1918

Measurement of air under high pressure by orifice method

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MEASUREMENT OF AIR UNDER HIGH PRESSURE
BY ORIFICE METHOD

by

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A

THESIS

submitted to the faculty of the

SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI

in partial fulfillment of the work required for the

DEGREE OF

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING

Rolla, Mo.

1918.

Approved by H. B. Dickerson
Professor of Mechanical Engineering.

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INTRODUCTION.

The measuring of compressed air, under high pressures, by means of observing the drop in pressure on passing thru an orifice, is in a new field of endeavor.

The necessity of measuring compressed air, in order to handle it economically, is obvious. Hence, the importance of a simple device by which this may be done. A device, which may be duplicated at any time, at any place, with very little expense, and ordinary materials.

Some of the more important works, which were used as references, in general compressed air work, with some consideration of measurement of air, are:

"Flow of Fluids thru Venture Meter," Coleman, A.S.M.E. Nov. '06,p.39.

"A High Duty Air Compressor" - O.P. Hood, A.S.M.E. Nov. '06,p.39.

"Air Practice", Richards.

"Compressed Air", Harris.

"Compressed Air" - Simons.

"Air Compression and Transmission",Thorkelson.

"Measurement of Air" - C. A. Treat - A.S.M.E. Vol.34 - 1912.

References which are more directly concerned with orifice measurement are:

"Flow of Air thru Orifices into Atmos."
R.T.Durley, A.S.M.E. Vol.27.

"Flow of Air thru Thin Plate Orifices" -
E.O. Hickstein,A.S.M.E.Mar.1916.

The aim of this work is to determine whether it is possible, as a commercial proposition, to accurately measure the quantity of flow of compressed air under various conditions of temperature and pressure, by means of the observation of the drop in pressure thru an orifice, the coefficient of which has been previously determined.

The first part of the work, then, is the accurate determination of the coefficient, under various conditions of temperature and pressure.

Mention should be made here of the valuable assistance given by Walter F. Lottman, a fellow-student, and Professor H. S. Dickerson, in the laboratory and also in the calculations. Without the aid of these men, the work would have been impossible.

Basis of Procedure.

The apparatus was so arranged that Fliegner's formula or Weisbach's formula, for the quantity of flow thru an orifice, could be used.

Fleigner's formula:-

$$Q = K \times .530\ F \frac{P}{\sqrt{T_1}}$$

When K= coefficient for orifice.
F= area of orifice in sq.in.
P_1=abs.press.above orifice.
T_1=abs.temp.above orifice.

Weisbach's formula:-

$$W = K \times 1.06\ F \sqrt{\frac{P_a(P_1-P_a)}{T_1}}$$

When

K= coefficient for orifice.
F= area of orifice in sq.in.
P_a= pressure below orifice lb.per sq.in.
P_1= pressure above orifice lb.per sq.in.
T_1= abs.temp.above orifice deg.F.

Description of Apparatus.

Compressors:-

The compressed air was supplied by the regular compressed air equipment in the engine room of the Missouri School of Mines, Rolla, Missouri, consisting of a Sullivan 2-stage-compound and a Laidlow-Dunn two - stage compressor.

Measuring Tanks:

The measuring tanks were two cylindrical sheet steel tanks each 5 ft. internal diameter and 15 ft. 10 in. high, having a volume of 2944 cu.ft. each. The tanks were connected at the bottom by a 12 in. pipe, provided with a gate valve and each tank stood half full of water, so that the compressed air could be measured by the water displacement method. From the top of these tanks a 4 in. pipe led down to an air switch (designed by Prof. E. G. Harris, of the M.S.M.) and from this switch a 4 in. pipe led to the orifice drum; this pipe was also provided with a valve. Each tank was provided with a glass gage running its entire length and behind these gages were scales graduated in feet and tenths of a foot. At the top of each of these glass gages was attached a $\frac{1}{4}$in. pipe which led to the differential gage, G_2. The pressure in the tanks was obtained by the use of pressure gages connected to the tanks thru gage testing platforms, such as are used for the calibration of steam gages. The platforms were tapped thru the bottom so as to receive a $\frac{3}{4}$ in. pipe from the tank. The purpose of these special gages was to accurately check the pressure indicated by the dial gage, by means of the floating weight platform of the gage testing instrument. Thermometer wells were tapped into the tanks along the side and also in the top so that the average temperature of the air could be obtained.

Orifice Drum:

The orifice drum was made up of two lengths of 14 in. cast iron pipe flanged at each end, one section 4 ft. long and the other 3 ft. long. The 4 ft. length was placed at the end nearer the air switch, that is, the air passed thru the longest section first. Wood baffle boards, $\frac{1}{2}$ in. thick perforated with $\frac{1}{2}$ in. holes, placed 1 ft. apart, the first one being 1 ft. from the end, were fastened in the 4 ft. length. One foot from the second baffle board a screen was placed made of 50 mesh copper wire. The purpose of the baffles and the screen was to break up the air currents in the drum and to distribute the flow evenly over the entire area of the drum. Between the adjacent flanges of the two sections the orifice plate was fastened. The orifice was 2 in. in diameter, accurately drilled and reamed in a thin plate of tool steel. It was found necessary to use an orifice not larger than 2 in. in diameter because it was found that with larger sizes the volume of air circulating, and hence the speed of the water in the glass gage on the measuring tanks, was too great to permit very accurate reading. At the discharge end of the drum, a 4 in. pipe led back to the low pressure cylinder of the Sullivan compressor to permit the recirculation of the air. At a point 6 in. from the orifice plate, and on each side of it, connections were made to the differential pressure gage in order to measure the pressure drop thru the orifice. This gage was an ordinary glass -tube, in which mercury was used as the liquid. From the same connection in the 4 ft. drum section connection was also made to a similar -tube gage for the purpose of determining the pressure drop between the measuring tank and the orifice.

Barometer:-

An ordinary mercury barometer, graduated to read to 0.002 of an inch between 26 and 33 in. was used to measure the atmospheric pressure.

Air Circuit:-

The air circuit was as shown in detail in Figure 1. The general scheme of circulation was, however, from the compressors thru the switch to either tank, from either tank thru the orifice drum and back to the low pressure cylinder of the Sullivan compressor to be circulated again.

Manipulation.

To start run, the valve, F, was closed and the cold air intake valve on the Sullivan compressor was opened and the Sullivan compressor was then started and was used to raise the pressure in the measuring tanks to the desired value. After the desired pressure was attained, valve F was opened and at the same time the atmospheric intake valve on the compressor was closed, thus the compressor circulated the air in the entire system under pressure. After circulation had been established, the speed of the compressor was regulated, since the speed determined the velocity of flow of air in the system; this speed was then kept constant throughout the run. When the air started to circulate, the switch was in such position that the air from the compressors entered tank No. 1, thus forcing the water thru pipe P and into tank No. 2, which caused the air in tank No. 2 to pass thru the switch, thru the orifice drum and back again to the compressor. When the water level in No. 1 reached the 1 ft. mark, the time was recorded, the switch reversed, and the water from No. 2 tank then was forced back into No. 1. When the water level in No. 1 reached the 14 ft. mark, the time was again recorded, the switch was then reversed and when the water level was again 1 ft., the operation was repeated. This procedure was continued during the entire run. Thus, knowing the volume of the tanks between the marks, and the time required for this volume of air to pass out of the tanks, the cubic feet of air passing thru the system per unit of time was determined.

In order to determine the weight of this volume of air, the pressure and temperature had to be obtained. The pressure of the air in the tanks was read from the combination pressure gages and the temperature was read on the thermometer inserted in the top of the tank.

The pressure difference between the tanks and a point above the orifice was found by the differential gage , G_2, Thus, knowing the pressure in the tanks and the pressure drop between the tank and the orifice, subtracting the pressure drop from the tank pressure determined accurately the pressure in lbs. per sq.in. above the orifice. Knowing the pressure before the orifice and the pressure drop thru the orifice, as measured by the differential gage G_1, subtracting the pressure drop from the pressure before the orifice determined the pressure in lbs. per sq.in. below the orifice.

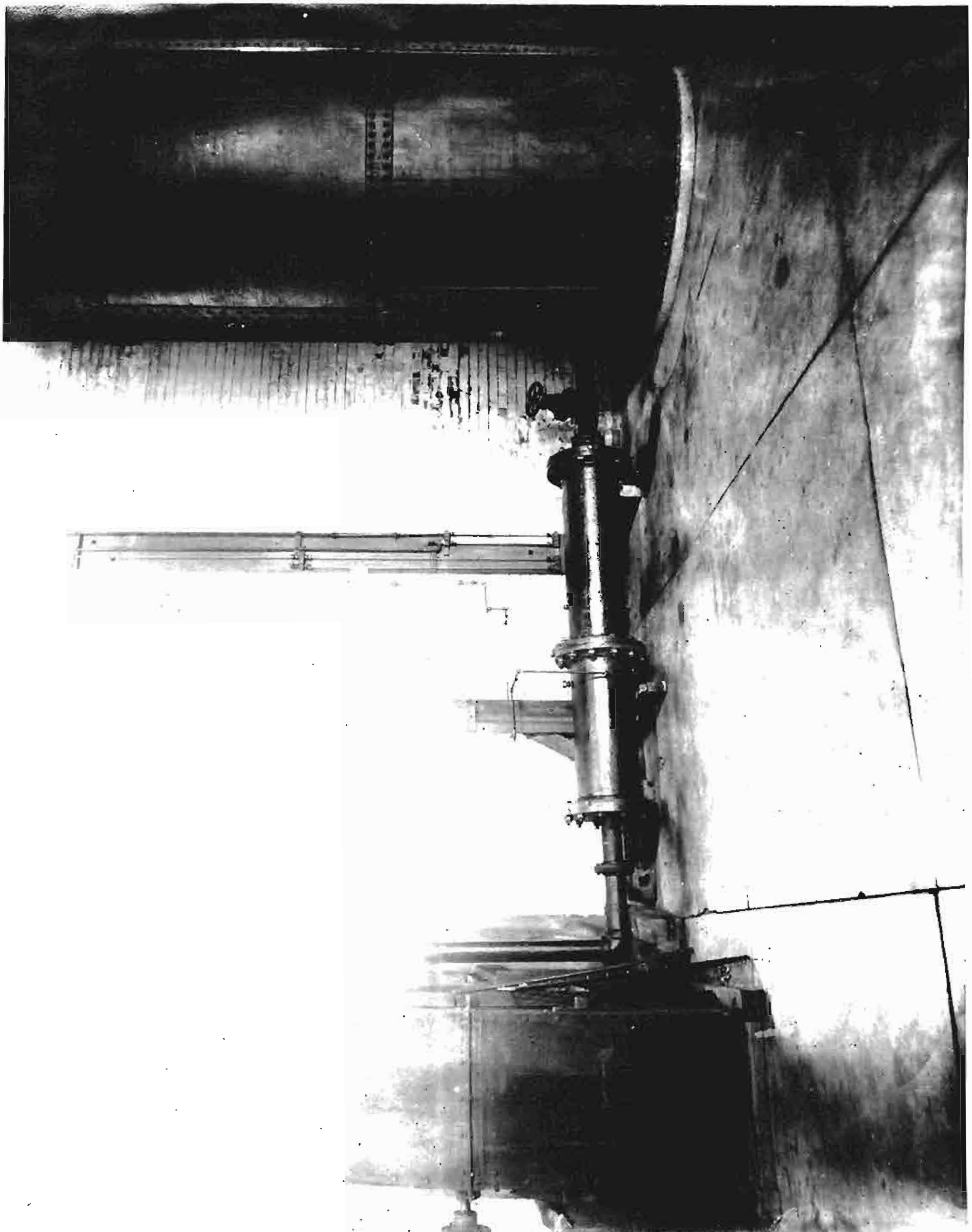
The temperature of the air flowing thru the orifice was read on a thermometer above the orifice.

CONCLUSIONS.

The experimental determination of the coefficient was made, and it came out to be practically constant, as the curve and data show.

Therefore, the experiment proves the theory set forth in the paper, and a simple device is shown to be an accurate means of measuring air under high pressures.

A reproduction of such an apparatus is inexpensive, and since the coefficient is found constant, the formula may be used with freedom, and it is hoped that this method will become better known by reason of the work done upon it.



DATA SHEET — First Run — **Exp't No.**

Reading No.	Time of Day	Pressures North Tank	Pressures South Tank	Time of Emptying	Temp. of Tanks	Counter Reading	Double Strokes
1	3:21	124	123	—	92	67388	
2		117	119	1:47	90	67544	156
3		117	117	1:41	91	67702	158
4		112	113	1:39	89	67862	160
5		112	112	1:39	90	68021	159
6		107	108	1:39	88	68181	160
7		107	107	1:39	90	68342	161
8		102	103	1:39	88	68503	161
9		102	102	1:39	90	68664	161
10		97	98	1:38	88	68823	159
11		97	97	1:38	90	68983	160
12		92	94	1:38	88	69142	159
13		92	92	1:37	90	69302	160
14		89	90	1:37	88	69462	160
15		85	87		88	69799	
16		85	85	1:34	90	69958	159
— Second Run —							
1	2:10	115	117	—			
2		117	116	2:31	92		
3		103	105	2:37	90	62549	
4		102	102	2:35	91	62707	158
5		94	96	2:40	88	62864	157
6		93	93	2:33	90		
7		86	88	2:33	88	63104	
8		85	85	2:30	89	63260	156
9							

Barometric Pressure = 28.672 in. Hg.

Date May 10, 1918

Observers { Mellow, Lottmann / Prof. H. S. Dickerson

Form 130-10-15-1000-F. P. & S. Co.

MISSOURI SCHOOL OF MINES

— First Run —

DATA SHEET Manometers **Exp't No.**

Reading No.	① North Upper	① North Lower	② South Upper	② South Lower	Temp. in Drum
1	11.3	6.7	9.4	3.7	93
2	11.9	6.2	9.9	2.8	92
3	11.7	6.2	9.8	3.6	91
4	11.7	6.3	9.7	3.5	91
5	11.7	6.3	9.7	3.7	90
6	11.8	6.3	9.6	3.6	90
7	11.7	6.2	9.6	3.6	90
8	11.7	6.3	9.6	3.5	90
9	11.7	6.3	9.5	3.9	90
10	11.8	6.3	9.6	3.7	89
11	11.7	6.4	9.6	3.6	90
12	11.7	6.4	9.6	3.7	89
13	11.6	6.5	9.6	3.8	89
14	11.7	6.3	9.5	3.4	89
15	11.6	6.5	9.4	3.7	89
16	11.5	6.6	9.4	3.8	89

— Second Run —

Reading No.	① North Upper	① North Lower	② South Upper	② South Lower	Temp. in Drum
1	14.9	12.0	8.5	11.4	92
2	14.5	12.3	10.9	8.4	91
3	14.2	12.3	10.9	8.3	90
4	14.5	12.3	10.2	8.4	90
5	14.1	12.4	10.2	8.1	88
6	14.0	11.4	10.5	7.8	87
7	13.6	11.4	9.8	6.9	87
8	14.0	11.3	9.6	7.3	87

Date May 10, 1918 **Observers** { Mellow, Lottmann / Prof. H. S. Dickerson

Form 130-10-15-1000-F. P. & S. Co.

MECHANICAL ENGINEERING LABORATORY

MISSOURI SCHOOL OF MINES

RUNNING LOG —— Third Run —— **Exp't No.**..................

Reading No.	Time of Day	Pressures #/□" North Tank	South Tank	Time of Emptying	Temp. of Tanks	Counter Reading	Double Strokes
1	2:50	117	117	—	92	64641	—
2		117	117	1:52	89	64788	—
3		103	113	1:50	90	64946	158
4		102	104	1:50	88	65104	158
5		94	102	1:49	90	65[illegible]	159
6		93	97	1:51	88	65426	163
7	~~2:26~~	90	96	1:48	89	65588	162
8		85	92	1:47	97	65748	160
9		85	90	1:45	89	65906	158
10		85	87	1:46	87	66064	158

—— Fourth Run ——

Reading No.	Time of Day	North Tank	South Tank	Time of Emptying	Temp. of Tanks	Counter Reading	Double Strokes
1	4:18	114	113	—	91	72647	-
2		114	115	1:22	89	72810	163
3		115	114	1:21	91	72972	162
4		110	108	1:21	89	73134	160
5		107	105	1:21	90	73295	161
6		103	104	1:22	90	73459	164
7		103	103	1:22	92	73622	163
8		99	101	1:22	90	73784	162
9		100	100	1:22	93	73947	163
10		96	98	1:22	91	74100	163
11		97	97	1:22	93	74272	162
12		93	95	1:22	92	74435	163
13		94	94	1:22	93	74459	164
14		90	92	1:22	91	74762	163
15		91	91	1:22	94	74926	164
16		87	88	1:23	92	75092	166
17		85	86	1:22	94	75256	164

Date May 10, 1918 **Observers** { Mellow, Lottmann / Prof. H. S. Dickerson

Form 110—M E—10-16—1000—F. P. & S. Co.

MECHANICAL ENGINEERING LABORATORY

MISSOURI SCHOOL OF MINES

—— Third Run ——

RUNNING LOG Manometers (in. Hg) **Exp't No.**

Reading No.	① North Upper	① North Lower	② South Upper	② South Lower	Temp. in Drum (°F)
1	15.0	10.4	10.7	5.3	91
2	15.0	10.4	10.5	5.4	90
3	14.9	10.6	10.8	5.3	89
4	14.9	10.5	10.4	5.3	88
5	14.8	10.6	10.6	5.4	88
6	14.9	10.6	10.4	5.4	88
7	14.8	10.4	10.4	5.4	88
8	14.8	10.4	10.2	5.6	87
9	14.7	10.7	10.3	5.4	87
10	14.7	10.6	10.4	5.2	87

—— Fourth Run ——

Reading No.	① North Upper	① North Lower	② South Upper	② South Lower	Temp. in Drum (°F)
1	16.9	7.4	13.1	3.5	93
2	16.7	7.6	12.7	3.5	93
3	16.6	7.7	12.6	3.8	93
4	16.5	7.7	12.1	4.0	93
5	16.3	7.8	12.9	3.8	94
6	16.2	7.8	12.6	3.6	94
7	16.1	7.9	12.3	4.0	94
8	16.2	7.8	11.7	4.6	94
9	16.2	7.8	12.2	4.6	95
10	16.2	7.8	11.5	4.2	93
11	16.1	8.1	12.2	4.3	95
12	15.9	8.2	12.1	4.1	95
13	15.9	8.3	12.1	4.2	96
14	15.9	8.2	11.1	5.1	95
15	15.8	8.3	12.0	4.4	96
16	15.8	8.3	11.4	4.8	95
17	15.7	8.4	12.2	4.2	94

Date May 10, 1918 **Observers** { Mellow, Lottmann / Prof. H. S. Dickerson

Form 110—M E—10-16—1000—F. P. & S. Co.

Computations

Formula Used :-

$$W = K \times .~~106~~ F \sqrt{\frac{P_a(P_1 - P_a)}{T_1}}$$

Where

W = wgt. in lbs. of air flowing thru orifice per second

K = coefficient of orifice used, to be determined from results of this experiment

F = area of orifice (sq. in.)

P_a = absolute press. below orifice #/□"

P_1 = " " above " #/□"

W was computed from the volume of the tanks and the time of Emptying. The density of air was taken at the pressure and temp. of the experiment.

$$W = \frac{(\text{Vol. of tank})(\text{density of air})}{\text{Time of Emptying (sec)}}$$

$$W = \frac{(5)^2(.7854)\,13 \times .5710}{99}$$

$W = 1.473$ cu. ft. per second

Barom. Press. = 28.672 in. Hg = 14.060 lb. per sq. in.

P_1 = (press. in tank) − (press. drop from tank to orifice)

$= (102. + 14.07) - (5.8 \times .4912)$

$= 116.07 - 2.82$

$= 113.25$ lb./sq. in. abs. press.

P_a = (press. above orifice) − (press. drop thru orifice)

$= 113.25 - (5.4).4912$

$= 113.25 - 2.65$

$= 110.60$ lb./sq. in. abs. press.

T_1 = deg. F + 459.5°

$= 90° + 459.5°$

$= 549.5°$ abs. temp.

$F = (2)^2 .7854 = 3.1416$ sq. in. orifice area

$$W = K F \sqrt{\frac{P_a (P_1 - P_a)}{T_1}}$$

$$1.473 = K \; 3.1416 \sqrt{\frac{110.60 (113.25 - 110.60)}{549.5}}$$

$$K = 0.641$$

(when compressor was run at 97 R.P.M.)

Computed Data

MECHANICAL ENGINEERING LABORATORY

MISSOURI SCHOOL OF MINES

~~RUNNING LOG~~

Exp't No.

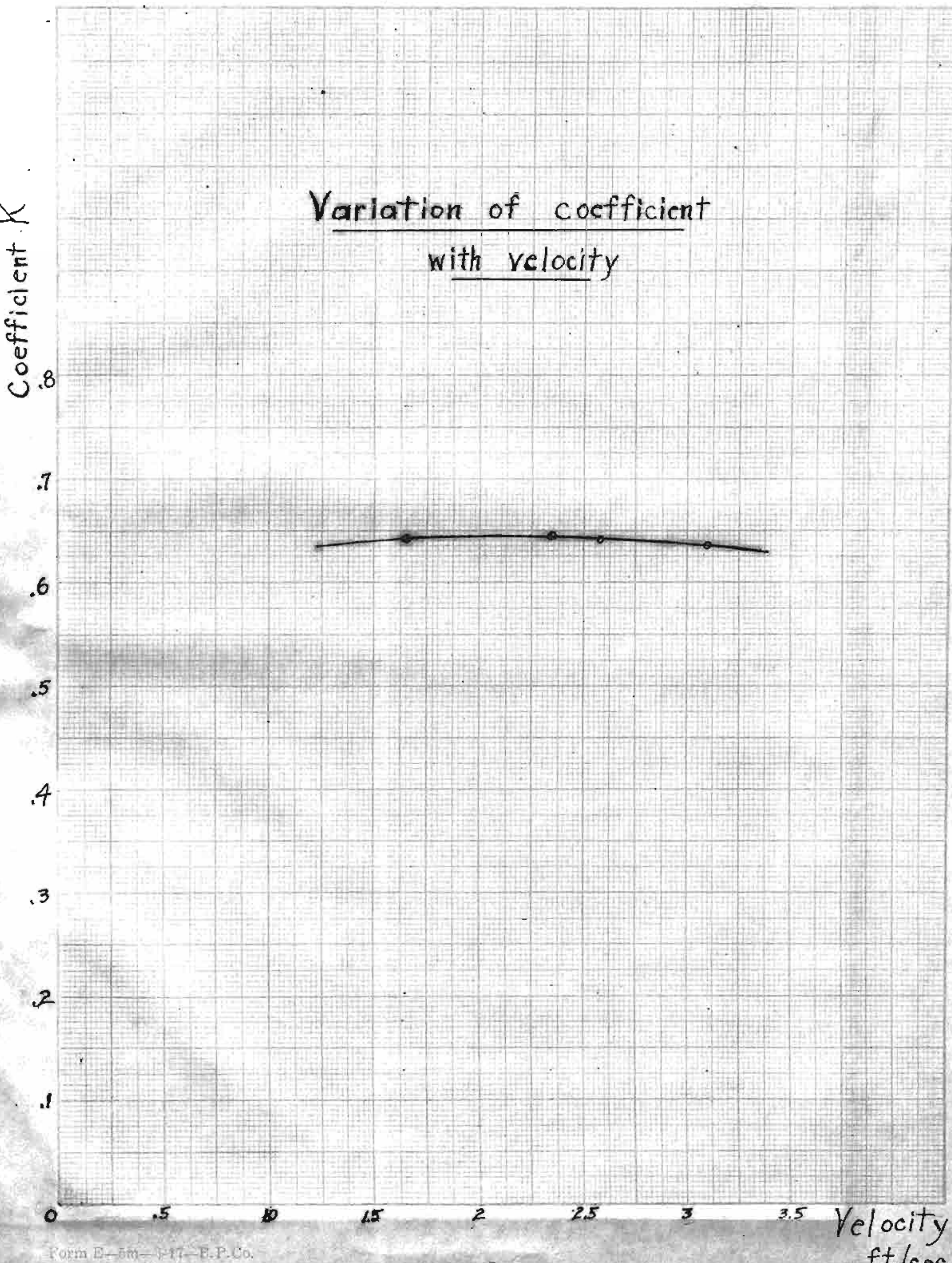
Revolutions per minute

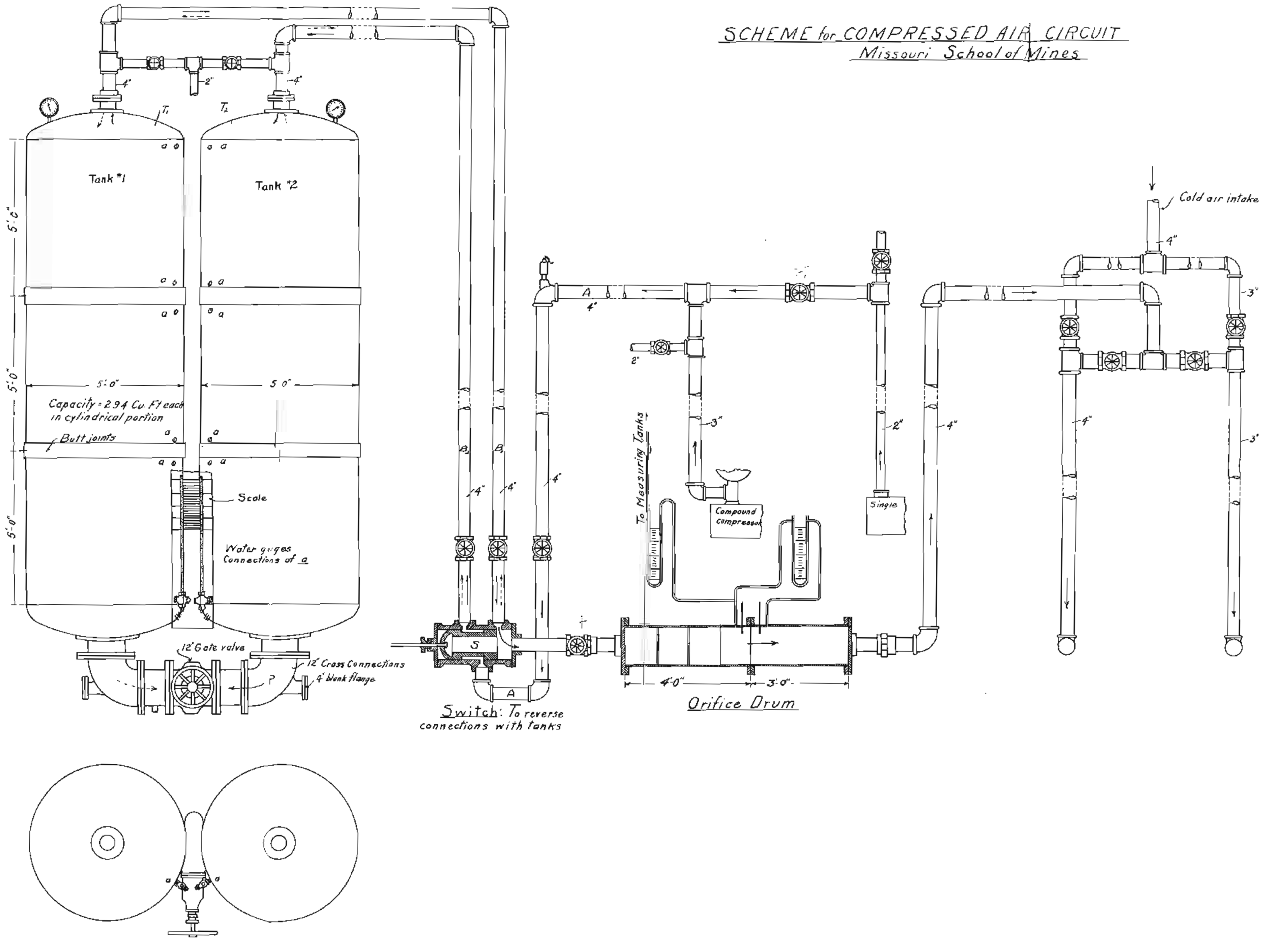
	61	87	97	119.5
Actual Velocity cu.ft./sec.	1.648	2.32	2.58	3.11
P_o = Tank Press. #/□"	116.07	116.07	116.07	117.07
T = Tank Temp. (deg. F)	91	90	90	92
Tank Press. Gage	102 #/□"	102 #/□"	102 #/□"	103 #/□"
Air density	0.5786	0.5710	0.5710	0.5740
P_1 (press. above Orifice)	115.19	113.52	113.25 #/□"	112.99 #/□"
P_a (press. below orifice)	114.11	111.51	110.60 #/□"	108.94 #/□"
T_1 = abs. temp.	550.5	549.5	549.5	551.5
$F\sqrt{\frac{P_a(P_1-P_a)}{T_1}}$	1.488	2.02	2.30	2.81
W (cu.ft. per sec.)	0.953	1.327	1.473	1.785
K (constant)	0.641	0.644	0.641	0.635

Date ....

Observers { ....

Form 110—M E—10-16—1000—F. P. & S. Co.


Variation of coefficient
with velocity
Coefficient K
.8
.7
.6
.5
.4
.3
.2
.1
0
.5
1.0
1.5
2
2.5
3
3.5
Velocity
ft./sec.


SCHEME for COMPRESSED AIR CIRCUIT
Missouri School of Mines
Tank #1
Tank #2
5'-0"
5'-0"
5'-0"
5'-0"
5'-0"
Capacity = 2.94 Cu. Ft each in cylindrical portion
Butt joints
Scale
Water gages Connections of a
12" Gate valve
12" Cross Connections
4" blank flange
Switch: To reverse connections with tanks
To Measuring Tanks
Compound compressor
Single
Orifice Drum
4'-0"
3'-0"
Cold air intake
4"
3"
2"