase two fluid flow, for the limited cases studied. It is pointed out, however, that his results are inconclusive in this respect. One of the chief difficulties lying in the fact that the fittings lay in a vertical plane - the differences in static head being mathematically corrected.

(4) Ref. 11

The results for pressure drops in straight pipe flow agree, within experimental accuracy, with those of Bergelin.

Alves presents an excellent physical and pictorial description of the "types" of flow encountered in his two phase air-water system, i.e. bubble, plug, stratified, wavy, slug, annular, and spray flows.

Chenoweth and Martin (5) present the latest (October 1955) work on two-phase two-fluid system pressure drops, an improved correlation being presented for test sections of 1½" and 3" pipe size as well as a 3" globe valve, 3" long radius return bend, and, of greatest interest to this thesis, a sharp edged orifice of diameter ratio 0.55. Apparatus used by Chenoweth was essentially the same as that of Martinelli and Alves. However, where Martinelli limited his studies to a maximum of 50 PSIG and 1" pipe, Chenoweth worked with 1½" and 3" pipe for pressures up to 100 PSIA. It was noted that the Martinelli correlation gave calculated results up to 250% too high for 3" pipe and 100 PSIA.

For turbulent flow Chenoweth offers an improved empirical correlation, which tends to correct for pressure. The correlation is a plot of two phase pressure drop divided by a fictitious all liquid pressure drop versus the Liquid Volume Fraction with the ratio of the fictitious "all gas" to the fictitious "all liquid" pressure drop for the system as a parameter. Figure 8 shows their complete correlation. Using the Chenoweth correlation, the average of absolute deviations is 19% for 1½" and 3" Horizontal pipes, for turbulent flow.

(5) Ref. 10

Chenoweth treats fittings by using the single phase friction coefficient for the fitting, as suggested by the Hydraulic Institute in 1948 (6). Inspection of Figure 8 shows that the parameter is reduced to the ratio of the specific gravities of the fluids at the test section, simplifying the calculations for orifice and Venturi alike.

The work presented in this thesis studies the air-water system through a test section of 3/4" pipe and a specially designed standard orifice and venturi meter, each having a nominal throat diameter of 5/32 inch. Flows of water varied from 0.1 to 1.7 GPM, being mixed with from 0.00022 to 0.0092 lbs/sec. of air. Throat pressures varied from 2 to a maximum of 30 PSIG. These ranges were selected to give a complete range of pressure drops of up to 50 inches of mercury; and the Venturi and orifice diameter of 5/32-inch was, by design, most suitable for producing the suitable pressure drops with available laboratory equipment. The design of the equipment proved to be very satisfactory for the study undertaken.

A literature survey was made on the "Pease Anthony" Venturi scrubber inasmuch as pressure drop across a Venturi scrubber are a measure of its efficiency (7). All references indicate a flow rate of from 2 to 6 GPM of water per 1000 CFM of air with a 9 to 15 inches of water pressure drop.

(6) Ref. 12 (7) Ref. 1, 15, 16, 17 & 18

Considerable work has been done on two phase single fluid flow in orifices and to a lesser extent in venturies. (See Ref. 21, 22, 23, 27, 30.). Monroe (11) has developed an equation for relationship among a series of knife-edged orifices for the following variables: mass flow, viscosity, temperature, density, and pressure drop across all the orifices.

The most important system for single fluids is steam and water - and much work has been done in this direction for steam trap design, boiler design and related equipment.

(11) Ref. 27

EQUIPMENT

The equipment was designed and installed strictly in accordance with Figure 1 and the Equipment Schedule which is part of Figure 1. It is to be noted that three test sections were available, Test Section V for all Venturi runs, Test Section O, for runs 19 through 22, and Test Section O_2 for all other orifice runs. Pressure taps for Venturi and Orifice were standard, as indicated in Figures 2 and 3 except for Test Section O_2 which had pressure taps 38 pipe diameters up and downstream of orifice as shown in Figure 1.

The temperature, pressure, and pressure drop measuring instruments are labeled to conform to match the calculated and uncalculated data columns in Tables 2 and 3, except for rotameter readings R_A and R_W which are obviously for air and water and are tabulated in Column 4 and 8, respectively, in Table 2.

Water Rotameter "L" was calibrated and found correct to ±.05 G.P.M.; pressure gages were checked to maximum of 50 inches of mercury and were correct to ±.5 PSIG, the maximum deviation occurring below 5 PSIG.

EQUIPMENT SCHEDULE

A - Pressure Reducer, Foster Engineering Company #567030, 1/2", 10 SCFM air from 90 PSIG to 45.

B - Safety Valve, Lunk. 629, 1/2" Bronze, Set at 45 PSIG, when used.

C - Temperature Indicator, glass laboratory thermometer, range -10-0-60°C.

D - Compound Gage, Ashcroft 1010, range -30-0-60 PSIG; 3 1/2" Dial

E - Fischer and Porter Company, SCFM Air Meter @ 14.7 P.S.I.A. and 70°F., Range 0.3 to 3.5, Serial No. W5-1326-2

F - Fischer and Porter Company, SCFM Air Meter @ 14.7 P.S.I.A. and 70°F., Range 0.1 to 1.2, Serial No. W5-1326-1

G - Schutte Koerting Syphon Fig. 217, 1/2" Size, Bronze, Capacity 270 GPH at 40 PSIG, 1 Ft. Suction and 20 Ft. Discharge

H - Schutte Koerting Water Jet Eductor, Fig. 264, 1/2" Size, Bronze, Capacity 127 GPH Water @ 10 PSIG Pressure, 0 Suction, 0 Discharge

J - Liquid Pump, Oberdorfer, 1/2" x 1/2" Bronze, Capacity, by Lab test, approx. 4 GPM @ 40 PSIG

K - Pressure Gage 0-120 PSIG

L - Rotameter, Brooks Type I Serial 399, 0.1 to 1.7 GPM of 1.0 Sp.

Gravity fluid, Tube Size R-8M-25-2. (For water service)

M - Venturi Tube - See Figure 2 (For Test Section V, in Figure 1) - 5/32" Throat with standard Venturi Angles.

N - Manometer, Miriam, Type W, Model M-100, Serial C-14941, Range 50 inches

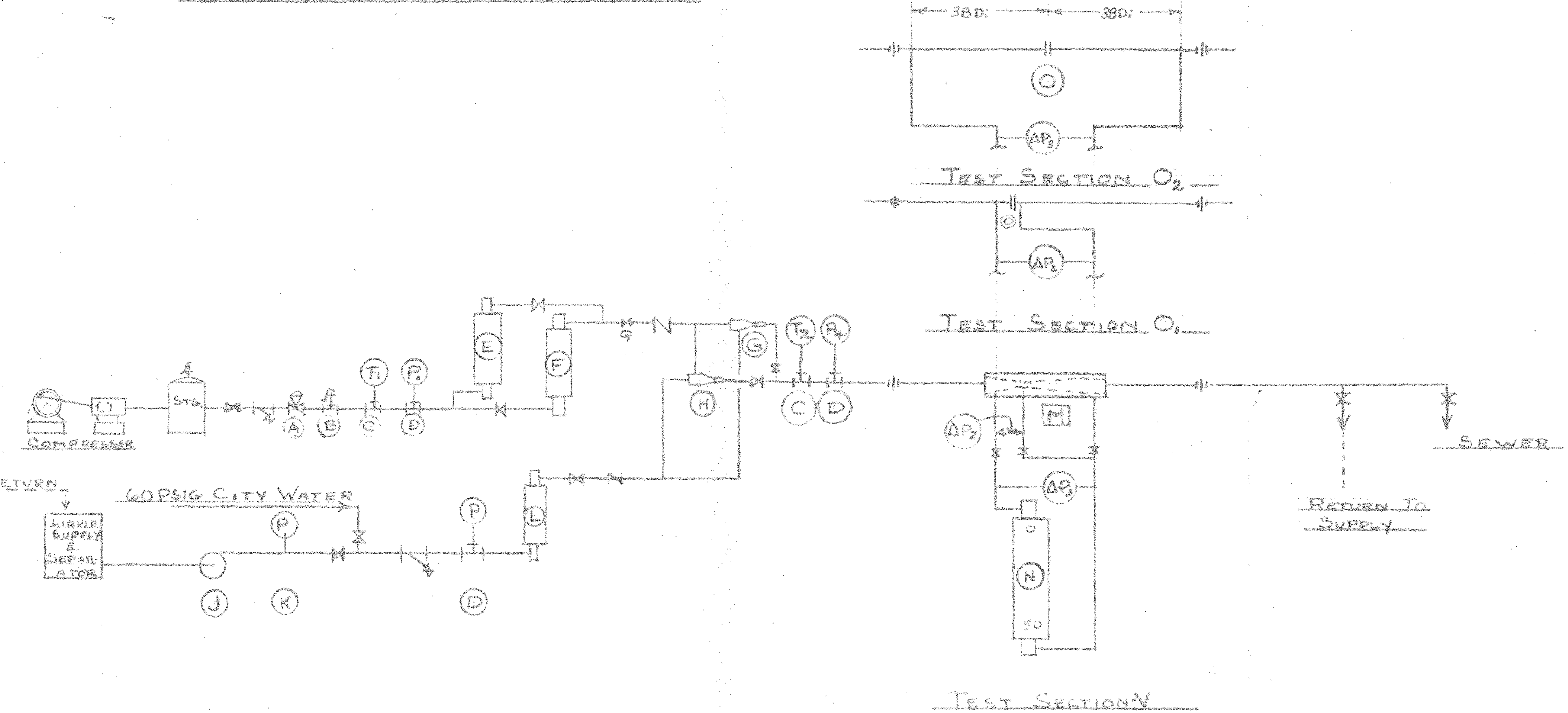
O - Orifice, - See Figure 3 (For test sections O_1 & O_2 in Figure 1) Approximately 9/64, sharp edged.

Q - Globe Valve

FIGURE - 1

LIQUID-GAS FLOW IN VENTURI METER AND SHARP-EDGED ORIFICE

"ENGINEERING" FLOW DIAGRAM



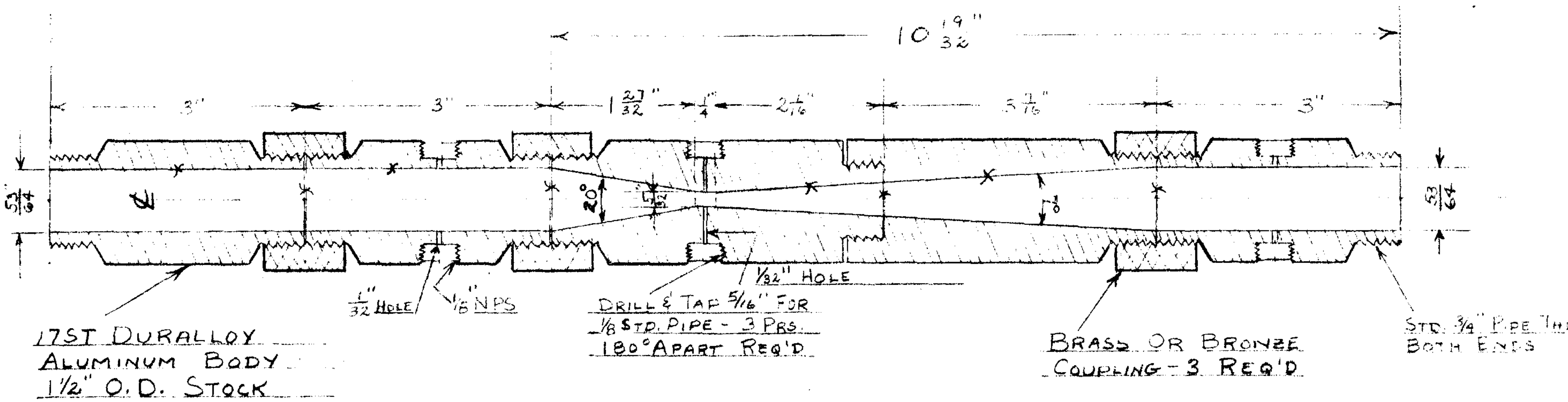
SEE EQUIPMENT SCHEDULE FOR DESCRIPTION OF ITEMS. ALL TEST SECTIONS MADE OF 3/4" NPS SCHED. 40 GALV. STEEL PIPE AND GALV. 125 LB C.I. SCWD FITTINGS

F.J.C.
4-10-56

EXPERIMENTAL VENTURI NOZZLE

FIGURE 2

1/2" = 1" - SCALE



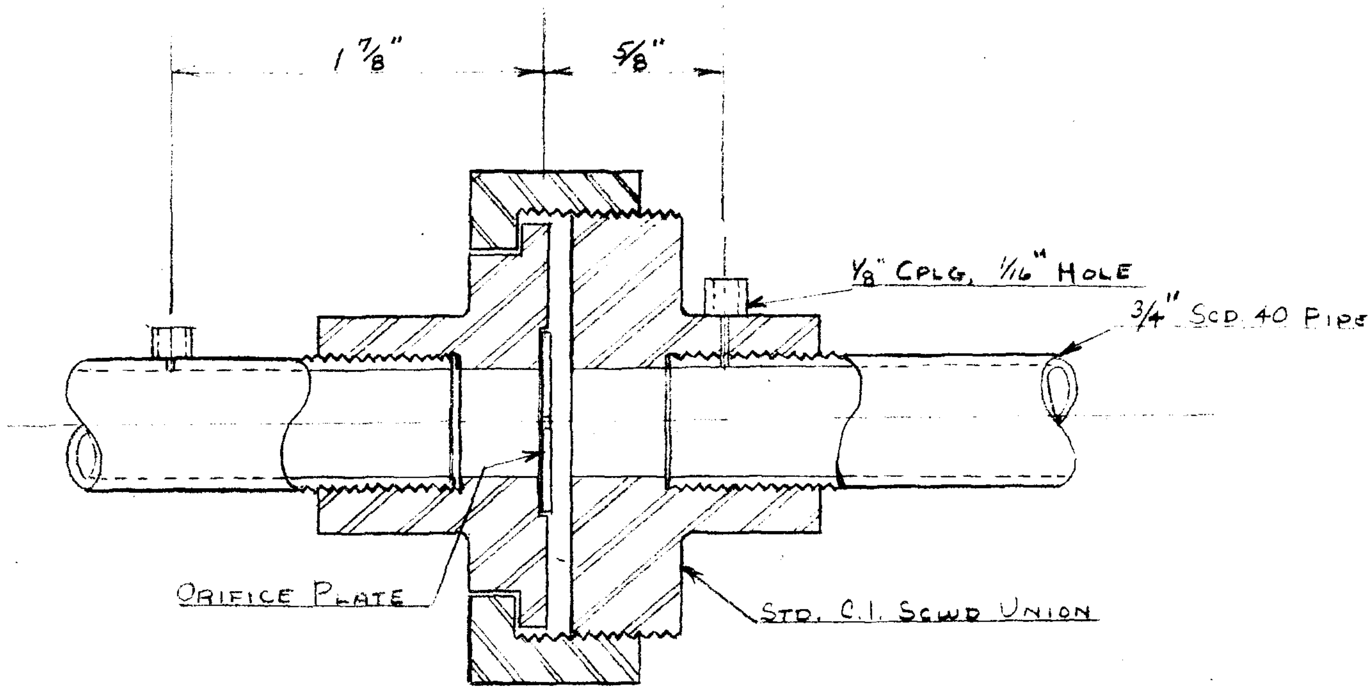
NOTE

ALL INTERNAL & MATING SURFACES - CLASS 3½ FINISH*.
ALL INTERNAL JOINT-SURFACES MUST BE SMOOTH TO FEEL,
AFTER ASSEMBLY & WATER TIGHT AT 100 PSIG -.
NO GASKETS PERMISSIBLE.
*32 MICROINCHES - NEW G.E. ROUGHNESS SCALE - CAT 342×60

FIGURE 3

ORIFICE DETAILS

(NO SCALE)



ORIFICE UNION SECTION

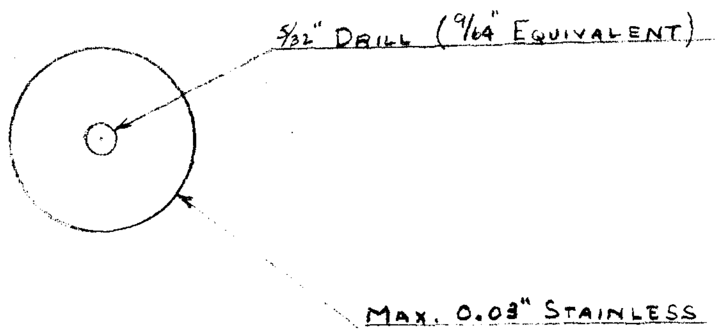


PLATE
ORIFICE DETAIL

JC
5-4-56

PROCEDURE

The operation of the apparatus, as shown in Figure 1, was successfully done by always keeping a positive water pressure on the system, i.e. keeping air out of the manometer taps.

A constant flow of water, 1.0 GPM for example, was maintained through water rotameter - L and flow of air through the rotameters E (or F) was varied by controlling globe valve Q. Pressure was adjusted at regulator A to keep P_1 at a constant pressure. Jet-G was designed to be used for high air flows and low water flows; and Jet-H for high water flows and low air flows. In practice it was found that jet selection was not critical.

Pressure downstream to the test sections was controlled by valves at the discharge.

It is of note that several minutes were required for each reading to manipulate the equipment and approach reproducable conditions. A study of the data in Tables 2 and 3 will indicate that many single phase, water test runs were made to check and re-check reproducibility. However, once the system was properly freed of trapped air pockets, by vents not shown in Figure 1, very little trouble was experienced from the equipment and water alone always gave very reproducable results.

No temperature control was attempted, other than permitting equipment to reach "steady" condition.

RESULTS

The data obtained are presented in Tables 1, 2, and 3. Table 2 includes laboratory data for which calculations were made, Table 3 includes only data for which no calculations were made. Inspection of the data in Table 3 indicates reasonable reproducability. Data were selected for calculation at random, to give a complete range of coverage.

Single phase water-flow vs. temperature of water are plotted in Figure 4.

Figure 5 incorporates single phase pressure drop versus water flow calculated using standard formulae for orifice and venturi and actual experimental results.

Figures 6 and 7 are plots of water flow rate versus pressure drop at all air flows studied.

Figure 14 is a plot of water flow versus pressure drop as obtained experimentally and used in calculations for determining the "all liquid" pressure drop.

Figure 15A and Figure 15B are the plotted predicted pressure drops versus actual pressure drops.

Note that each of the Figures 15A and 15B indicates a correction equation for modifying the predicted result to give the actual pressure drop within 15% (approximate) accuracy for 85% of the data plotted.

DISCUSSION

In initial runs while the equipment was being tested, it was observed that here was a marked increase in pressure drop across the venturi with an increase in temperature. A study of Figure 4 shows grouping of data when temperature of the water was in the range of 12 to 22°C, but a further increase in temperature to 40° caused a 10% increase in pressure drop.

These data were plotted from runs where warm tap water was run through Test Section-V, during start up and continued as the tap water cooled to outside (winter) conditions.

The grouping of the data at the lower temperatures is explained by the fact that runs were made on different days when solubility of air in water probably varied. Variations in the low temperature group was about 2 to 3%.

Figure 5 shows the comparison of calculated pressure drops of single-phase water flow in the venturi and in the orifice as well as experimental results. The curves for the venturi coincided; the curves for the orifice did not. The orifice deviation is explained by the fact that the unit was "home-made" and subject to the calibration curve for laboratory use. Figure 5 served as a calibration curve for the orifice for subsequent calculations.

Figure 5 is a plot of Table 5, the orifice calculations being obtained from these values, corrected, for orifice coefficients.

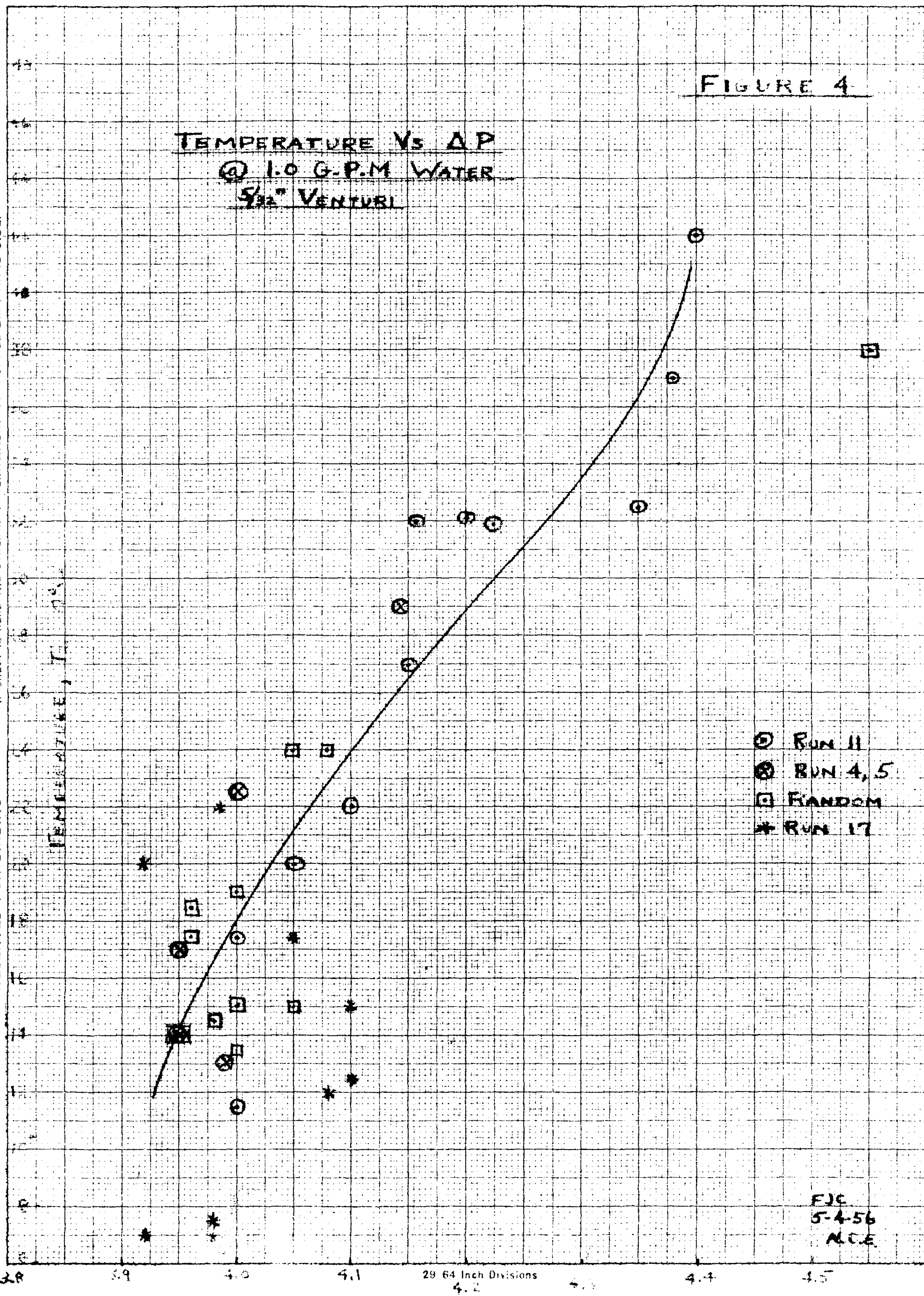


FIGURE 4
TEMPERATURE Vs ΔP
@ 1.0 G.P.M WATER
5/32" VENTURI
TEMPERATURE, T
RUN 11
RUN 4, 5
RANDOM
RUN 17
29 64 Inch Divisions
3.8
3.9
4.0
4.1
4.2
4.4
4.5
FJC
5-4-56
M.C.E.

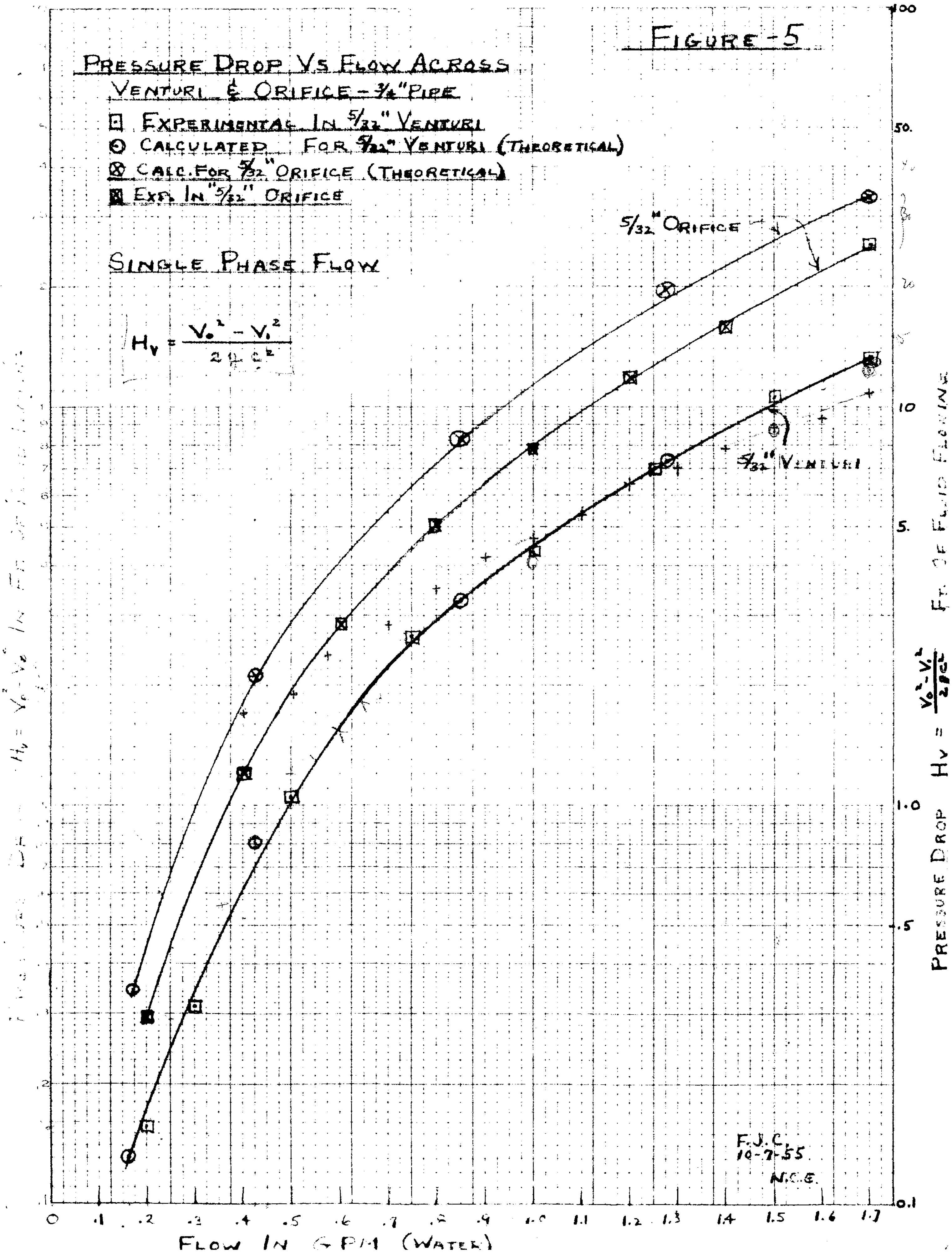


FIGURE - 5
PRESSURE DROP VS FLOW ACROSS
VENTURI & ORIFICE - 3/4" PIPE
EXPERIMENTAL IN 5/32" VENTURI
CALCULATED FOR 5/32" VENTURI (THEORETICAL)
CALC. FOR 5/32" ORIFICE (THEORETICAL)
EXP. IN "5/32" ORIFICE
SINGLE PHASE FLOW
$H_V = \frac{V_o^2 - V_i^2}{2 g c^2}$
5/32" ORIFICE
5/32" VENTURI
PRESSURE DROP $H_V = \frac{V_o^2 - V_i^2}{2 g c^2}$ FT. OF FLUID FLOWING
FLOW IN GPM (WATER)
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7
100
50.
10
5.
1.0
.5
0.1
F.J.C.
10-7-55
N.C.E.

The experimental curves were plotted from data for single phase runs.

The results are shown to be within limits of experimental error by studying Figures 6 and 7, which show water flow rate in G.P.M. versus pressure drop at various flow rates of air expressed in pounds per second. Each of the points plotted is accompanied by a flow rate of air noted with it. Curves have been drawn to indicate a parameter, R_A, of air rates. Inasmuch as the figures are plotted on regular linear graph paper, the resulting curves are accurate enough for approximating pressure drops for the air-water system at pressures up to 30 PSIG, with about 20% accuracy. Because data for pressure drops across the orifice were more limited, the Venturi plot, Figure 6, is more usable. Figures 6 and 7 were primarily used to check for reproducibility of runs.

The Chenoweth-Martin (5) correlation is best represented by Figure 8 which has been reproduced from their data and used for calculations in this thesis.

Figures 9, 10, 11 and 13 are nomographs used in reducing the data to usable terms. Figure 9 was used to obtain the density of air at the test sections and results are tabulated in Table 2 Column 6. Figures 10 and 11 gave the air rate expressed in lbs./sec.; the results are plotted in Column 5. Figure 13 converted GPM of water to lbs./sec.; results are tabulated in Column 9.

(5) Ref. 10

FIGURE 6

WATER FLOW-RATE VS PRESSURE DROP AT VARIOUS AIR RATES - VENTURI - 5/32"

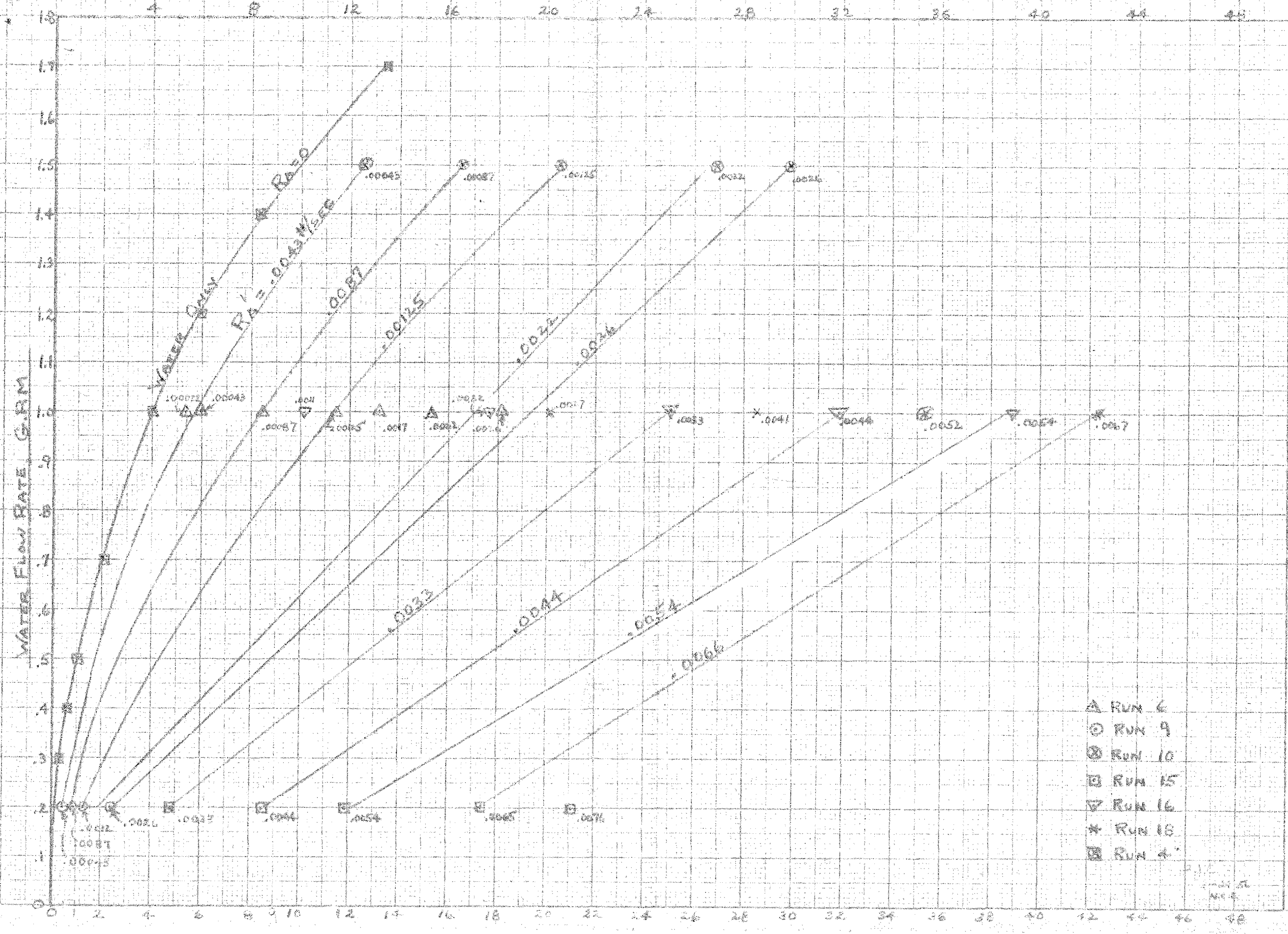
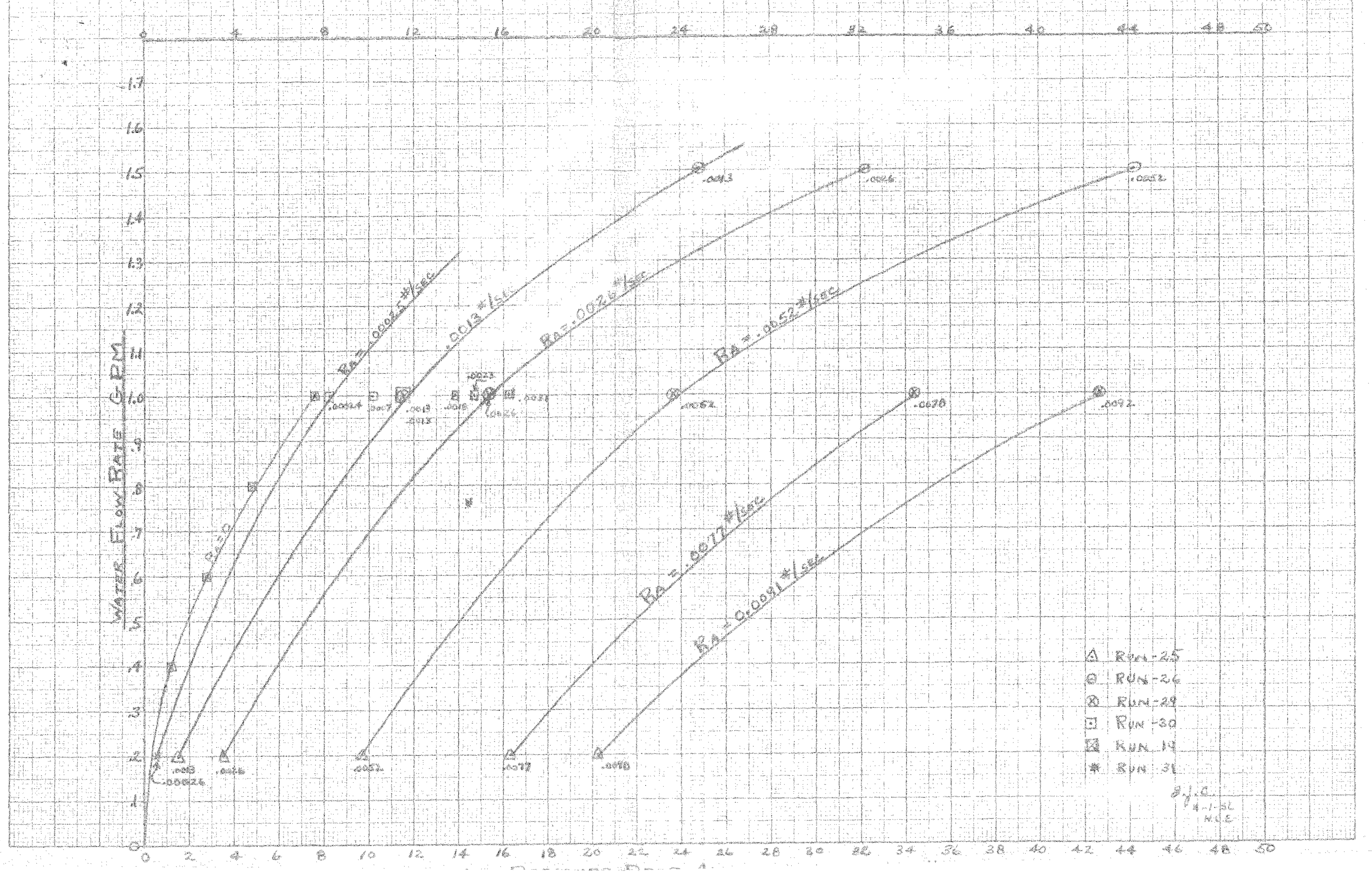


FIGURE - 7

WATER FLOW RATE VS PRESSURE DROP AT VARIOUS AIR RATES - ORIFICE - 5/32"



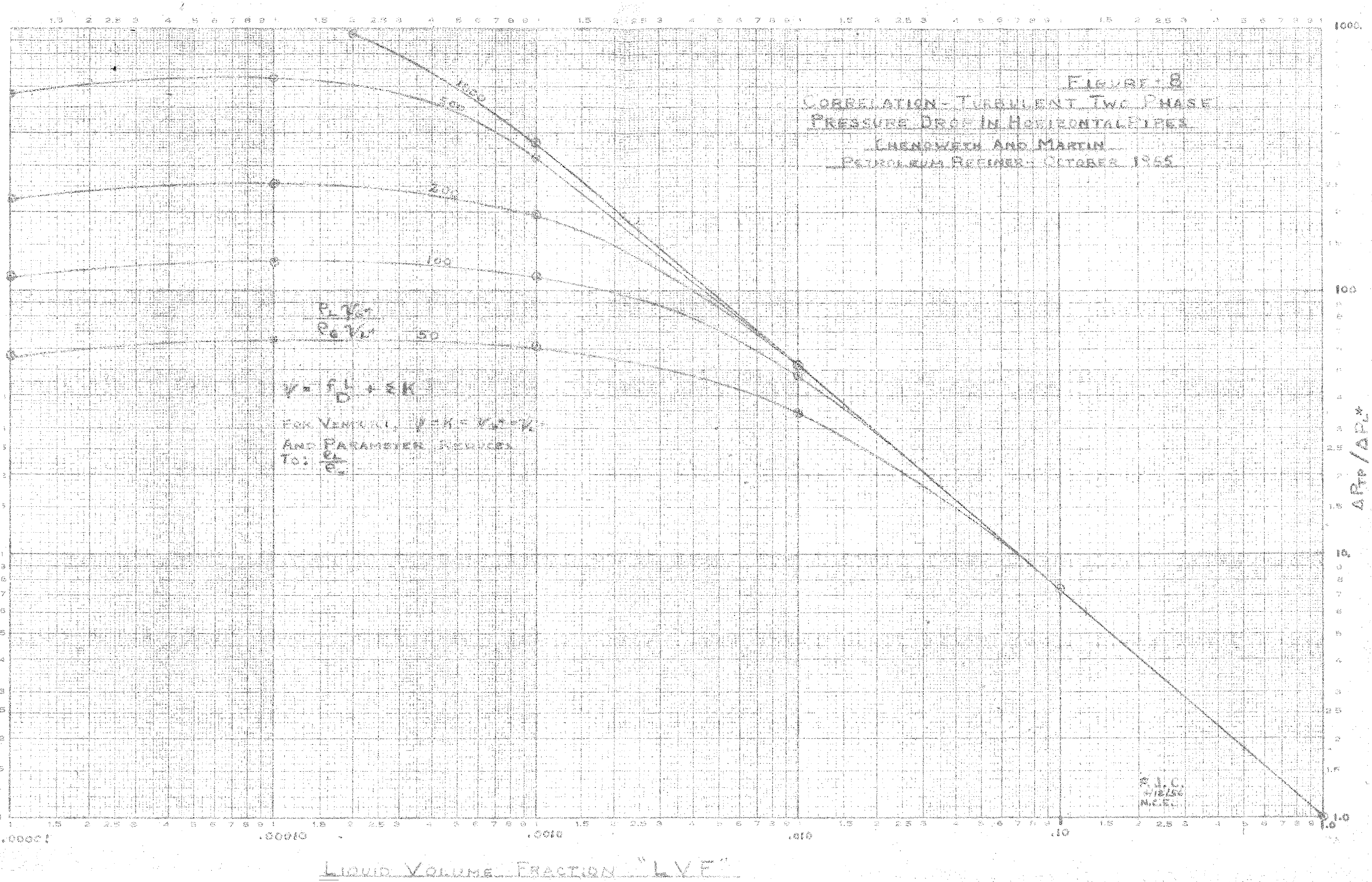
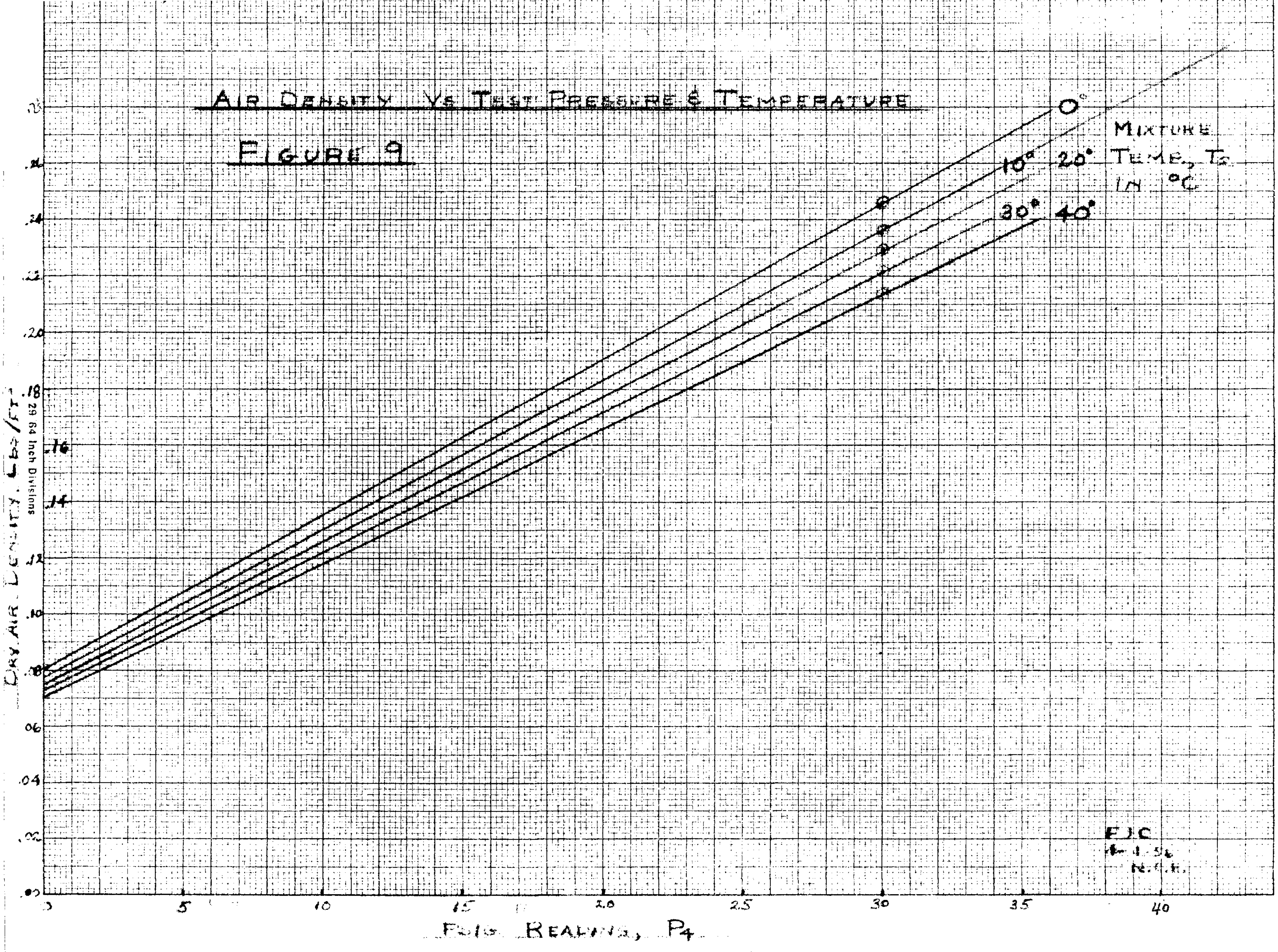
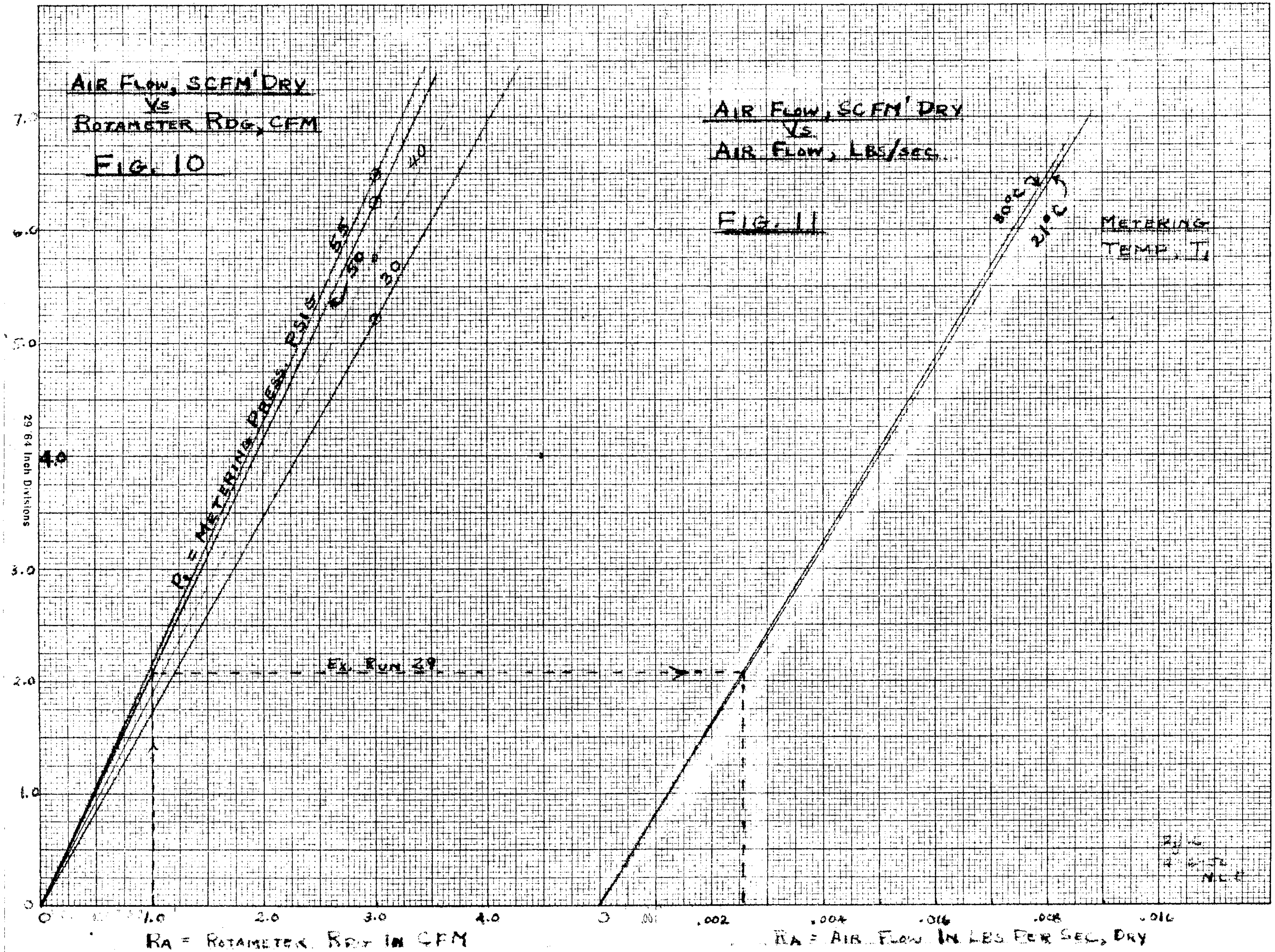


FIGURE 8
CORRELATION - TURBULENT TWO PHASE
PRESSURE DROP IN HORIZONTAL PIPES
CHENOWETH AND MARTIN
PETROLEUM REFINER - OCTOBER 1955
1000
500
200
100
50
1000.
100.
10.
1.0
.00001
.00010
.0010
.010
.10
1.0
LIQUID VOLUME FRACTION "LVF"


AIR DENSITY VS TEST PRESSURE & TEMPERATURE
FIGURE 9
0°
10°
20°
30°
40°
MIXTURE
TEMP., T5
IN °C
DRY AIR DENSITY, LBS/FT³
29 64 Inch Divisions
.20
.18
.16
.14
.12
.10
.06
.04
0
5
10
15
20
25
30
35
40
PSIG READING, P4
EJC


AIR FLOW, SCFM' DRY
VS
ROTAMETER RDG, CFM
FIG. 10
AIR FLOW, SCFM' DRY
VS
AIR FLOW, LBS/SEC
FIG. 11
METERING
TEMP. T₁
80°C
21°C
P₁ = METERING PRESS. PSIG
55
50
40
30
0
EX. RUN 29
29.64 Inch Divisions
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
1.0
2.0
3.0
4.0
.002
.004
.008
RA = ROTAMETER RDG IN CFM
RA = AIR FLOW IN LBS PER SEC, DRY

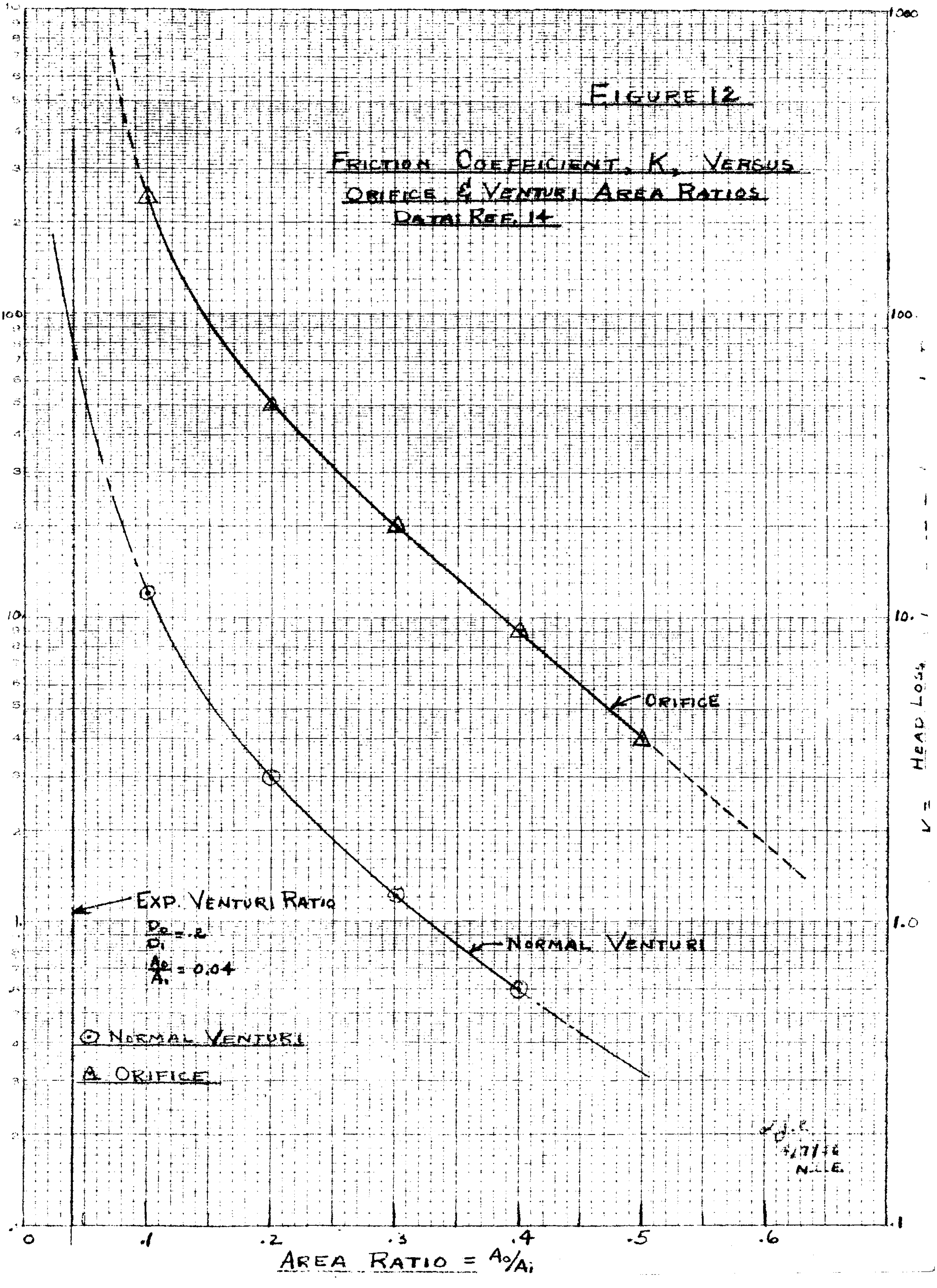


FIGURE 12
FRICTION COEFFICIENT, K, VERSUS
ORIFICE & VENTURI AREA RATIOS
DATA: REF. 14
ORIFICE
NORMAL VENTURI
EXP. VENTURI RATIO
$\frac{D_o}{D_i} = .2$
$\frac{A_o}{A_i} = 0.04$
⊙ NORMAL VENTURI
△ ORIFICE
K = HEAD LOSS
1000
100
10.
1.0
.1
0
.1
.2
.3
.4
.5
.6
AREA RATIO = A_o/A_i
4/7/76
N.L.E.

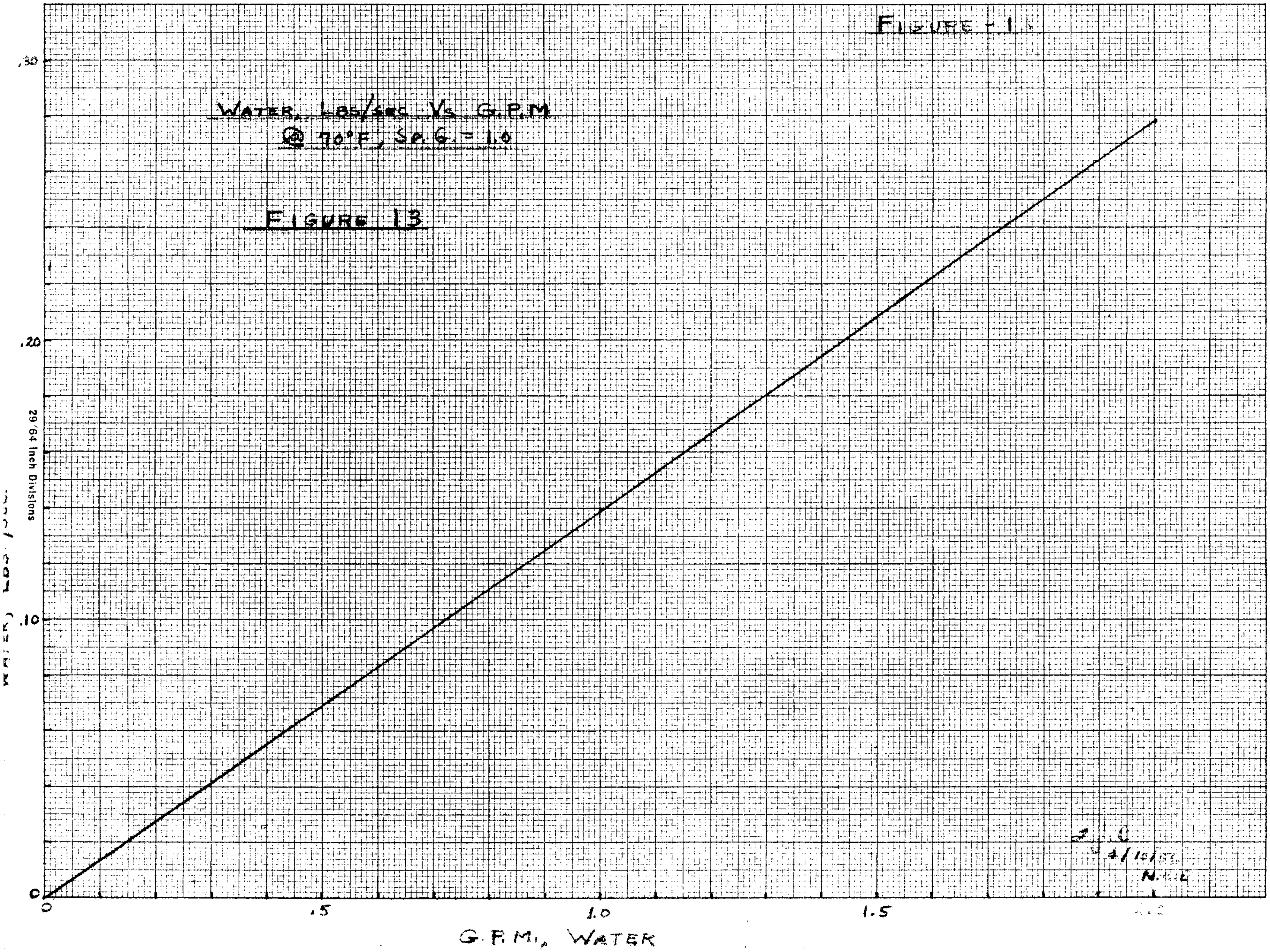


FIGURE - 1
WATER, LBS/SEC VS G.P.M
@ 70°F, SP. G. = 1.0
FIGURE 13
.30
.20
.10
0
0
.5
1.0
1.5
G.P.M., WATER
29/64 Inch Divisions
4/18/57
N.E.L

Figure 12 has been plotted to show the values of Friction Coefficients, K, for Orifices and Venturi sections, for various area ratios. Inasmuch as the values for the test orifice and venturi of this thesis lay on the extrapolated curve, the K factor was not used, (nor was it required).

Inasmuch as the 1948 Edition of the Hydraulic Institute Hydraulic Data were not available, the values suggested by Addison (9) have been plotted.

Figure 14 is essentially the same data as in Figure 5 for experimental results, plotted to give a more usable graph. Orifice run 19 is for Test Section O_1; orifice run 27 is for test section O_2. This fig. was used to obtain ΔP_L* which is the pressure drop calculated assuming total mass flow to be water, as tabulated in Table 2, Column 21, from the total flow in Column 16. In effect Figure 14 is the calibration curve for the venturi and orifice. The liquid volume fraction, LVF, is the ratio of liquid volume to total volume flow. Column 19 is the ratio of water density to density at the test section conditions.

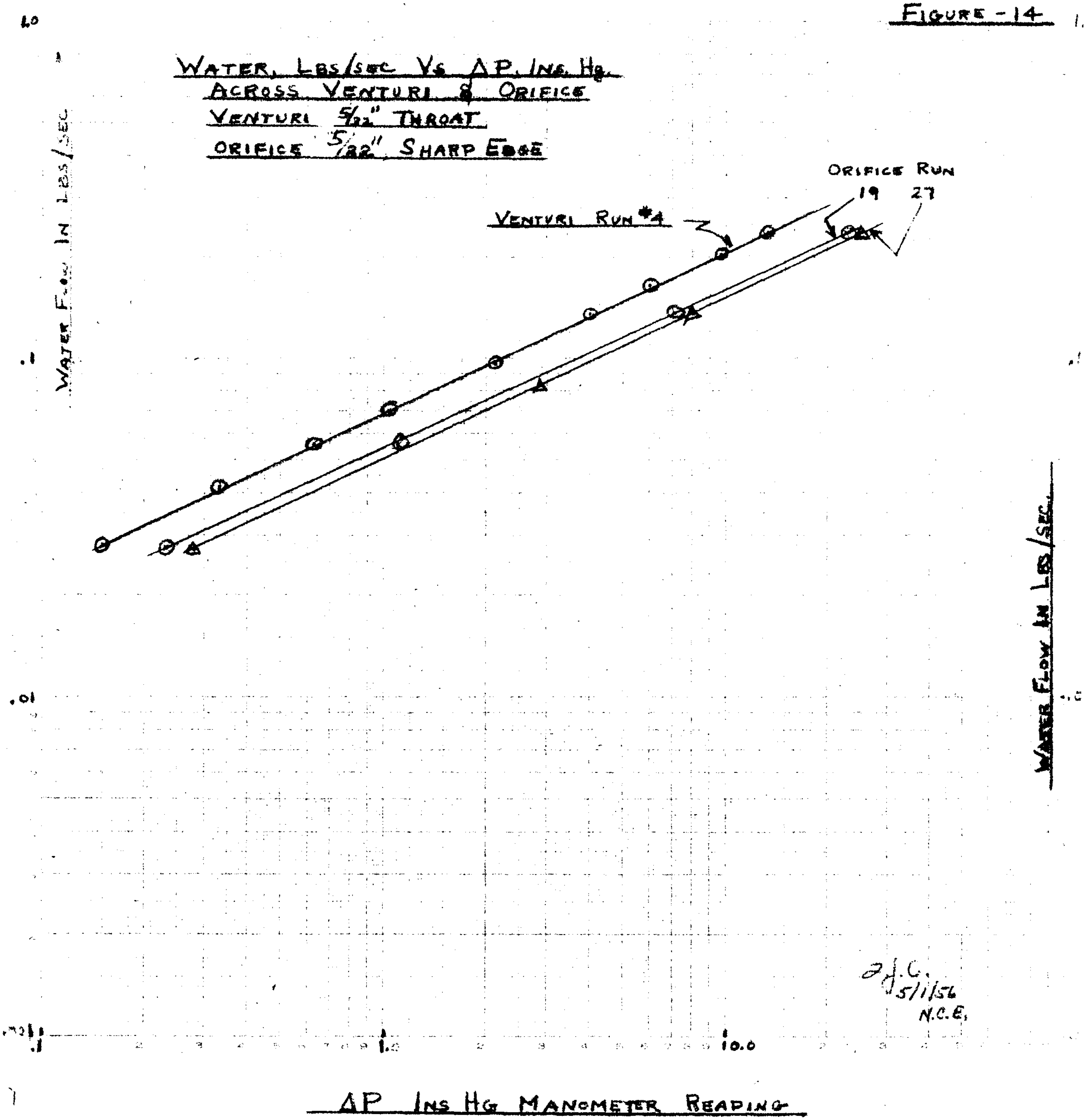
Figures 15A and 15B is the plot of actual pressure drop as obtained experimentally, (ΔP_2 or ΔP_3) versus the two phase pressure drop, (ΔP_{TP}), as obtained from the Chenoweth Martin correlation (Physically, multiplying columns 20 and 21 in Table 2). The plotted points on Figure 15-B for the orifice, are comparable in grouping to

(9) Ref. 14

those of Chenoweth and Martin (1) and the results are at least as consistent. This is of interest because the diameter ratio of their orifice was 0.55 while the orifice of this thesis is 0.19.

(1) Ref. 10 p.154

FIGURE - 14


WATER, LBS/SEC VS ΔP, INS. Hg.
ACROSS VENTURI & ORIFICE
VENTURI 5/32" THROAT
ORIFICE 5/32" SHARP EDGE
ORIFICE RUN
19 27
VENTURI RUN #4
WATER FLOW IN LBS/SEC
WATER FLOW IN LBS/SEC
1.0
.1
.01
.1
1.0
10.0
ΔP INS HG MANOMETER READING
5/1/56
N.C.E.

A straight line drawn through the orifice experimental data of this thesis as plotted in Figure 15B permits a logarithmic equation:

$$\text{(I)} \quad \Delta P_{TP\ ACT} = 0.22 \left(\Delta P_{TP\ PRED}\right)^{1.17}$$

where ($\Delta P_{TP\ ACT}$) is the proposed predicted pressure drop of this thesis and $\Delta P_{TP\ PRED}$ is the Chenoweth-Predicted Value.

Figure 15-A is a similar plot for the venturi, which has no counterpart in recent literature. A similar expression is developed for the venturi:

$$\text{(II)} \quad \Delta P_{TP\ ACT} = 0.40 \left(\Delta P_{TP\ PRED.}\right)^{1.17}$$

With the terms defined as above. The equations are developed on Figure 15A and 15B. It is of much significance that the slopes of the straight line curves plotted are the same, within experimental accuracy, and both expressions correct the predicted value to read within 15% of the actual pressure drops for about 85% of the data. It is concluded that the above correllation, as expressed in equation form, when used with the Chenoweth-Martin correlation gives a more satisfactory estimation of pressure drops under conditions of flow of this thesis.

From the Chenoweth-Martin plot a similar expression can be derived. A curve drawn through their data indicates an expression:

$$\text{(III)} \quad \Delta P_{TP\ ACT} = 0.45 \left(\Delta P_{TP\ PRED.}\right)^{1.17}$$

Because the exponent of the ($\Delta P_{TP\ PRED.}$) term is exactly the same it is suggested that the following general form of the equation is possible for venturis and orifices:

$$\text{(IV)} \quad \Delta P_{TP\ ACT} = K' \left(\Delta P_{TP\ PRED}\right)^{1.17}$$

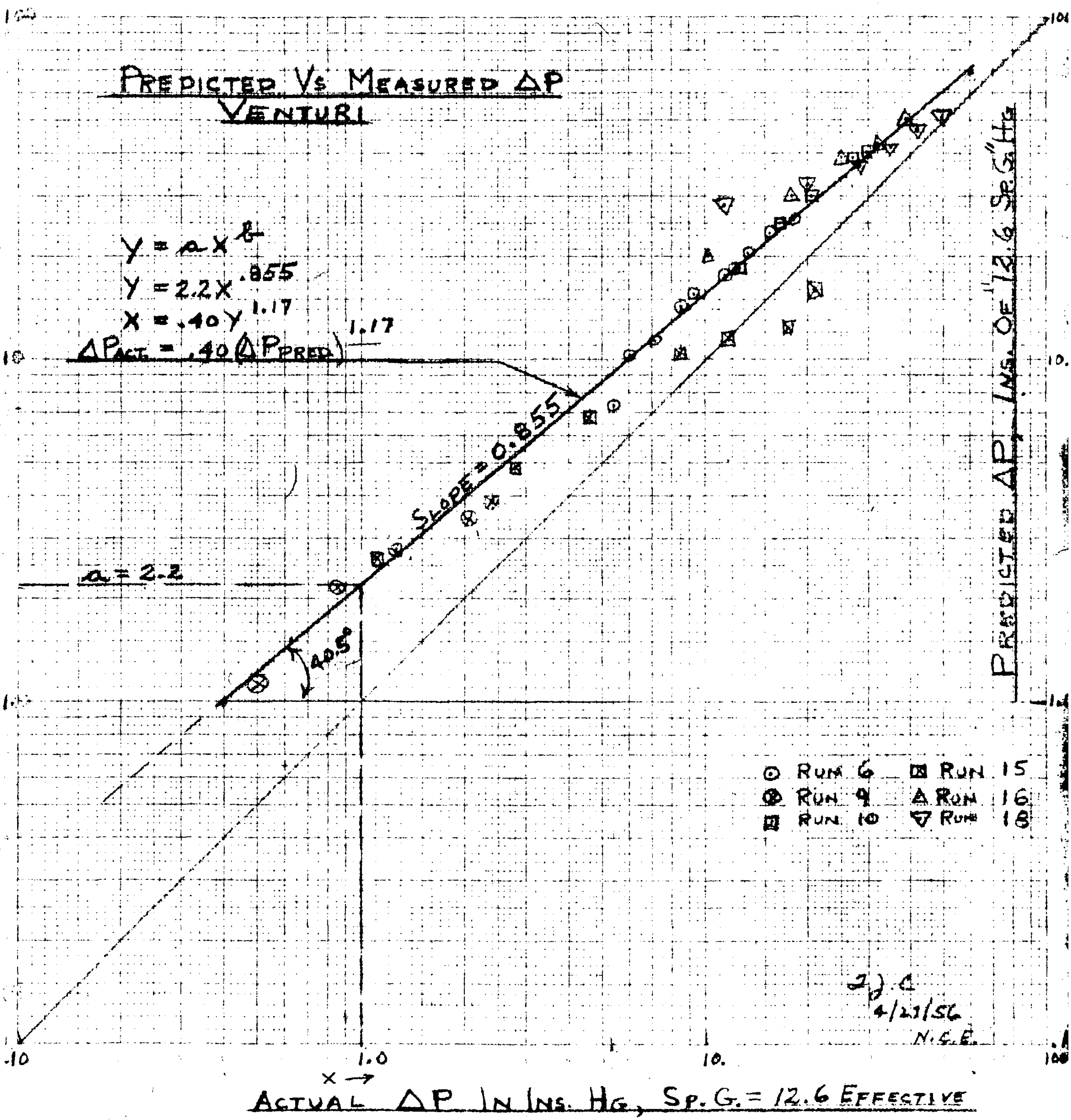
Where K^1 would be a constant for a given orifice or venturi in two-phase two fluid flow, depending on throat and pipe diameters. In Word form, "Predicted two phase pressure drop equals a constant, K', times the 1.17 power of predicted two phase pressure drop as predicted by Chenoweth".

It is noted that two-phase two-fluid flow is an unsteady state flow as evidenced by fluctuations in manometer and pressure readings. Dampening pressure lines permitted readings to be taken.

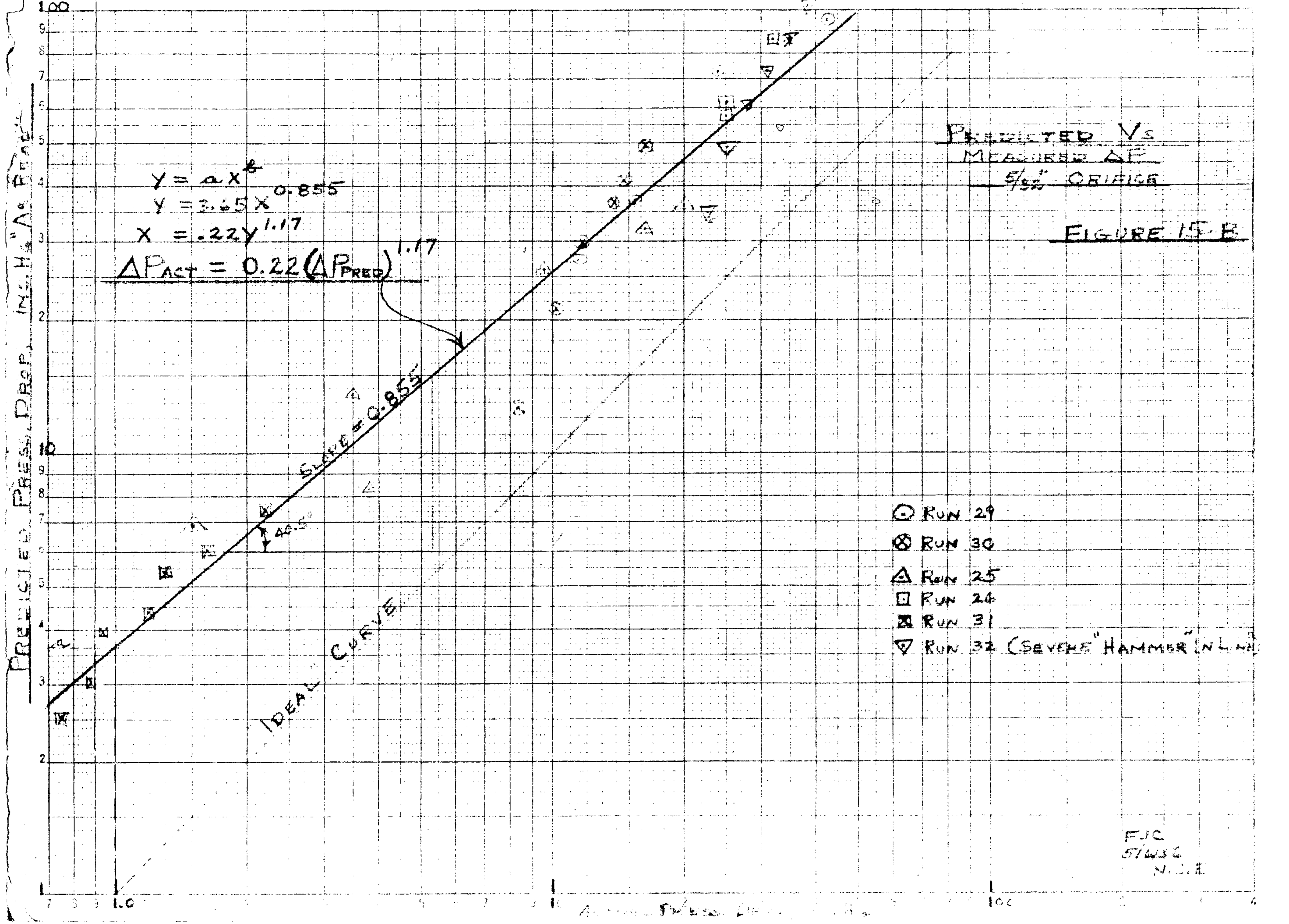
Pressures of air had to be raised from 30 to 50 PSIG to exceed the stability curve minimum of 45 PSIG for the air rotameter. The increase in pressure did not materially affect the "unsteady state" condition.

Because the Reynolds number did not vary appreciably, the 10% change in two phase pressure drop was attributed to the change in solubility of air in water (see Figure 4) where temperature varied from 10°C to 40°C. The change in surface tension, viscosity, velocity, and gravity were not sufficient to cause the marked change.

FIG. 15-A



PREDICTED VS MEASURED ΔP
VENTURI
$Y = aX^b$
$Y = 2.2X^{.855}$
$X = .40Y^{1.17}$
$\Delta P_{ACT.} = .40(\Delta P_{PRED.})^{1.17}$
SLOPE = 0.855
a = 2.2
40.5°
RUN 6
RUN 9
RUN 10
RUN 15
RUN 16
RUN 18
.10
1.0
10.
100
X →
ACTUAL ΔP IN INS. HG, SP. G. = 12.6 EFFECTIVE
PREDICTED ΔP, INS. OF 12.6 SP. G. "HG
4/21/56
N.C.E.


PREDICTED VS MEASURED ΔP 5/32" ORIFICE
FIGURE 15-B
Y = aX^b
Y = 3.65 X^0.855
X = .22 Y^1.17
ΔP_ACT = 0.22 (ΔP_PRED)^1.17
SLOPE = 0.855
44.5°
"IDEAL" CURVE
PREDICTED PRESS. DROP, INS. H2O ΔP PRED
Run 29
Run 30
Run 25
Run 26
Run 31
Run 32 (SEVERE "HAMMER" IN LINE)
FJC
5/6/56
N.C.E.

CONCLUSIONS

It is concluded that for turbulent air and water flow through a venturi or orifice meter:

(1) Pressure drops can be predicted to within 15% - the best previous correlation treats the orifice only and give results from with deviations from 50% to 250%.

(2) The use of the following equation is possible for predicting pressure drops to within 15%: for <u>both</u> orifice and venturi:

$$\Delta P_{TP, (Predicted)} = K' \ (\Delta P_{TP}')^{1.17}$$

where $\Delta P_{TP}'$ is the predicted pressure drop of Chenoweth and Martin for an orifice and K' is a constant depending on diameter ratios.

(3) Pressure drops are affected markedly by temperature changes and that these changes are not attributable to changes in the Reynolds' number. Solubility of gases in a fluid, surface tension, velocity, surface phenomena, and other variables such as the flashing of liquids affect pressure drops to a much greater extent in the two phase two fluid systems than in single phase or in single fluid systems.

RECOMMENDATIONS

Beyond the scope of this thesis, the following are suggested as avenues for further work on two-phase two-fluid flow.

1. Investigation of the effect of surface tension (The WEBER number) on pressure drops in the Venturi. Pardoe [10] indicates a variation of over 1/2% in the Fanning Friction Factor, f, due to the effect of ambient temperature, for single phase flow. This indicates that the friction factor is not a function of the Reynold's Number and a roughness factor alone.

2. Moody[10] also suggests that the friction factor may be affected by the MACH or CAUCHI which introduce acoustic velocity, and FROUDE'S number which considers "Free surface" phenomena. The orifice and venturi coefficients may be a function of these variables.

The apparatus is well suited to these possible investigations.

(10) Ref. 9 pp. 679,683

TABLE 1

Summary of Data

Venturi Runs	Air Flow CFM	Water Flow GPM
1 to 5	0	.2 to 1.7
* 6, 7, 8	.1 - 1.2	1.0
* 9	.2 - 1.2	0.2
* 10	.2 - 1.2	1.5
11	0	1.0
12	.2 - 1.2	0.2
13	.2 - 1.2	1.5
14	0	.2 - 1.7
* 15	.5 - 3.5	.20
* 16	.5 - 2.5	1.0
17	0	1.0
* 18	.5 - 3.0	1.0

Orifice Runs	Air Flow CFM	Water Flow GPM
19	0	.2 - 1.7
20, 21, 22	.5 - 3.0	1.0
23, 24	0	.2 - 1.7
* 25	.5 - 3.5	.2
* 26	.5 - 2.0	1.50
27	0	.2 - 1.7
28	0	1.0
* 29	.5 - 3.5	1.0
* 30	.1 - 1.2	1.0
* 31	.1 - 1.2	0.2
* 32	.1 - 1.2	1.7

* Calculated-Tabulated Values.

TABLE 2

COLUMNS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Run	T_1 °C	P_1 PSIG	R_A CFM	R_A #/Sec	Air Dens. #/Ft³ at P_4 and T_2	R_A Ft³/Sec. at P_4	R_W GPM +.02 -.00	R_W #/Sec.	R_W Ft³/Sec.	T_2 °C	P_4 PSIG .84 +0%	ΔP_2 In.Hg	ΔP_3 In.Hg	P_5 PSIG	Total Flow R_A & R_W #/Sec.	Total Flow Ft³/Sec.	RVF	$\Delta P_S^*/\Delta P_L^*$	$\Delta P_{TP}/\Delta P_L^*$	ΔP_L^* In.Hg	In.Hg ΔP_{TP}
6	-	30.0	0.1	.00022	.103	.00213	1.00	.139	.00223	14.0	5.5	3.35		0-4	.1392	.00436	.511	568	1.8	4.07	7.3
	-		.2	.00043	.103	.0042					5.3	6.00		1-5	.1394	.00643	.347	588	2.5	4.07	10.2
	20.0		.3	.00065	.110	.00590					6.5	7.05		2-6	.1395	.00813	.274	562	3.1	4.08	12.7
	20.0		.4	.00087	.118	.00737					8.0	8.45		2-6	.1397	.00950	.232	568	3.5	4.09	14.3
	20.3		.5	.00105	.126	.00833					9.0	9.55		2-8	.1399	.01078	.0207	507	3.8	4.09	15.5
	20.4		.6	.00125	.127	.00985					10.0	11.45		2-9	.1401	.0121	.184	491	4.3	4.09	17.6
	20.6		.7	.00150	.139	.0108					12.0	12.15		3-10	.1403	.0130	.174	455	4.5	4.10	18.4
	20.9		.8	.00170	.146	.0122					12.5	13.80		0-12	.1404	.0144	.155	445	5.0	4.11	20.5
	21.0		1.0	.00215	.154	.0140					15.0	15.35		3-13	.1408	.0162	.137	413	5.7	4.12	23.4
	21.2		1.2	.00255	.165	.0155					17.0	18.15		3-15	.1412	.0177	.126	388	6.1	4.12	25.2
9	22.0	30.0	0.2	.00043	.103	.0042	0.29	.0238	.000406	13.8	4.5	.50		0-3	.02516	.0046	.097	617	7.6	0.16	1.12
			0.4	.00087	.105	.00827				14.5	3-8	.65		0-8	.02852	.0087	.030	588	13.5	0.16	2.16
			0.6	.00125	.117	.0107				14.8	8-12	1.25		0-12	.0288	.0111	.0410	528	16.0	0.17	2.72
			1.0	.00215	.149	.0144				15.0	14.0	2.05		11.5	.0296	.0148	.0310	424	20.0	0.17	3.4
			1.2	.00255	.163	.0156				15.0	17.0	2.40		15.0	.02996	.0160	.0279	387	22.0	0.18	3.95
10	22.0	30.0	0.2	.00043	.118	.00365	1.50	.209	.00335	13.2	8.0	12.45		2-7	.2094	.00703	.477	520	1.90	9.7	18.4
			0.4	.00087	.133	.00655				-	11.0	16.9		3-8	.2097	.00990	.338	469	2.55	9.8	25.0
			0.6	.00125	.1492	.00839				13.0	14.0	20.5		3-10	.2101	.01174	.284	425	3.0	10.0	30.0
			1.0	.00215	.181	.0119				13.2	20.0	26.9		5-15	.2108	.0156	.214	350	3.80	10.2	38.7
			1.2	.00255	.191	.0123				13.0	22.0	29.7		5-17	.2112	.0162	.206	334	3.9	10.3	40.0
15	22.5	30.0	0.5	.0011	.097	.0108	.020	.0278	.000346	14.8	3-6	1.10		0-6	.0287	.0112	.0395	642	16.7	0.16	2.67
			1.0	.00215	.102	.0211				15.6	5.0	2.80		3.4	.0296	.0215	.0207	611	29.0	.17	4.92
			1.50	.00325	.117	.0276				15.2	8.0	4.80		6.0	.0310	.0282	.0158	533	37.0	.185	6.85
			2.00	.00435	.106	.0411				15.5	6.0	8.50		2.5	.0321	.0415	.0107	588	51.0	.20	10.2
			2.50	.0054	.120	.0456				15.5	8.5	11.90		3.5	.0332	.0460	.0097	528	55.0	.23	11.5
			3.00	.0065	.122	.0507				15.5	10.0	17.35		2.0	.0343	.0511	.0089	496	60.0	.22	13.2
			3.50	.0076	.133	.0572				15.7	12-13	21.1		2-3	.0354	.0576	.0077	476	66.6	0.24	15.8
16	22.0	30.0	.5	.0011	.099	.011	1.0	.139	.00223	15.0	4-5	10.15		0-1	.1399	.0132	.169	628	4.7	4.4	20.7
			1.0	.00215	.120	.0179				15.0	7-10	17.7		0-3	.1408	.0201	.112	528	6.7	4.50	30.1
			1.5	.00325	.133	.0244				14.8	10-13	25.0		0-4	.1417	.0256	.0840	480	8.4	4.6	38.6
			2.0	.00435	.162	.0268				14.8	15-18	31.9		0-4	.1426	.0291	.0770	397	9.1	4.85	42.3
			2.5	.0054	.186	.0290				15.0	19-23	38.9		0-5	.1435	.0312	.0643	340	10.0	4.70	50.5

COLUMNS

1 Run	2 T_1 °C	3 P_1 PSIG	4 R_A CFM	5 R_A #/Sec	6 Air Dens. #/Ft³ at P_4 and T_2	7 R_A Ft³/Sec. at P_4	8 R_V GPM .02 –.00	9 R_V #/Sec.	10 R_V Ft³/Sec.	11 T_2 °C
18	20.5	55.0	0.90	.00135	.113	.0102	1.0	.139	.00223	7.5
			1.00	.00270	.143	.0189				7.5
			1.50	.00405	.171	.0229				8.0
			2.00	.0053	.201	.0264				8.2
			2.50	.0067	.225	.0298				8.3
			3.00	.0081	.260	.0312				7.5
25	28.0	50.0	.5	.0013	.088	.0148	0.20	.0278	.000446	28.9
	28.0		1.0	.00255	.083	.0307				28.0
	27.5		2.0	.0052	.093	.056				28.0
	27.5		3.0	.0077	.118	.0651				28.0
	27.5		3.5	.0090	.156	.0653				27.5
	27.5		1.0	.00255	.148	.0172				27.5
26	27.5	50.0	0.5	.0013	.168	.00775	1.50	.209	.00335	27.0
			1.00	.00255	.180	.0142				27.0
			2.0	.0052	.214	.0242				22.5
			0.5	.0013	.144	.0090				20.0
29	22.5	50.0	0.50	.0013	.166	.0078	1.0	.139	.00223	12.5
			1.00	.00255	.216	.0118	1.0			12.5
			2.00	.0052	.184	.0282	1.0			12.0
	22.8		3.00	.0078	.230	.0339	1.0			11.5
			3.5	.0092	.24	.0383	1.0			11.3
30	22.5	50	0.10	.00084	.128	.00187	1.0	.139	.00223	11.0
	22.5		0.30	.00070	.140	.0050				
	22.8		0.50	.0013	.150	.00865				
	23.0		0.70	.0018	.161	.0112				
	23.0		0.90	.00235	.169	.0139				
	23.0		1.20	.0031	.185	.0167				
31	23.4	50.0	0.10	.000255	.105	.00243	0.20	.0278	.000446	11.5
			0.20	.00052	.109	.00476				13.0
			0.30	.00078	.135	.00578				13.8
			0.40	.00104	.133	.00782				14.5
			0.50	.0013	.152	.0085				14.7
			0.70	.00182	.165	.0110				15.0
			0.90	.00234	.194	.0121				15.0
			1.30	.00335	.234	.0143				15.2

1 Run	12 P_4 PSIG -5%	13 P_2 In.Hg	14 P_3 In.Hg	15 P_5 PSIG	16 Total Flow R_A, R_V #/Sec.	17 Total Flow Ft³/Sec.	18 LVF	19 PW*/ P_L*	20 P_{TP}/P_L	21 P_L* In.Hg	22 P [illegible]
18	6-7	11.2		0-4	.1401	.0124	.118	542	6.4	4.4	28.2
	11-13	20.1		0-8	.1412	.0211	.106	442	7.0	4.55	31.8
	17-20	28.5		3-12	.1424	.0251	.089	362	8.1	4.65	37.6
	21-25	35.3		4-13	.1434	.0286	.081	325	8.8	4.70	41.3
	25-30	42.3		5-20	.1446	.0320	.0697	294	10.0	4.75	47.5
	32-35	>50.0		5-40	.1457	.0334	.065	252	10.9	4.88	52.5
25	3.0		1.50	0.0	.0291	.0152	.0293	707	21.5	.32	6.88
	2.0		3.50	-	.0303	.0311	.0143	750	40.0	.34	19.6
	4.0		9.70	3.0	.0330	.0564	.00791	669	64.0	.41	26.2
	9.0		16.3	3-5	.0355	.0655	.00681	527	73.0	.47	34.2
	12-13		20.2	4-5	.0368	.0667	.00668	457	71.0	.50	35.5
	15.0		3.8	-	.0303	.0176	.0253	421	24.0	.34	8.15
26	18-20		24.8	0-12	.210	.01125	.297	371	2.9	20.0	58.0
	20-23		32.2	0-15	.212	.0177	.189	346	4.2	20.5	85.0
	25-30		44.2	3-17	.214	.0277	.121	291	6.4	20.0	133.0
	12-15		24.7	0-8	.2.10	.0125	.268	433	3.1	20.0	62.0
29	16-18		11.55	5-15	.140	.0100	.223	380	3.6	7.65	27.2
	25-28		15.3	5-15	.141	.0146	.159	289	4.85		37.2
	18-23		23.7	3-15	.144	.0304	.074	339	9.6		73.3
	27-31		34.3	5-20	.145	.0360	.062	271	11.0		85.0
	28-35		42.6	5-20	.148	.0405	.055	271	12.5		95.5
30	9-10		8.25	2-7	.139	.0041	.542	487	1.65	7.65	12.6
	11-13		10.15	3-10	.140	.0072	.309	450	2.75		21.1
	13-15		11.75	0-13	.140	.0109	.205	420	3.90		29.9
	14-18		13.85	0-13	.141	.0134	.166	397	4.8		35.7
	16-19		14.70	2-15	.141	.0161	.138	370	5.5		42.1
	17-23		16.15	2-18	.142	.0189	.118	348	6.4		49.0
31	3-7		.3-.7	0-7	.0281	.00268	0.155	592	5.0	.3.0	1.5
	4-9		.58-.92	0-8.5	.0283	.00513	.087	571	8.3	.385	2.53
	8-15		.7-1.05	0-13.0	.0286	.00622	.0718	461	9.9	.385	3.02
	5-18		.7-1.18	4.5-18	.0288	.00826	.0540	468	12.0	.31	3.95
	8-20		.9-1.45	8-19	.0291	.00894	.0500	410	13.5	.32	4.38
	16-18.5		1.40	15-17	.0296	.0114	.0301	377	16.5	.347	5.40
	22.5		1.63	21.5	.0301	.0125	.0357	321	18.0	.335	6.65
	30.3		2.2	28.8	.0311	.0147	.0393	256	21.0	.355	7.45

COLUMNS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Run	T_1 °C	P_1 PSIG	R_A CFM	R_A #/Sec	Air Dens. #/Ft^3 at P_4 and T_2	R_A Ft^3/Sec. at P_4	R_W GPM .02 -.00	R_W #/Sec.	R_W Ft^3/Sec.	T_2 °C	P_4 PSIG [illegible]	P_2 In.H_G	P_3 In.H_G	P_5 PSIG	Total Flow R_A & R_W #/Sec.	Total Flow Ft^3/Sec.	LVF	P_G*/ P_L*	P_{TP}/ P_L	P_L # In.H_G	P_{TP}
32	23.7	50.	.10	.000255	.178	.00143	1.7	.237	.0038	13.[illegible]	18.[illegible]		22.85	7.5	.237	.00523	.726	350	1.35	26.5	35.8
	23.8		.30	.00078	.200	.0039				13.[illegible]	22.[illegible]		25.2	8.5	.238	.0077	.495	312	1.85	26.6	49.0
	24.0		.50	.0013	.210	.0062				13.[illegible]	23-26		28.3	7-15	.238	.0100	.38	296	2.3	26.6	61.0
	24.0		.70	.00182	.222	.0082				14.[illegible]	25-29		31.2	5-20	.239	.0120	.317	281	2.75	26.7	73.0
	24.0		1.0	.00255	.228	.0112				14.[illegible]	26-30		35.4	0-20	.240	.0150	.254	273	3.25	26.8	87.2
	24.0		1.2	.0031	.234	.0133				14.[illegible]	27-31		37.8	0-22	.240	.0171	.222	266	3.8	26.8	102.0

Table 3

TABULATED DATA

Run	T_1 °C	P_1 PSIG	Ra CFM	Rw GPM	T_2 °C	P_4 PSIG	P_2 In. Hg	P_3 In. Hg	P_5 PSIG
1			0	.20		53.5	.15	.05	53.0
				.30		54.5	.30	.10	52.5
				.50		53.0	1.0	.25	52.5
				.75		51.5	2.15	.45	50.8
				1.0		49.5	4.1	0.80	47.5
				1.25		45.5	6.6	1.2	44.0
				1.50		40.5	10.0	1.9	38.5
				1.70		36.5	12.5	2.6	34.5
2			0	.20			.40	.25	
				.30			.60	.30	
				.50			1.15	.40	
				.75			2.45	.55	
				1.0			4.7	1.05	
3			0	1.7	38	7	13.5	2.55	5
				1.5	38	18	10.4	1.90	17
				1.25	38	13.5	7.15	1.20	13
				1.0	38	7	4.55	0.80	6
				.75	38	15.0	2.45	0.50	14
				.50	38	10.0	1.12	0.25	9
				.25	38	13.5	0.29	0.075	12.5
4			0	0	22.0	0	0	-	0
				0.20	22.0	4.8	0.15	-	4.2
				0.30	22.0	8.8	0.33	-	8.0
				0.40	22.0	13.3	0.62		12.5
				0.50	22.0	19.7	1.05		19.0
				0.60	-	25.2	1.55		24.5
				0.70	21.8	31.5	2.10		30.5
				0.80	-	37.3	2.6		36.0
				0.90	21.8	42.5	3.25		41.3
				1.00	22.5	14.5	4.00		13.7
				1.10	-	17.0	4.90		16.2
				1.20	23.0	20.7	5.95		19.5
				1.30	23.5	24.3	7.05		23.0
				1.40	24.0	28.8	8.35		27.2
				1.50	30.5	37.5	9.70		36.8
				1.60	32.0	28.2	11.60		26.5
				1.70	32.8	32.5	13.45		30.0
5			0	1.40	32.8	21.8	8.52		20.5
				1.00	32.2	11.3	4.20		10.3
				0.50	32.0	2.8	1.10		2.2
				0.20	31.5	4.0	0.17		3.3

Run	T_1 °C	P_1 PSIG	Ra CFM	Rw GPM	T_2 °C	P_4 PSIG	P_2 In. Hg	P_3 In. Hg	P_5 PSIG
5			0	0.20	30.5	4.0	0.17		3.3
				0.0	-	0	0		0
				1.0	29.0	43.0	4.17		41.2
				1.0	17.0	33.0	3.95		32.0
				1.0	14.0	30.2	3.95		29.3
				1.0	13.0	2.0	3.98		-
7	-	30	.20	1.00	25.0	5.0	6.75		4.5
		30	.40	1.00	25.5	8.0	8.65		0-4
	22.0	30	.60	1.00	-	11.5	11.25		-
	22.5	30	.80	1.00	-	15.0	14.6		3-8
	-	30	1.0	1.00	-	18.0	16.7		4-12
	23.0	30	1.2	1.00	30.5	17.0	21.5		3-14
8		30	.20	1.0	16.5	6.0	5.9		2-5
		30	.40	1.0	16.0	8.0	8.25		2-7
	20.5	30	.60	1.0	-	10.0	10.8		2-8
	22.0	30	1.0	1.0	14.0	15.0	15.7		8-13
		30	1.2	1.0	14.0	17.0	17.35		8-15
11				1.0	42.0	11.0	4.40		10.0
				1.0	37.0	0	4.38		0.0
				1.0	32.5	11.5	4.35		10.5
				1.0	27.0	22	4.15		21.0
				1.0	22.0	34.0	4.10		33.0
				1.0	20.0	4.0	4.05		3.0
				1.0	18.5	4.0	4.0		3.0
				1.0	17.5	4.0	4.0		3.0
12	-	30	.2	.20	18.0	3-6	0.55		4-6
	23.0	30	.4	.20	18.0	4-10	0.85		0-9
	23.0	30	.6	.20	-	9-11	1.25		5-10
	23.0	30	1.0	.20	19.5	15.	2.05		13.5
	-	30	1.2	.20	18.5	18.5	2.40		17.0
13	-	0	0.0	1.5	14.5	2.5	9.15		1.0
	-	30	.20	1.5	13.5	6.5	13.35		2-5
	23.5	30	.40	1.5	13.5	9-10	17.0		2-8
	23.5	30	.60	1.5	13.5	13.0	20.9		0-8
	-	30	1.0	1.5	11.5	18.0	28.3		3-12
	23.5	30	1.2	1.5	11.5	20.0	31.3		3-12

14 & 17 - This was "Water Run" recheck similar to Run 11 after cleaning and checking Venturi.

Run	T_1 °C	P_1 PSIG	Ra CFM	Rw GPM	T_2 °C	P_4 PSIG	P_2 In. Hg	P_3 In. Hg	P_5 PSIG
19				0	28.0	-	0.0		0
Orifice				.2	28.0	2.5	0.28		2.0
				.40	28.5	9.5	1.15		8.5

Run	T_1 °C	P_1 PSIG	R_a CFM	R_w GPM	T_2 °C	P_4 PSIG	P_2 In. Hg	P_3 In. Hg	P_5 PSIG
19				.60	29.0	10.9	2.75		9.0
Orifice				.80	29.5	12.1	4.82		9.7
				1.0	30.5	13.2	7.60		9.5
				1.2	31.0	17.0	11.3		12.0
				1.4	32.5	16.3	16.2		9.0
				1.7	34.0	19.9	24.3		8.8
20	24.5	30.0	0.50	1.0	30.5	5-7	12.1		0-3
Or-	24.5	30.0	1.0	1.0	29.5	8-10	16.2		0-3
i-	24.5	30.0	1.5	1.0	28.0	10-13	21.3		0-4
fice	24.5	30.0	2.0	1.0	27.5	10-15	26.9		0-4
	24.3	30.0	2.5	1.0	26.5	15-18	31.6		0-4
	24.3	30.0	Max. Reprod. Reading	1.0					0-4
21	25.5	50	.5	1.0	32.0	16.0	13.40		5-15
Or-	25.5	50	1.5	1.0	33.0	32-34	19.2		15-30
i-	25.5	50	2.5	1.0	36.0	34-37	29.9		15-30
fice	25.5	50	3.0	1.0	37.0	38-42	34.1		15-30
	-	-	0.0	0.0	-	-	0.0		-
22	-	-	-	0.0	29.5	0.0	-		0.0
				1.0	29.5	4.0		7.2	1.0
				1.0	29.5	3.0		7.8	0.0
	27.0	50	0.5	1.0	28.8	5-8		12.3	0-3
	27.0	50	1.0	1.0	28.9	7-11		17.3	0-3
	27.0	50	1.5	1.0	28.8	10-15		23.7	0-4
	26.8	50	2.0	1.0	30.0	14-19		30.4	0-5
	26.8	50	2.5	1.0	32.5	17-23		36.1	0-5
	26.8	50	3.0	1.0	33.8	23-30		44.3	0-7
	26.8	50	1.0	1.0	39.5	7-12		18.6	0-3
23				1.0	41.5	3.0		7.85	-
				1.3	41.5	5.0		13.85	-
				1.7	41.0	10.0		23.55	-
				1.0	40.5	3.0		7.80	
				0.7	39.0	1.0		3.55	
				0.4	38.0	0.-		1.2	
				0.2	37.5	0.-		0.23	
				0.0	-	-		0.0	
24				.20	37.5	3.5		0.25	2.5
				0.40	37.0	3.8		1.05	2.5
				0.70	37.0	5.3		3.68	3.0
				1.0	35.	6.0		7.45	2.3
				1.3	34.5	10.2		12.95	4.0
				1.7	32.0	14.5		23.3	3.3
				1.3	29.5	9.5		12.65	3.5

Run	T_1 °C	P_1 PSIG	Ra CFM	Rw GPM	T_2 °C	P_4 PSIG	P_2 In. Hg	P_3 In. Hg	P_5 PSIG
27			0	0.20	25.5	5.0		0.23	4.7
				0.40	26.0	6.5		1.10	5.8
				0.70	26.0	6.5		3.58	4.8
				1.00	27.0	7.2		7.1	3.7
				1.30	27.0	11.0		12.55	6.
				1.70	28.0	15.2		22.8	4.5
28				1.0	30.0	13.2		7.2	9.5
				1.0	31.0	13.8		7.38	9.8
				1.0	33.0	14.0		7.40	10.0
				1.0	18.0	10.2		6.75	7.0
				1.0	13.0	7.5		6.70	4.5

TABLE 4

NOMENCLATURE

A - cross-sectional area of pipe, square feet

D - pipe diameter, feet

f - friction factor for Fanning equation, dimensionless

g - acceleration constant due to gravity, ft/sec^2

G - mass flow rate, lb (mass)/sec ft^2

K - friction coefficient for a valve or fitting, dimensionless

L - length of pipe, feet

Re - Reynolds number, dimensionless

W - flow rate of fluid, lb (mass) /sec

ΔP - pressure drop, lb $(force)/ft^2$, or $In.H_g$, where applicable

μ - viscosity, lb (force)/ft sec

ρ - density, lb $(mass)/ft^2$

ϕ - ratio $(\Delta P_{TP}/\Delta P_{SP})^{\frac{1}{2}}$ dimensionless
Ordinate for Lockhart and Martinelli correlation

X - ratio $(P_1/P_g$, dimensionless
Abscissa for Lockhart and Martinelli correlation

ψ - dimensionless group equal to $\frac{fl}{D} + K$

Vo - orifice velocity, ft/sec., average

V_1 - velocity, upstream to orifice, ft/sec, average

H_v - static head difference between upstream and Vena Contracta in ft.

c - contraction coefficient, dimensionless

u - velocity, ft/sec

T - temperature, $^\circ C$

P - pressure, PSIG or Ins.H_g

Ra - air flow, #/sec., ft^3/sec

Rw - water flow, #/sec., ft^3/sec

Subscripts

g - actual gas flow in total pipe cross-section, used in Lockhart and Martinelli correlation

G - actual gas flow

G* - fictitious all-gas flow

l - actual liquid flow in total pipe cross-section, used in Lockhart and Martinelli

L - actual liquid flow

L* - fictitious all-liquid flow

SP - single-phase

TP - two-phase

tt - turbulent-turbulent flow, used in Lockhart and Martinelli correlation

TABLE 5

Pressure Drop Across Venturi for Water

Flow, GPM	V_1 ft./sec.	V_o ft./sec.	H_v ft.	H_v Ins. H_G (12.6 Sp.G.)
1.7	1.02	28.4	13.0	12.4
1.275	.77	21.3	7.35	7.0
0.85	.51	14.15	3.24	3.07
0.425	.27	7.1	.815	.78
0.17	.102	2.84	.131	.125

These data plotted Figure 5.

SAMPLE CALCULATION

Press Drop Across Orifice (Or Venturi) [8]

$$\sqrt{V_o^2 - V_1^2} = c\sqrt{2gH_v}$$

$$H_v = \frac{V_o^2 - V_1^2}{2gc^2}$$

For 5/32" Venturi, 1.7 GPM Water, & 3/4" Sch. 40 Pipe

$$V_1 = \frac{1.7\ \text{GPM}}{} \bigg| \frac{}{60\ \text{SEC/MIN}} \bigg| \frac{8.33\ \#/\text{GAL}}{.231\ \#/\text{FT}} = 1.02\ \text{FT/SEC}$$

$$V_o = \frac{1.7}{} \bigg| \frac{144 \times 4}{60 \times (.1562)^2 \pi} \bigg| \frac{\text{FT}^3}{7.4} = 28.4$$

c = .98 (Assumed Constant For Venturi) varies

For Orifice, Depending on R_{EO} and

Diameter Ratio.

$$H_v = \frac{(28.4)^2 - (1.02)^2}{2 \times 32.17 \times (.98)^2} = 13.0\ \text{FT. WATER}$$

$$H_v = \frac{13.0\ \text{FT. } H_2O}{} \bigg| \frac{\text{IN. HG}}{1.045\ \text{FT } H_2O} = 12.4\ \text{IN. HG}$$

Note:

H_G has effective Sp.G. of 12.6

because water is above mercury

in manometer.

(8) Ref. 3

REDUCTION OF CHENOWETH EQUATION

$$\frac{\Delta P_G^*}{\Delta P_L^*} = \frac{\left[\left(\frac{f_G^* L}{D}\right) + \Sigma K\right]\left[\frac{W_L + W_G}{A}\right]\left[\frac{1}{2g\rho_G}\right]}{\left[\left(\frac{f_L^* L}{D}\right) + \Sigma K\right]\left[\frac{W_L + W_G}{A}\right]\left[\frac{1}{2g\rho_L}\right]}$$

Because L = 0 For Venturi:

$$\frac{\Delta P_G^*}{\Delta P_L^*} = \frac{\Sigma K \rho_L}{\Sigma K \rho_G}$$

$$= \frac{\rho_L}{\rho_G}$$

The above expression is tabulated in Column 19 and is obtained by dividing water density = 62.3 #/Ft^3 by air density Column 7, determined for test conditions.

REFERENCES

1 - Perry, J.H., Chemical Engineer's Handbook, 3rd ed. McCraw Hill Co., New York, N.Y. 1950.

2 - Badger and McCabe, Elements of Chemical Engineering, 2nd ed. McCraw Hill Co., New York, N.Y. 1936.

3 - Walker, Lewis, McAdams and Gilliland, Principles of Chemical Engineering, 3rd ed. McCraw Hill Co. New York, N.Y. 1937.

4 - Bergelin, O.P., "Flow of Gas Liquid Mixtures", Chemical Engineering, May, 1949.

5 - Lockhart, R.W. and Martinelli, R.C., "Proposed Correlation of Data for Isothermal Two Phase, Two component Flow", Chemical Engineering Progress Vol. 45 #1 January, 1949, pp. 39-48.

6 - Martinelli, R.C., and Nelson, D.B., Trans. A.S.M.E., 70 695 (1948).

7 - Martinelli, R.C., Putman, J.A. and Lockhart, R.W., "Two Phase, Two Component Flow in the Viscous Regions", University of California, Berkeley, California, December 1945 - Presented at Chicago, Ill. meeting.

8 - Brown and Associates, Unit Operations, John Wiley and Sons, New York, N.Y. 1950.

9 - Moody, L.F., "Friction Factors for Pipe Flow", Transactions of the A.S.M.E., November, 1945, pp. 671-684.

10 - Chenoweth, J.M. and Martin, M.W., "Turbulent Two-Phase Flow", Petroleum Refiner, October, 1955 pp. 151-155.

11 - Alves, George E., "Cocurrent Liquid-Gas Flow in a Pipe Line Contactor", Chemical Engineering Progress, Vol. 50, No. 9, September, 1954, pp. 449-456.

12 - Pipe Friction Manual, Hydraulic Institute, 122 East 42nd St., New York, New York, 1954.

13 - Spink, L.K., Principles and Practice of Flow Meter Engineering, 7th ed., The Foxboro Company.

14 - Addison, Herbert, Hydraulic Measurement, 2nd ed., J. Wiley and Sons, Inc., New York 1946.

15 - Collins, T.T., "Scrubbing of Sulfate Recovery Furnace Stack Gases", Journal Paper Industry and Paper World 29, 680-6, 830-4, 984-7, (1947).

16 - Jones, W.P., "Development of the Venturi Scrubber", Industrial Engineering Chemistry, 41, 2424-7, (1949).

17 - Johnstone, H.F. and Roberts, M.H., "Deposition of Aerosol Particles from Moving Gas Stream", Industrial and Engineering Chemistry, Vol. 41, No. 11, November, 1949, p. 2417.

18 - Ellman, F.O. and Johnstone, H.F., "Collection of Aerosols in a Venturi Scrubber", Industrial and Engineering Chemistry, 43, 1358-63, (1951)

19 - Johnson, H.A., American Society of Mechanical Engineers, Paper 54-A-150, (1954).

20 - Hughes, R.R., Oppenheim, A.K., "Fluid Dynamics", Industrial and Engineering Chemistry, March, 1956 pp. 633-654.

21 - Stuart, M.C. and Yarnall, D.R., Fluid Flow Through Two Orifices in Series, Mechanical Engineering, Vol. 58 pp. 479-484, August, 1936.

22 - Straub, E., Adiabatic Flow of Compressible Fluids, New College of Engineering, Thesis, 1954.

23 - Pressure Loss With Orifice Plates or Flow Nozzles, A.S.M.E. Power Test Codes, 1949 Supplement on Instruments and Apparatus, Par. 56.

24 - Johnson, H.A., A.S.M.E., Paper 54-A-150, 1954.

26 - Johnson, H.A., and Abou-Sabe, A.H., Transactions A.S.M.E., Vol. 74, 1952, pp. 977-987.

27 - Monroe, E.S., A.S.M.E., Paper 54-A-118, 1954.

28 - Flow of Fluids, Gas-Liquid System, Industrial and Engineering Chemistry, March, 1956, p. 537.

29 - Gould, T., The Absorption of Ammonia With Water in A Venturi Scrubber, Newark College of Engineering, Thesis, May, 1952.

30 - Benjamin, M.W., Miller, J.G., The Flow of a Flashing Mixture of Water and Steam Through Pipes, Trans. A.S.M.E., Vol. 64, pp. 657-669, October, 1942.

31 - Stearns, R.F., Jackson, R.M., Johnson, R.R. and Larson, C.A., Flow Measurement With Orifice Meters, D. Van Nostrand Company, Inc., New York.