ENGINEERING RESEARCH INSTITUTE
THE UNIVERSITY OF MICHIGAN
ANN ARBOR

INVESTIGATION OF THE PERFORMANCE OF VANE-TYPE ANEMOMETERS IN A FOUR-INCH DUCT

Report No. 37

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November 1955

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INTRODUCTION

The Biram's type vane anemometer has been widely used for measuring air velocities in finned-tube heat transfer investigations. As a result of inconsistencies in the heat transfer data obtained by the use of this instrument, an investigation of the influence of the duct diameter on the performance of the instrument was undertaken. The instrument is sensitive to fluctuations in air velocity and appears to give excellent reproducibility. It averages out the variations in flow during a test run and is very simple to operate. The instrument is ideally suited for accurate velocity measurements, provided the influence of the duct diameter is known.

DESCRIPTION OF ANEMOMETER

The Biram's type anemometers under consideration were manufactured by the Taylor Instrument Co., Rochester, N. Y. Figure 1 shows one of the anemometers tested and the orifices used in the critical-flow prover. The unit is identified by the manufacturer as the "No. 3132 Taylor Anemometer." It has a four-inch-diameter frame with three dials reading to 10,000 feet. The movement has jeweled bearings, a disconnector, and an automatic zero-setting attachment. The instrument is delivered with calibration corrections obtained in wind-tunnel testing by the Taylor Instrument Co. The calibrations are obtained by comparative tests with standard instruments certified by the National Physical Laboratory (England) and the Bureau of Standards. The instrument is designed for use with air speeds from 200 to 3000 ft/min.

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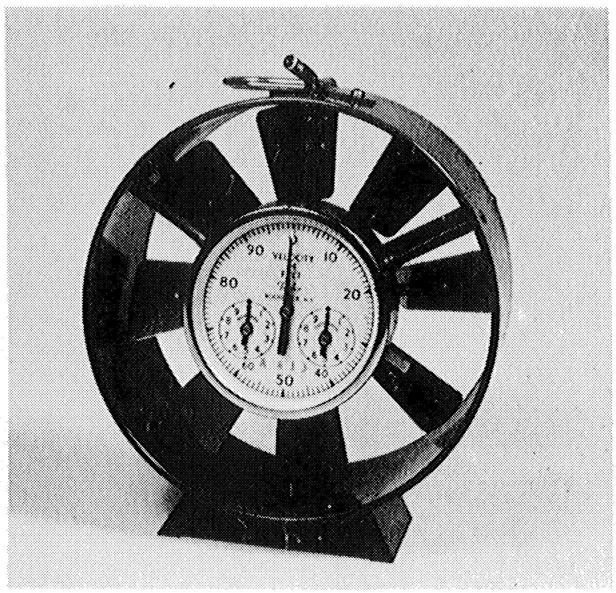
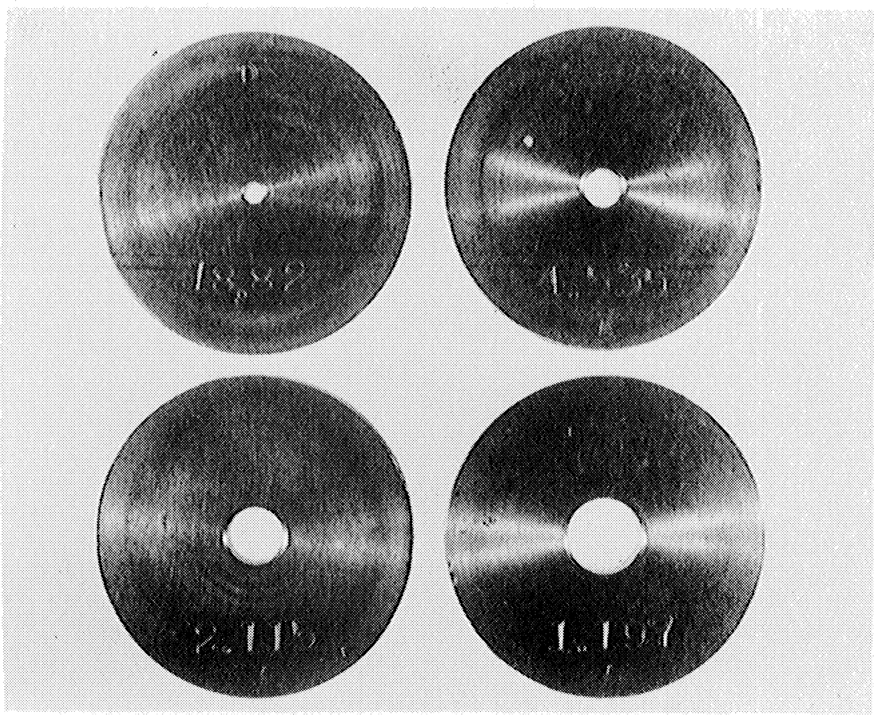


Taylor No. 3132 vane anemometer



Critical-flow orifices

Fig. 1. Anemometer and orifices used in testing.

ing through a rotameter, a four-inch-diameter duct and then through the four-inch anemometer, discharging to the atmosphere. Figure 2 presents a schematic diagram of the test arrangement. A gas rotameter was placed between the critical-flow prover and the anemometer for a second check on the volumetric throughput. The rotameter had previously been calibrated with water. This calibration is given in Table IV and graphically in Fig. 4.

Air pressures and temperatures were measured upstream from the orifice by means of a mercury-in-glass thermometer and a calibrated pressure gage. The Sargent ID6489 thermometer was previously calibrated against Bureau of Standards certified thermometers and the pressure gage was calibrated against a Meriam one-hundred-inch mercury column. These calibrations are given in Tables V and VI, respectively.

A typical experimental run was made in the following manner, referring to Fig. 2:

1. The air-line control valve was opened until the pressure gauge read higher than 15 psig (see page 8). The barometric pressure was recorded.

2. The system was allowed to reach a steady-state operating condition as indicated by constant inlet air temperature and pressure.

3. The air anemometer and stop watch were started simultaneously.

4. During the run, several readings of the rotameter, air temperature, and air pressure were taken and recorded.

5. The anemometer and stop watch were stopped simultaneously, completing the test run, and the data were recorded.

Table I presents a typical laboratory test run.

FIGURE 2

CRITICAL-FLOW PROVER — TEST APPARATUS (SCHEMATIC)

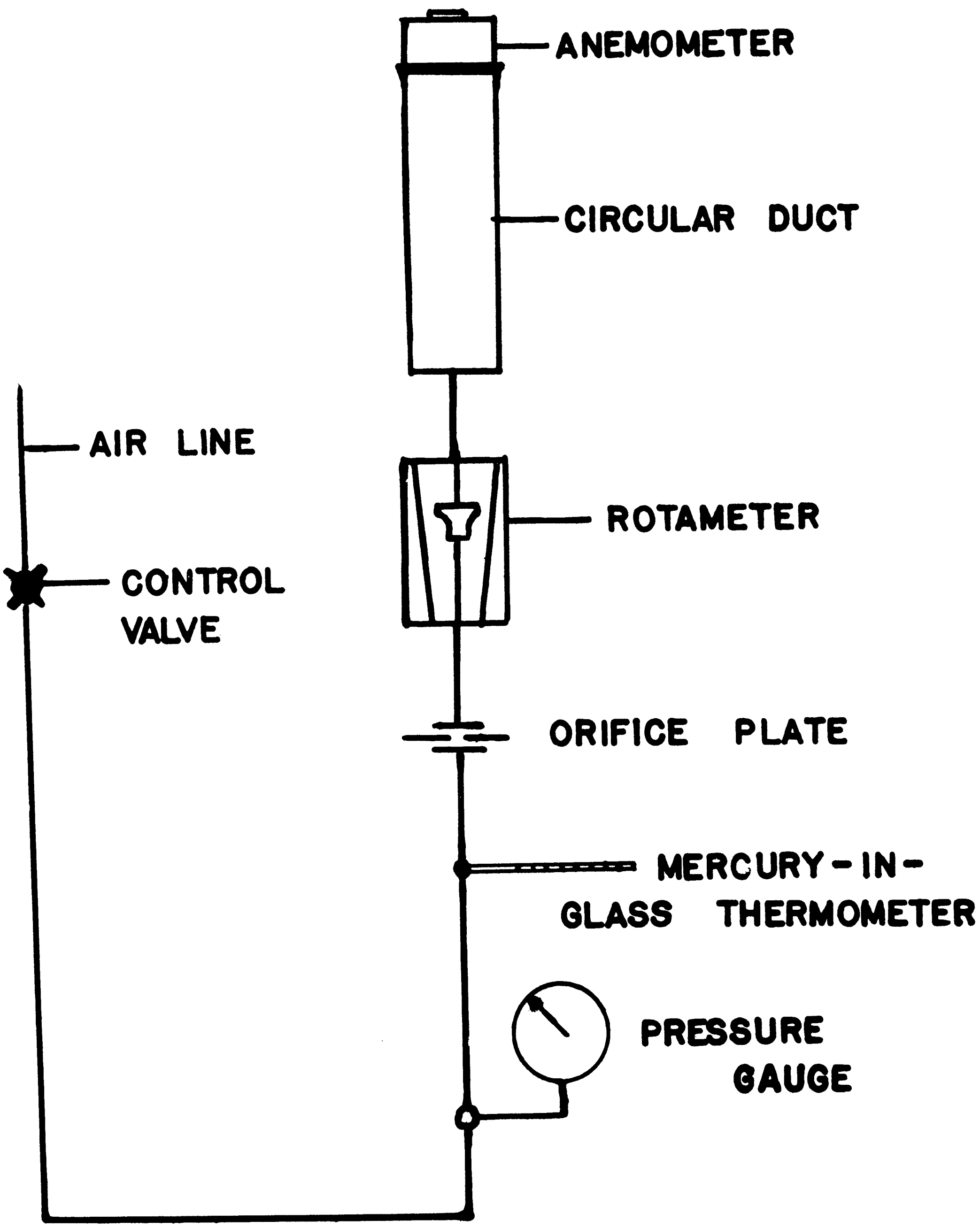


TABLE I

TYPICAL EXPERIMENTAL DATA
RUN NO. 10

Taylor Anemometer No. A413.
Barometric Pressure = 739 mm Hg.
Duct Size = Four Inches, ID.
Rotameter No. D8-1638.
Critical-Flow Prover Orifice = 3/8 in. Nominal.
Orifice Constant = 2.115 sec/ft^3.

Pressure-Gage Reading psig	Air Temperature °C	Rotameter Reading
22.4	32.9	34.4
22.5	32.9	34.4
22.5	32.85	34.4
22.5	32.80	34.4
22.5	32.80	34.4
Avg 22.48	32.85	34.4

Elapsed time of run = 1 min, 31.5 sec.
Anemometer reading = 2000 ft.

Table VII contains a summary of the experimental data.

DISCUSSION OF TEST PRINCIPLES

A. CRITICAL-FLOW ORIFICE THEORY

The throughput of a critical-flow orifice is based on the theory of "sonic flow." When the pressure drop across the orifice exceeds a certain critical value, sonic velocity is reached in the orifice throat. Under this condition, any further increase in upstream pressure does not increase the velocity of flow through the orifice. Therefore, the volumetric throughput through the orifice is constant. The mass throughput, (lb/hr), however, does increase with increase in air density. The air-time constants for the orifices used are tabulated in Table II.

TABLE II

AIR-TIME CONSTANTS FOR CRITICAL FLOW ORIFICES

Nominal Orifice Diameter in.	Air Time for One Cu Ft at 60°F sec
1/16	80.7
1/8	18.82
1/4	4.535
3/8	2.115
1/2	1.197
5/8	0.757

The "gas time" for a test with an orifice depends on the size of the orifice, the ratio of specific heats, the temperature, and the specific gravity of the gas. The correction factors as provided by the manufacturer, for air at temperatures other than 60°F, are tabulated in Table III.

To determine the air throughput from such an orifice, fundamental relationships are required. Gas-flow relationships for flow of gas at high velocities through orifices have been developed and are available in the literature.[1,2,3,4] The derivations of the applicable theoretical re-

[1] Brown, G. G., *et al.*, *Unit Operations*. New York: John Wiley and Sons, Inc., 1950, pp. 198-205.

[2] Dodge, B. F., *Chemical Engineering Thermodynamics*. New York: McGraw-Hill Book Co., 1944, pp. 324-36.

TABLE III

TEMPERATURE-CORRECTION FACTORS

Temperature °F	Correction Factor
80	0.981
82	0.979
84	0.978
86	0.976
88	0.974
90	0.972
92	0.971
94	0.969
96	0.967
98	0.965
100	0.964

lationships therefore will not be presented here. A summary of the applicable relationships with restrictions will be given. The following discussion follows the development of Brown (see footnote 1).

For maximum mass velocity, the critical pressure ratio is determined by

$$\frac{P_o}{P_c} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} ,$$

where:

P_c = the upstream pressure, psi
P_o = the downstream pressure, psi
k = the ratio of C_p to C_v
C_p = specific heat at constant pressure
C_v = specific heat at constant volume.

3 Perry, J. H., Chemical Engineers' Handbook, 3rd ed. New York: McGraw-Hill Book Co., 1950, pp. 402-3.

4 Marks, L. S., Mechanical Engineers' Handbook, 4th ed. New York: McGraw-Hill Book Co., 1941, pp. 354-5.

For air $k = 1.403$ at 17°C. Therefore,

$$\frac{P_o}{P_c} = \left(\frac{2}{2.403}\right)^{\frac{1.403}{0.403}} = (0.832)^{3.481}$$

$$\therefore \frac{P_o}{P_c} = 0.527.$$

Therefore, if the discharge pressure is one atmosphere (14.7 psia), then the upstream pressure necessary to establish critical flow is:

$$P_c = \frac{P_o}{0.527} = \frac{14.7}{0.527} = 27.9 \text{ psia.}$$

If the atmospheric pressure is 14.7, then $P_c = 27.9 - 14.7 = 13.2$ psig.

The velocity of the gas through the orifice under critical-flow conditions is given by the well-known equation for the velocity of sound in an ideal gas (see footnote 2):

$$V_{(max)} = \sqrt{g\ k\ p_2\ v_2}\ ,$$

where

$V_{(max)}$ = orifice velocity, ft/sec
g = gravitational constant, ft/sec^2
k = ratio of specific heats
p_2 = upstream pressure, psfa
v_2 = specific volume of upstream gas, cu ft/lb.

The acoustical velocity given by the above equation when critical flow is reached represents the maximum velocity at which the gas can flow through an orifice under the influence of pressure effects. This velocity is independent of the upstream pressure as long as the upstream-downstream pressure ratio exceeds the critical value.

B. ROTAMETER THEORY

The theory of gas and liquid flow measurement by means of rotameters is available in the literature.[5] The relationship derived from the

[5] Brown, G. G., *et al.*, *op. cit.*, pp. 161-2.

forces involved is:

$$W = C_r A_o \sqrt{\frac{2g\ \rho(\rho_f - \rho)V_f}{A_f}} \quad ,$$

where

W = mass rate of flow, lb/sec
C_r = coefficient of discharge of the float
A_o = area of flow, sq ft
g = gravitational constant, ft/sec^2
ρ = density of flowing fluid, lb/ft^3
ρ_f = density of float, lb/ft^3
V_f = volume of float, ft^3
A_f = area of float, ft^2.

In the case of calibration of a rotameter for air by means of water throughput, the amount of air flowing at a given rotameter reading may be obtained from the corresponding water flow rate as follows:

$$\frac{W_w}{W_a} = \sqrt{\frac{\rho_w(\rho_f - \rho_w)}{\rho_a(\rho_f - \rho_a)}} \quad ,$$

where

W_w = mass flow rate of water, lb/sec
W_a = mass flow rate of air, lb/sec
ρ_w = density of water
ρ_a = density of air
ρ_f = density of float.

Since the density of air is infinitesimal in comparison with that of the float metal, the value of $(\rho_f - \rho_a)$ is set equal to ρ_f.

$$\therefore \frac{W_w}{W_a} = \sqrt{\frac{\rho_w(\rho_f - \rho_w)}{\rho_a \rho_f}} \quad .$$

The above relationship permits conversion of a water calibration to an air calibration.

EXAMPLE CALCULATIONS

Example calculations of test run No. 10 are presented for the critical-flow orifices and for the rotameter. The data are presented in Table I, page 5.

A. COMPUTATION OF AIR FLOW FROM FLOW PROVER

Atmospheric pressure = 739 mm Hg
= 14.29 psia

Upstream absolute pressure = 14.29 + 22.49
= 36.78 psia

Correction for pressure-gage calibration = -0.25

∴ Air pressure = 36.53 psia

Air temperature = 32.85°C = 94.17°F

Temperature-correction factor (Table V) = 0.969

Orifice constant = 2.115 sec/ft^3

Corrected orifice constant = (0.969)(2.115) = 2.050

$$\text{Air density} = \left(\frac{29}{359}\right)\left(\frac{492}{554.17}\right)\left(\frac{36.53}{14.7}\right) = 0.1782 \text{ lb/cu ft}$$

$$\therefore W = \left(\frac{0.1782}{2.050}\right)(60) = 5.21 \text{ lb/min}$$

$$\text{Four-inch duct cross-sectional area} = \frac{16\pi}{576} = 0.0872 \text{ ft}^2$$

$$\text{Mass flow rate in duct} = \frac{5.21}{0.0872} = 59.75 \text{ lb/ft}^2\text{/min}$$

$$\text{Air density in duct} = 0.074\left(\frac{530}{554.17}\right)\left(\frac{14.29}{14.7}\right) = 0.0688 \text{ lb/ft}^3$$

$$\text{Air velocity in duct} = \frac{59.75}{0.074} = 807 \text{ std ft/min}$$

B. AIR VELOCITY AS MEASURED BY THE ANEMOMETER

$$\frac{2000 \text{ ft}(60)}{91.5 \text{ sec}} = 1311 \text{ ft/min}$$

Correction for density of air:[6]

$$V_o = V\sqrt{\frac{\rho}{\rho_o}}$$

Standard air density = 0.074 lb/ft^3

$$\therefore V = 1311\sqrt{\frac{0.0688}{0.074}} = 1265 \text{ std ft/min}$$

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6 Ower, E., Measurement of Airflow. London: Chapman and Hall, Ltd., 1927, pp. 118-9.

Taylor anemometer calibration correction = -17

∴ Corrected anemometer reading = 1248 ft/min

$$\text{Ratio of velocities} = \frac{1248}{807} = 1.54$$

Therefore, the anemometer is reading 54% high.

C. CHECK BY ROTAMETER

Rotameter reading = 34.4

Corresponding water flow = 8,700 lb/hr at 11°C

$$W_{air} = W_{water}\sqrt{\frac{\rho_a \rho_f}{\rho_w(\rho_f - \rho_w)}}$$

$$\rho_{water} = 0.99963 \times 62.4 = 62.4 \text{ lb/ft}^3$$

$$\rho_{float} = 7.8 \times 62.4 = 486 \text{ lb/ft}^3$$

$$\rho_{air} = 0.0698 \text{ lb/ft}^3$$

Substituting:

$$W_{air} = 8700\sqrt{\frac{(0.0698)(486)}{62.4(486-62.4)}}$$

$$= 312 \text{ lb/hr}$$

$$= 5.20 \text{ lb/min}$$

$$\therefore \text{air velocity} = \frac{5.20}{0.0872(0.074)} = 806 \text{ std ft/min}$$

as compared to 807 ft/min by the flow prover. Therefore, the anemometer is reading 54% high.

DISCUSSION OF RESULTS

A summary of the calculated results is given in Table VIII. These results are presented graphically in Fig. 3.

Figure 3 indicates a linear relationship between the actual air velocity in the four-inch duct and the computed air velocity obtained from the anemometer reading. The slope of this line is:

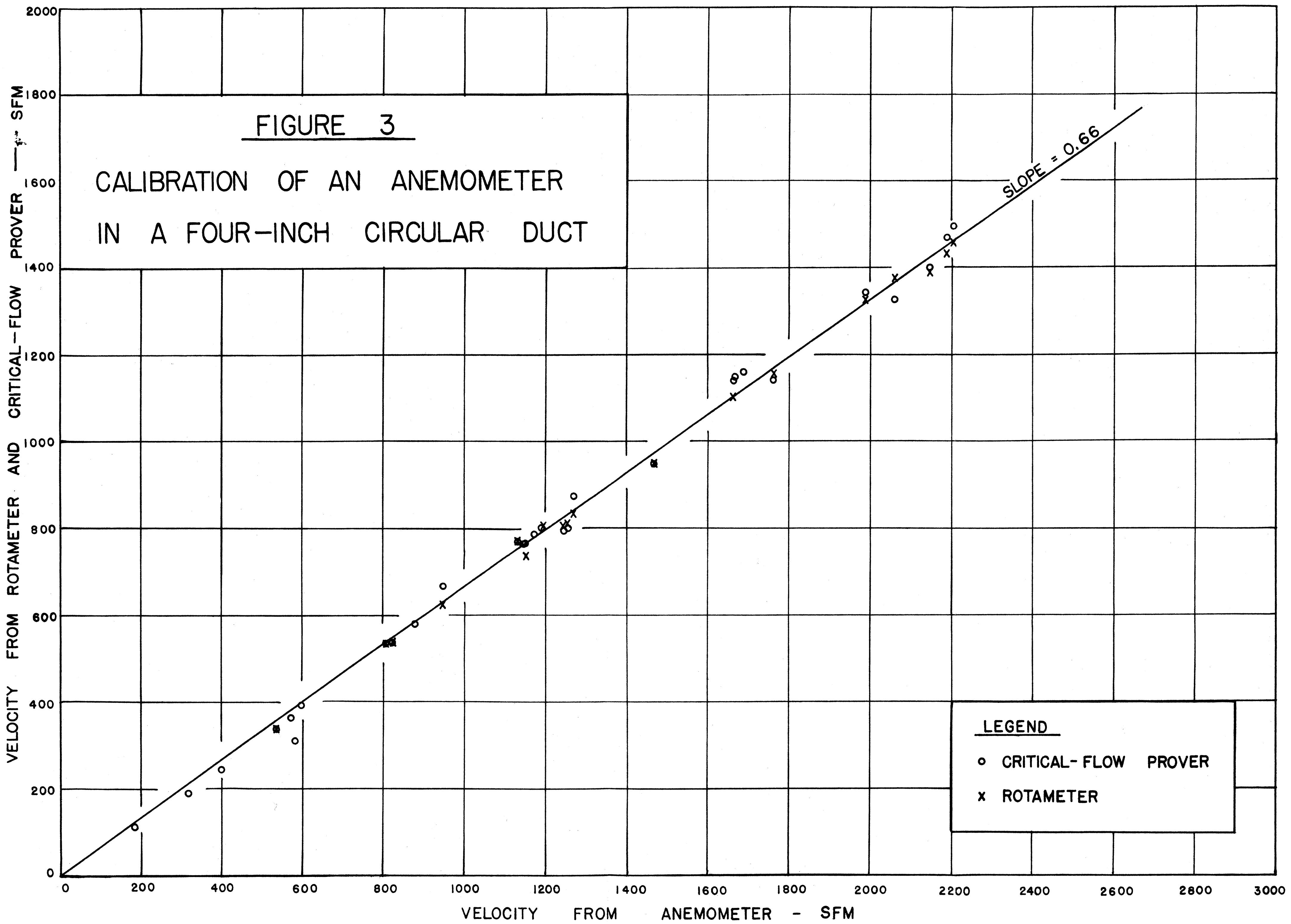
FIGURE 3
CALIBRATION OF AN ANEMOMETER
IN A FOUR-INCH CIRCULAR DUCT
SLOPE = 0.66
LEGEND
CRITICAL-FLOW PROVER
ROTAMETER
VELOCITY FROM ROTAMETER AND CRITICAL-FLOW PROVER — SFM
VELOCITY FROM ANEMOMETER - SFM
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000

$$\frac{\text{True Air Velocity (SFM)}}{\text{Anemometer Air Velocity (SFM)}} = 0.66.$$

This indicates that the actual air velocity is 66% of the anemometer indicated velocity. The anemometer is therefore indicating velocities which are 52% high. As indicated above, the true air velocity can be obtained by multiplying the anemometer air velocity by 0.66.

RECOMMENDATIONS

It is recommended that in all future air tests in which this model of anemometer is used with a four-inch duct the air velocities so indicated be reduced by 34%.

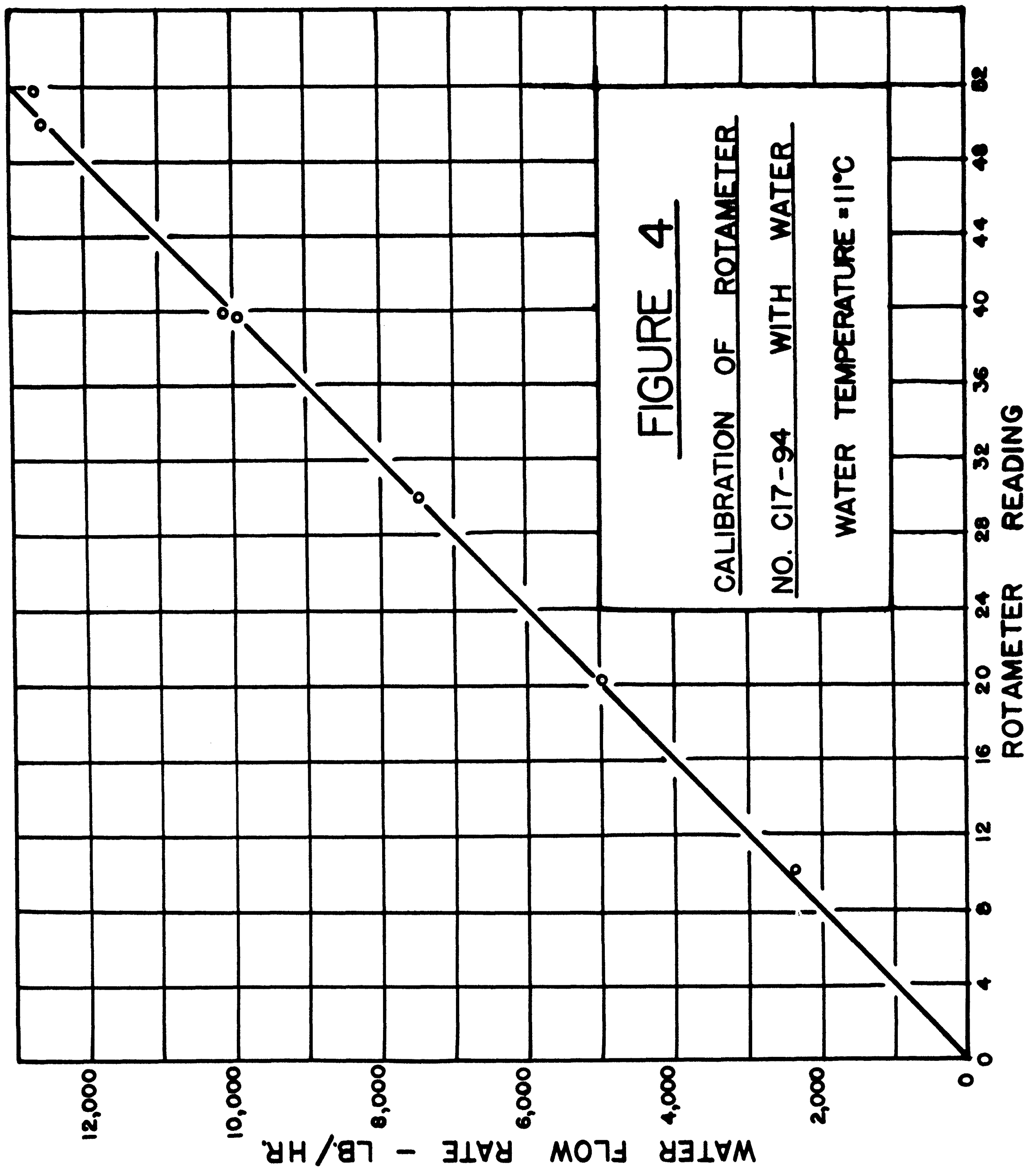
FIGURE 4
CALIBRATION OF ROTAMETER
NO. C17-94 WITH WATER
WATER TEMPERATURE = 11°C
ROTAMETER READING
0
4
8
12
16
20
24
28
32
36
40
44
48
52
WATER FLOW RATE – LB./HR.
0
2,000
4,000
6,000
8,000
10,000
12,000

TABLE IV

WATER CALIBRATION OF ROTAMETER NO. C17-94

Rotameter Reading	Water Temp °C	Lb of Water	Elapsed Time min	Elapsed Time sec	Lb/Hr
10.0	11	100	2	33.3	2350
20.2	11	200	2	24.2	4990
30.0	11	300	2	25.6	7420
39.7	11	300	1	49.	9910
39.8	11	300	1	46.9	10,110
49.0	11	300	1	25.8	12,590
49.9	11	300	1	25.2	12,690

TABLE V

CALIBRATION OF SARGENT 1D6489 MERCURY-IN-GLASS
THERMOMETER FOR USE IN CRITICAL-FLOW ORIFICE PROVER

Thermometer Reading °C	Correction to be Added °C
0.5	-.10
5	-.15
10	-.10
15	-.10
20	-.10
25	-.10
30	0
35	0
40	-.05
45	-.10
50	-.20
55	-.25
60	-.20
65	-.15
70	-.20
75	-.20
80	-.35
85	-.40
90	-.45
95	-.55

TABLE VI

CALIBRATION OF PRESSURE GAUGE C2-347 WITH
MERIAM ONE-HUNDRED-INCH MERCURY COLUMN AS A STANDARD

C2-347 Observed Pressure psig	Meriam Column Inches of Hg	Correction to be Added psig
3.5	6.60	-.27
6.3	12.20	-.33
10.3	20.34	-.35
15.0	29.62	-.52
20.0	39.90	-.49
24.0	48.56	-.25
30.0	60.61	-.36
35.0	70.90	-.23
40.0	80.98	-.40
45.0	90.51	-.74
49.55	100.52	-.40

TABLE VII

SUMMARY OF EXPERIMENTAL DATA

Run No.	Observed Upstream Pressure psig	Observed Air Temperature °C	Barometric Pressure mm Hg	Orifice Constant sec/ft³	Rotameter Reading	Anemometer Reading ft	Anemometer Time sec	Anemometer No.
1	29.66	33.70	737	18.82		300	103.8	A413
2	61.00	34.02	737	18.82		500	97.4	A413
3	82.00	34.19	737	18.82		600	91.8	A413
4	82.00	34.11	737	18.82		600	92.8	A413
5	21.54	33.49	737	4.535		1000	103.2	A413
6	19.15	33.00	739	4.535	14.40	800	89.6	A413
7	39.63	33.30	739	4.535	22.64	1200	85.7	A413
8	60.40	33.49	739	4.535	31.38	2000	100.6	A413
9	21.97	33.00	739	2.115	33.95	2100	97.1	A413
10	22.48	32.85	739	2.115	34.40	2000	91.5	A413
11	29.26	33.56	739	2.115	40.12	2200	85.3	A413
12	38.37	32.57	739	2.115	48.70	3000	95.9	A413
13	24.50	33.20	739	1.198	61.94	5000	123.8	A413
14	23.82	33.33	739	1.198	60.96	4000	101.4	A413
15	22.52	34.15	739	2.115	34.17	2200	103	6759
16	20.93	31.22	740	2.115	32.38	2000	99.6	6759
17	36.52	31.33	740	2.115	46.38	3000	100	6759
18	21.00	32.08	740	1.197	56.85	3400	91.4	6759
19	19.81	32.93	740	1.197	54.58	5000	139.2	6759
20	22.56	33.55	740	1.197	58.7	5500	140.8	6759
21	38.21	33.21	740	4.535	22.8	1500	106.6	6759
22	49.22	33.22	740	4.535	26.39	2400	142.2	6759
23	70.94	33.27	740	4.539	35.29	3000	131.8	6759
24	20.88	33.24	741.5	2.115		2000	100.8	A413
25	21.99	33.56	741.5	2.115		2000	98.4	A413
26	38.33	32.90	741.5	2.115		3000	101.4	A413
27	38.90	32.94	741.5	2.115		3000	100.4	A413
28	21.73	32.96	741.5	4.535		1000	105.6	A413
29	24.26	33.13	741.5	4.535		1000	100.6	A413
30	42.86	33.58	741.5	4.535		2000	133.6	A413

TABLE VIII

SUMMARY OF CALCULATED RESULTS

Run No.	Velocity from Anemometer SFM	Velocity from Critical-Flow Prover SFM	Velocity from Rotameter
1	184	111	
2	315	191	
3	315	191	
4	392	244	
5	578	361	
6	534	336	339
7	819	536	533
8	1143	762	739
9	1240	791	801
10	1250	807	806
11	1465	949	947
12	1759	1140	1150
13	2202	1497	1458
14	2186	1471	1433
15	1190	800	805
16	1128	767	768
17	1660	1140	1100
18	2061	1327	1378
19	1988	1341	1323
20	2144	1400	1388
21	803	536	539
22	944	669	623
23	1269	873	834
24	1140	764	
25	1166	787	
26	1667	1147	
27	1682	1159	
28	567	365	
29	593	392	
30	874	578	