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TECHNICAL NOTE No: S.M.E. 377

ROYAL AIRCRAFT ESTABLISHMENT

Farnborough, Hants.

FLOW OF HIGH PRESSURE AIR IN SMALL PIPES

by

D. RENDEL, B.A.

and

J. RUDMAN, B.Sc.

[redacted]

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September, 1946

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R.A.E. Ref: ME.5/5354/DR/93

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SUMMARY

In order to assist in the design of pneumatic systems for aircraft some information on the flow of high pressure air in small pipes is urgently necessary. Fairly extensive search has revealed little useful information on this subject and accordingly a number of experiments have been made, from the results of which a formula is worked out which is shown to give reasonably accurate results for pipe sizes up to $\frac{3}{8}$" o.d., and pressures between 50 p.s.i. and 1250 p.s.i. The free air flows occurring under these conditions are in the region 0 - 100 cu.ft./min.

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1 Introduction

With the more general use of pneumatic systems in aircraft it has become increasingly necessary to have some fairly simple and reliable method of assessing the flow of high pressure air through small pipes. Fairly extensive search has not revealed any source of information on this subject which covers the conditions of pressure, velocity and pipe diameters obtaining in aircraft and therefore this note is intended to provide a method whereby an estimate of the performance of a pneumatic system from this aspect may be made.

A large number of experimental results were obtained with different pressures, flows, pipe sizes and lengths and a formula has been obtained which corresponds reasonably well with these results.

2 Experimental results

Three sizes of copper pipe were tested of outside diameter 3/16", $\frac{1}{4}$" and $\frac{3}{8}$". The wall thickness of all three was 20 s w g. These were considered to be representative of the sizes likely to be used in an aircraft pneumatic system. Tests were made on a number of lengths in each size as follows.

3/16"	10 ft.	20 ft.	40 ft.
¼"	25 ft.	50 ft.	85 ft.
⅜"	65 ft.	100 ft.	

The high pressure air was obtained from large capacity air cylinders and the pressures at each end of the pipe were measured by standard bourdon tube gauges. The pipes were in lengths of 10 ft. to 14 ft. and these were joined together by standard 1100 series A.G.S. couplings. The flow was measured at atmospheric pressure by Rotameter flowmeters up to 15 cu.ft./min. and above that by a British Standard orifice meter to B.S.1042. The inlet pressure was controlled by letting air from the large cylinders into a smaller capacity attached to the pipe length, and the back pressure by means of a finely adjustable restrictor.

Flows up to 70 cu.ft./min. at pressures up to 1250 p.s.i. were recorded.

A diagram of the apparatus is shown at Fig.1. It was found that, for any given pipe size, other conditions being equal the flow varied inversely as the square root of the length. Furthermore the ratio of the flows through two pipes of the same length but of different diameter under the same conditions of pressure and temperature was nearly proportional to the ratio of the cubes of the diameters and this index was therefore chosen as giving a simpler and more rational formula than a possibly more exact value. The inaccuracy resulting from this was corrected by choosing a different frictional constant for each pipe size.

Flows multiplied by the square root of the pipe length and divided by the cube of the pipe diameter are plotted against inlet pressure at Figs.2, 3 and 4 showing the justifiability of these choices of indices.

Some actual flow results are plotted at Figs.5, 6 and 7 together with the theoretical curves obtained from the formula given below. These show the degree of agreement obtained.

Throughout the tests the temperature was kept constant between 5°C and 10°C.

3 Symbols

c	-	velocity of sound	- ft./sec.
d	-	pipe diameter	- ft.
g	-	acceleration due to gravity	- ft./sec.^{2}
f,m,n	-	arbitrary indices	
k, k'	-	arbitrary constants	
L	-	pipe length	- ft.
P	-	pressure	- poundals/sq.ft. abs.
p_1	-	inlet pressure	- p.s.i. abs.
P_1	-	inlet pressure	- poundals/sq.ft. abs,
p_2	-	back pressure	- p.s.i. abs.
P_2	-	back pressure	- poundals/sq.ft. abs.

p_o	-	atmospheric pressure	-	p.s.i. abs.
P_o	-	atmospheric pressure	-	poundals/sq.ft.abs.
T	-	temperature of air	-	^oC. abs.
T_o	-	atmospheric temperature	-	^oC. abs.
v	-	velocity of air in pipe	-	ft./sec.
V	-	volume flow of free air	-	cu.ft./sec.
V_2	-	volume flow of air at p_2	-	cu.ft./sec.
γ	-	ratio of specific heats of air		
μ	-	viscosity of air	-	lb./ft.sec.
ρ	-	density of air	-	lb./cu.ft.
ρ_o	-	density of atmosphere	-	lb./cu.ft.

4 Theoretical analysis

Using the above symbols we have from dimensional theory,

$$\frac{dP}{dL} = k' \left(\frac{\rho v d}{\mu}\right)^m \left(\frac{v}{c}\right)^f \frac{\rho v^2}{d}$$

$$= k' \frac{d^{m-1}}{\mu^m} \rho^{m+1} \frac{v^{m+f+2}}{c^f}$$

Assuming an expansion law of the form

$$\frac{P}{\rho^n} = \text{constant}$$

we have the following relationships

$$v = \frac{4V}{\pi d^2}\left(\frac{P_o}{P}\right)^{1/n}$$

$$\rho = \rho_o \left(\frac{P}{P_o}\right)^{1/n}$$

$$c = \sqrt{\frac{\gamma P}{\rho}} = \sqrt{\frac{\gamma P_o^{1/n}}{\rho_o}} \; P^{\frac{1}{2}(1 - 1/n)}$$

$$\therefore \frac{dP}{dL} = k' \left(\frac{4}{\pi} V\right)^{m+f+2} \frac{\rho_o^{m+1+f/2}}{\gamma^{f/2} \mu^m d^{m+2f+5}} \; \frac{P_o^{\frac{1+f/2}{n}}}{P^{\frac{f(1+n)+2}{2n}}}$$

integrating

$$k'\left(\frac{4}{\pi}v\right)^{m+f+2} \cdot \frac{1}{\gamma^{f/2}\,\mu^{m}}\,\frac{\rho_o^{\,m+1+f/2}}{d^{m+2f+5}}\,P_o^{\frac{1+f/2}{n}} \cdot L = \int_{P_2}^{P_1} P^{\frac{f(1+n)+2}{2n}}\,dP$$

$$= \frac{2n}{(f+2)(1+n)}\left[P_1^{\frac{(f+2)(1+n)}{2n}} - P_2^{\frac{(f+2)(1+n)}{2n}}\right]$$

i.e. $$\frac{V}{P_1^{\frac{(f+2)(1+n)}{2(m+f+2)n}}}\;\frac{L^{\frac{1}{m+f+2}}}{d^{\frac{m+2f+5}{m+f+2}}}$$

$$= k \cdot \frac{\pi}{4}\left[\frac{2n}{(f+2)(1+n)}\right]^{\frac{1}{m+f+2}} \frac{\mu^{\frac{m}{m+f+2}}\,\gamma^{\frac{f}{2(m+f+2)}}}{\rho_o^{\frac{m+1+f/2}{m+f+2}}\,P_o^{\frac{1+f/2}{n(m+f+2)}}}\left[1-\left(\frac{P_2}{P_1}\right)^{\frac{(f+2)(1+n)}{2n}}\right]^{\frac{1}{m+f+2}}$$

Now from the experimental results it appears that

$$\frac{1}{m+f+2} = \frac{1}{2} \quad \text{and} \quad \frac{m+2f+5}{m+f+2} = 3$$

i.e.

$$M = -1, \quad f = +1$$

so that the original dimension equation may be written

$$\frac{dP}{dL} = \frac{k'}{d^2} \cdot \mu \cdot \frac{v^2}{o}$$

and the final result becomes

$$\frac{V\,L^{\frac{1}{2}}}{P_1^{3/4(1+1/n)}\,d^3} = k\,\frac{\pi}{4}\,\gamma^{\frac{1}{4}}\sqrt{\frac{2}{3}}\sqrt{\frac{n}{1+n}}\,\frac{\sqrt{1-\left(\frac{P_2}{P_1}\right)^{3/2(1+1/n)}}}{\mu^{\frac{1}{2}}\,\rho_o^{\frac{1}{4}}\,P_o^{\frac{3}{4}n}}$$

and converting pressure to p.s.i. and including the effect of temperature we get

$$\frac{V\,L^{\frac{1}{2}}}{P_1^{\frac{3}{4}(1+1/n)}\,d^3}\left(\frac{T_o}{T}\right)^{\frac{1}{4}} = \frac{2.13\times 10^5\,k}{P_o^{\frac{3}{4}n}}\sqrt{\frac{n}{1+n}}\sqrt{1-\left(\frac{P_2}{P_1}\right)^{3/2(1+1/n)}}$$

where

$\gamma = 1.4$

$\mu = 12.25 \times 10^{-6}$ lb./ft.sec.

$\rho_o = 7.6 \times 10^{-2}$ lb./cu.ft.

The flow at $p_2 = V_2 = V\left(\frac{p_o}{p_2}\right)^{\frac{1}{2}}$ so that

$$V_2 = \frac{2.13\,k \times 10^5 \left(\frac{T}{T_o}\right)^{\frac{1}{4}} p_o^{\frac{1}{4}n}\; p_1^{\frac{1}{4}(3-{}^1/_n)}\; \frac{d^3}{L^{\frac{1}{2}}}\left(\frac{p_1}{p_2}\right)^{1/n} \sqrt{\frac{n}{1+n}}}{\sqrt{1-\left(\frac{p_2}{p_1}\right)^{3/2(1+{}^1/_n)}}}$$

Theoretical curves of V against p_2 are plotted at figures 5, 6 and 7 since those are the only ones which can usefully be compared with the experimental results as only free air flows can be easily measured.

At Fig.8 the variation of k with pipe diameter and n with p_1 are shown, as obtained from the experimental results. It is probable that n in fact varies along the pipe as the pressure falls, but since this would greatly complicate the formula and the results are in reasonable agreement as shown, n has been assumed constant for a given inlet pressure.

The flows at which sonic velocity is theoretically reached at the low pressure end of the pipe are shown in Figs. 5, 6 and 7.

Attached: Figs. 1 to 8 - Drg. Nos. SME.16150/R to SME.16157/R inclusive.

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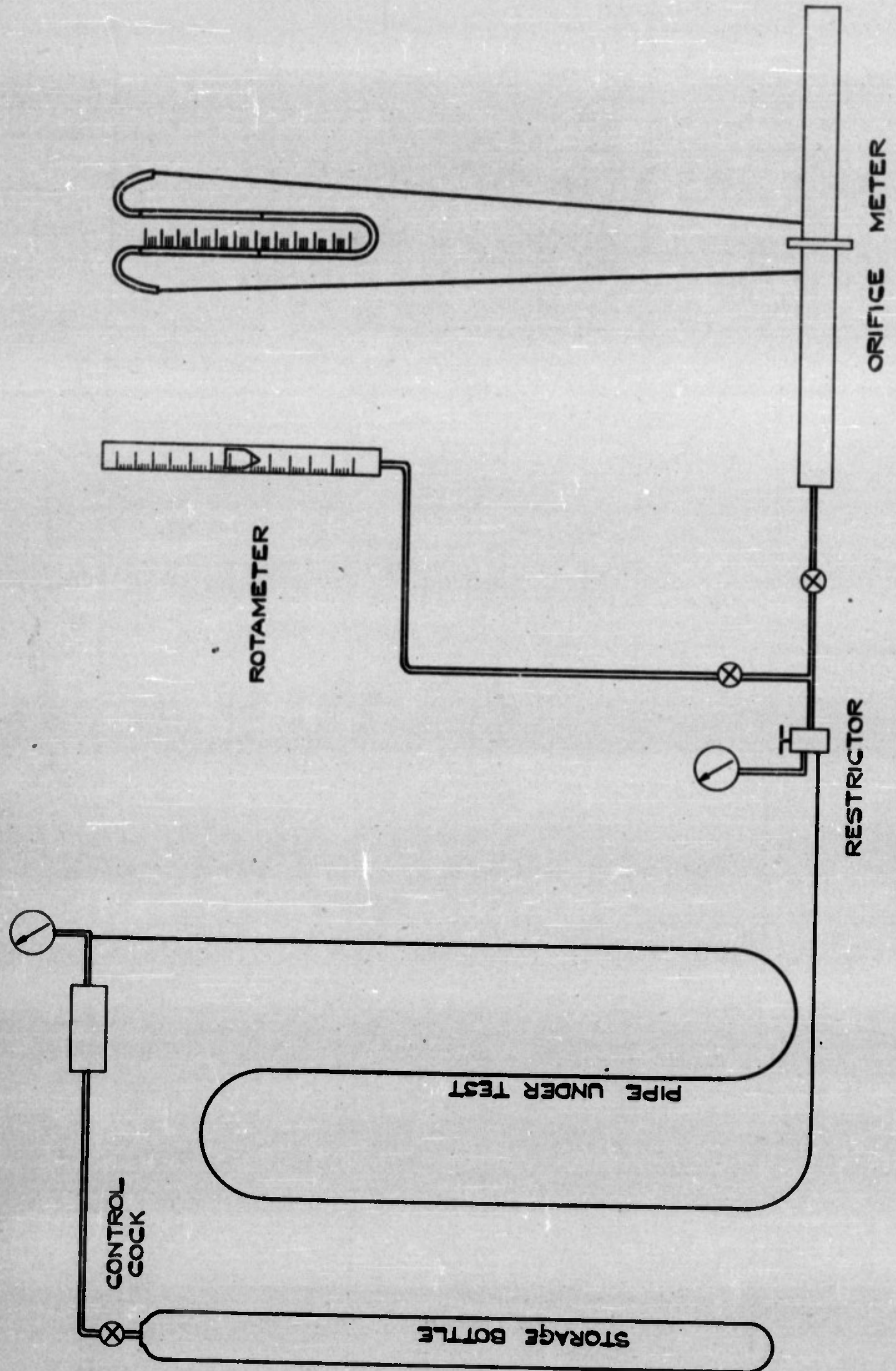
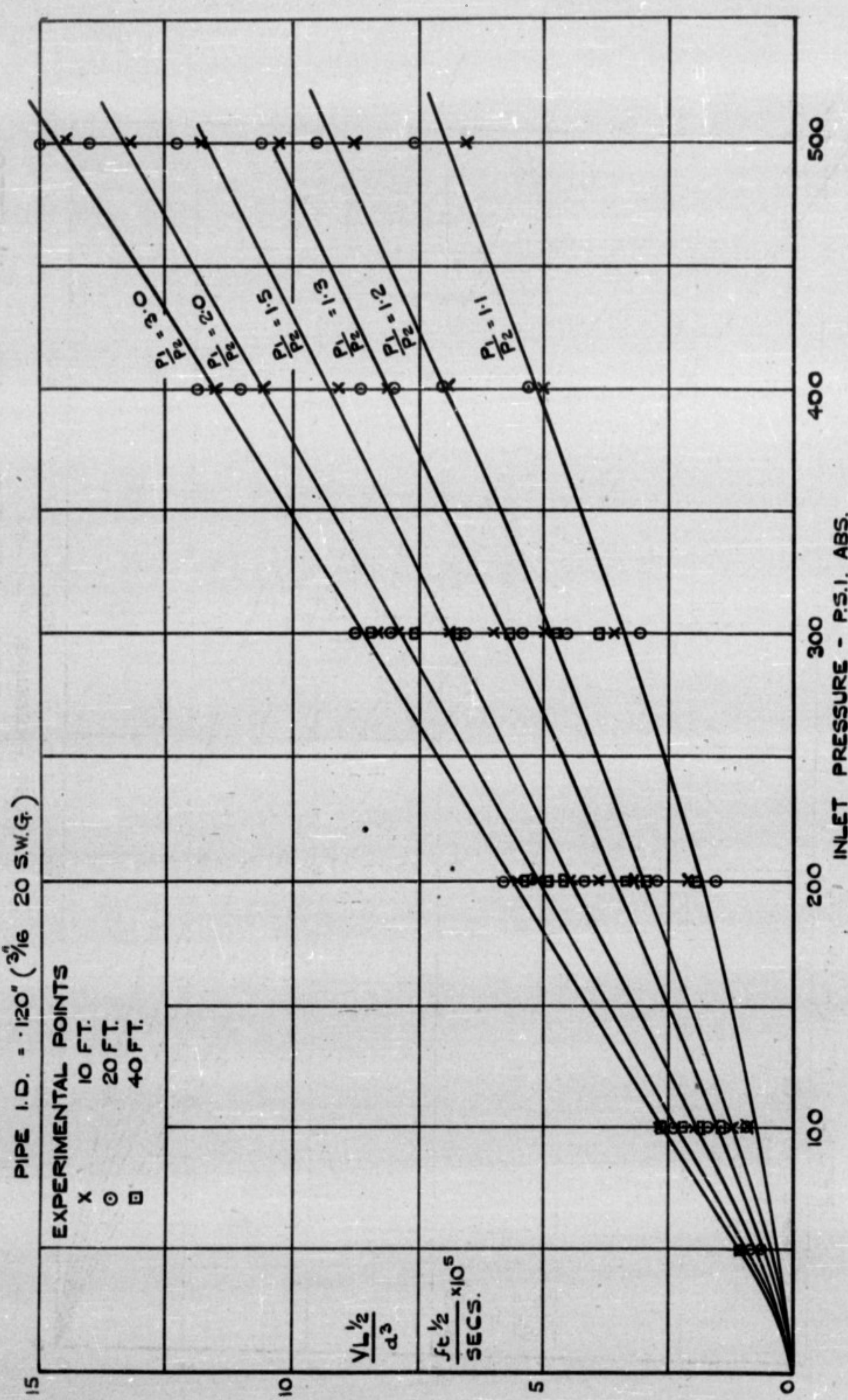


TEST CIRCUIT.

FIG. 2.



EFFECT OF VARIATION OF PIPE LENGTH AND DIAMETER.

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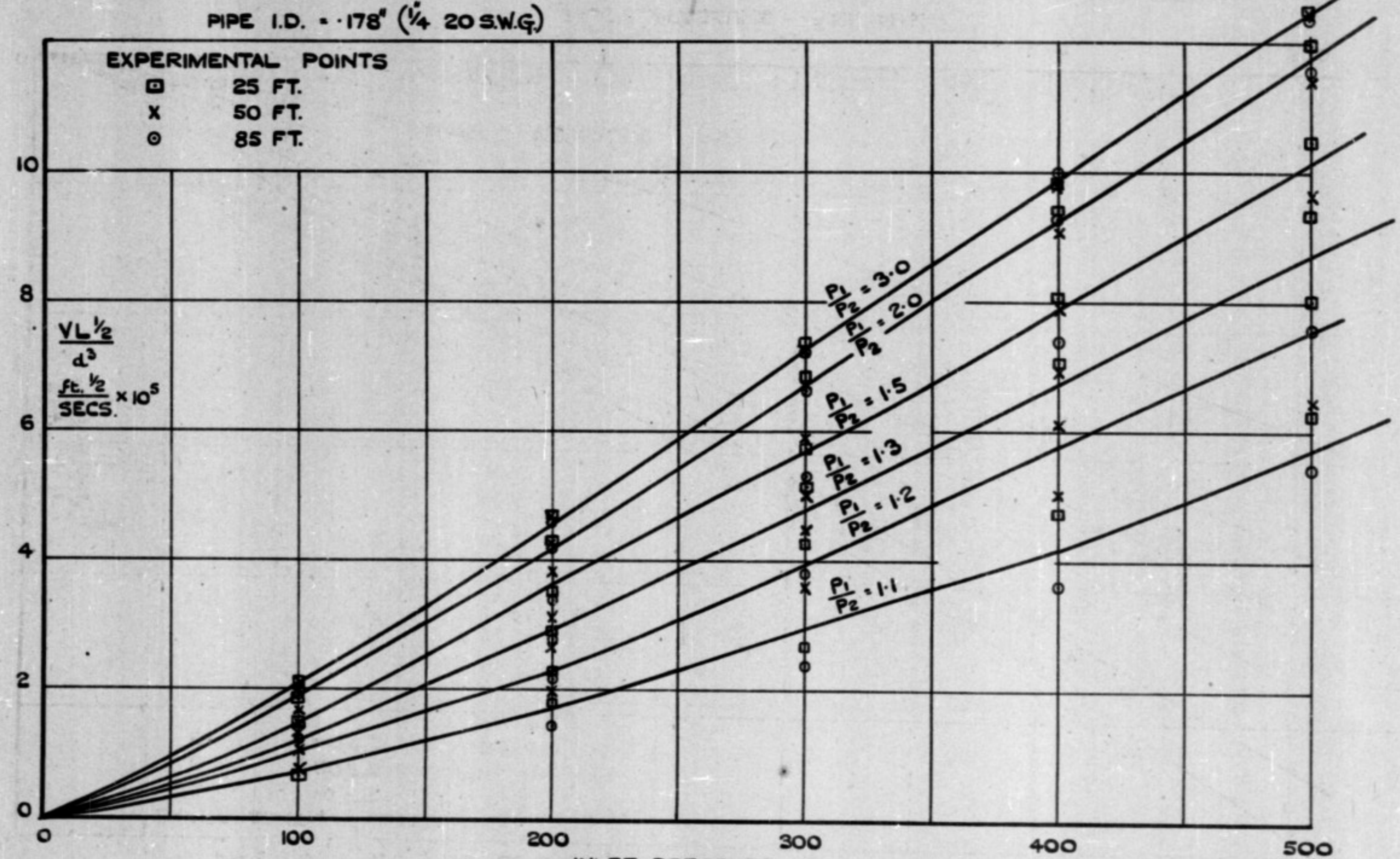
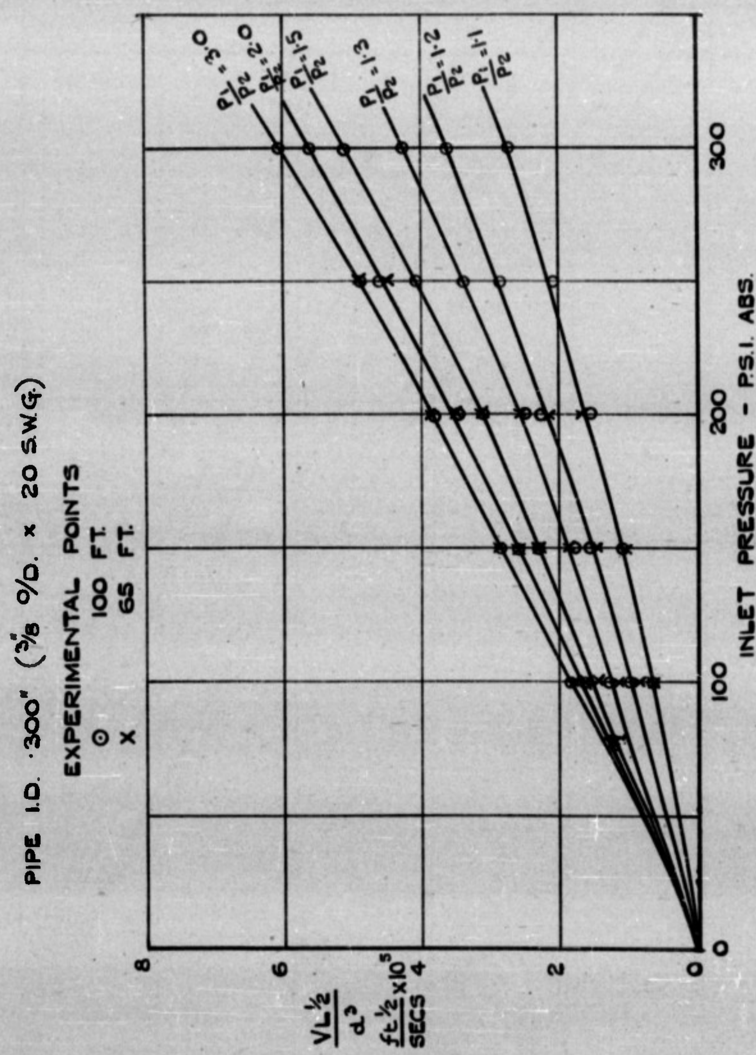
FIG. 3.



EFFECT OF VARIATION OF PIPE LENGTH AND DIAMETER.

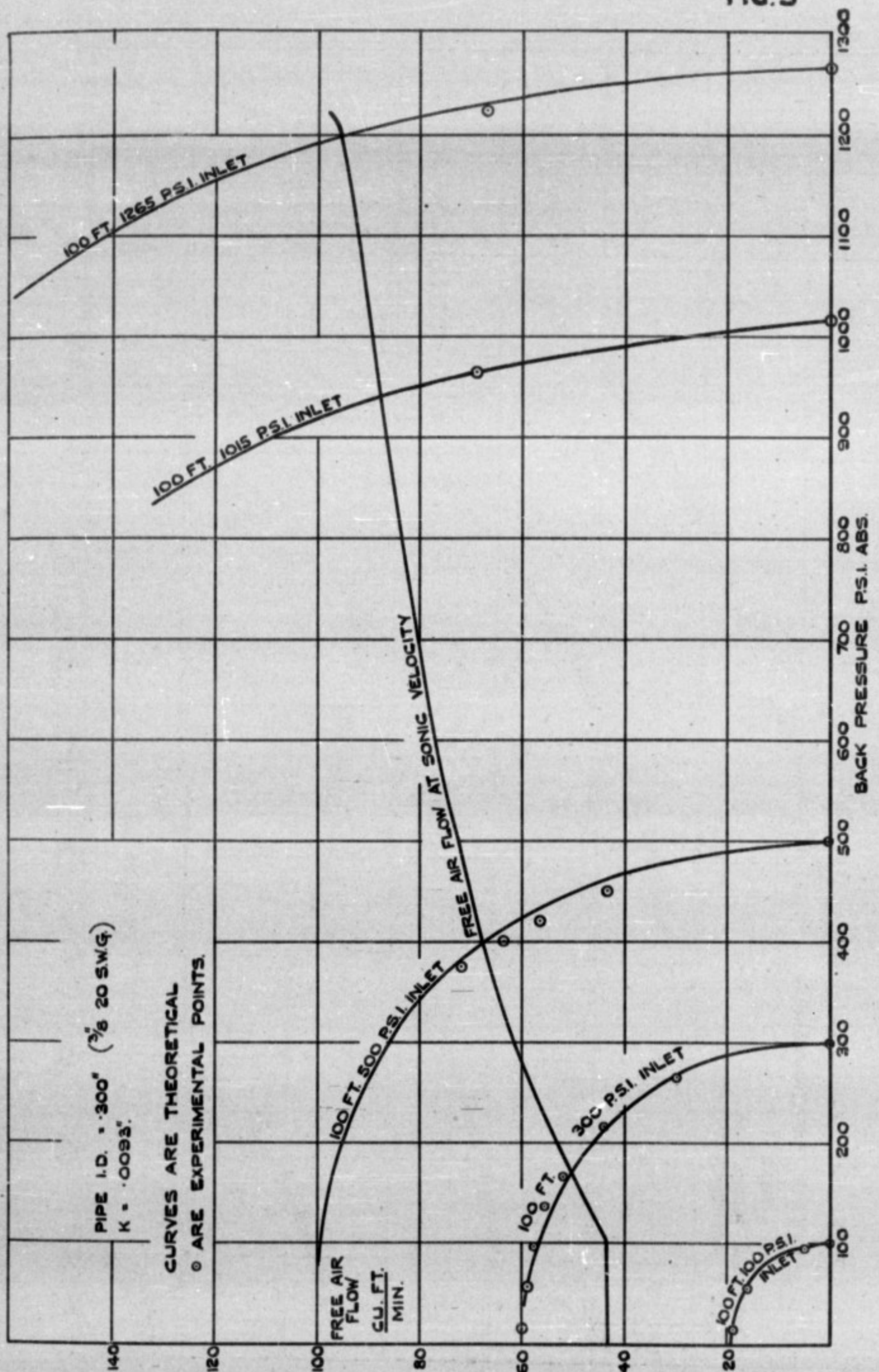
8

FIG. 4.



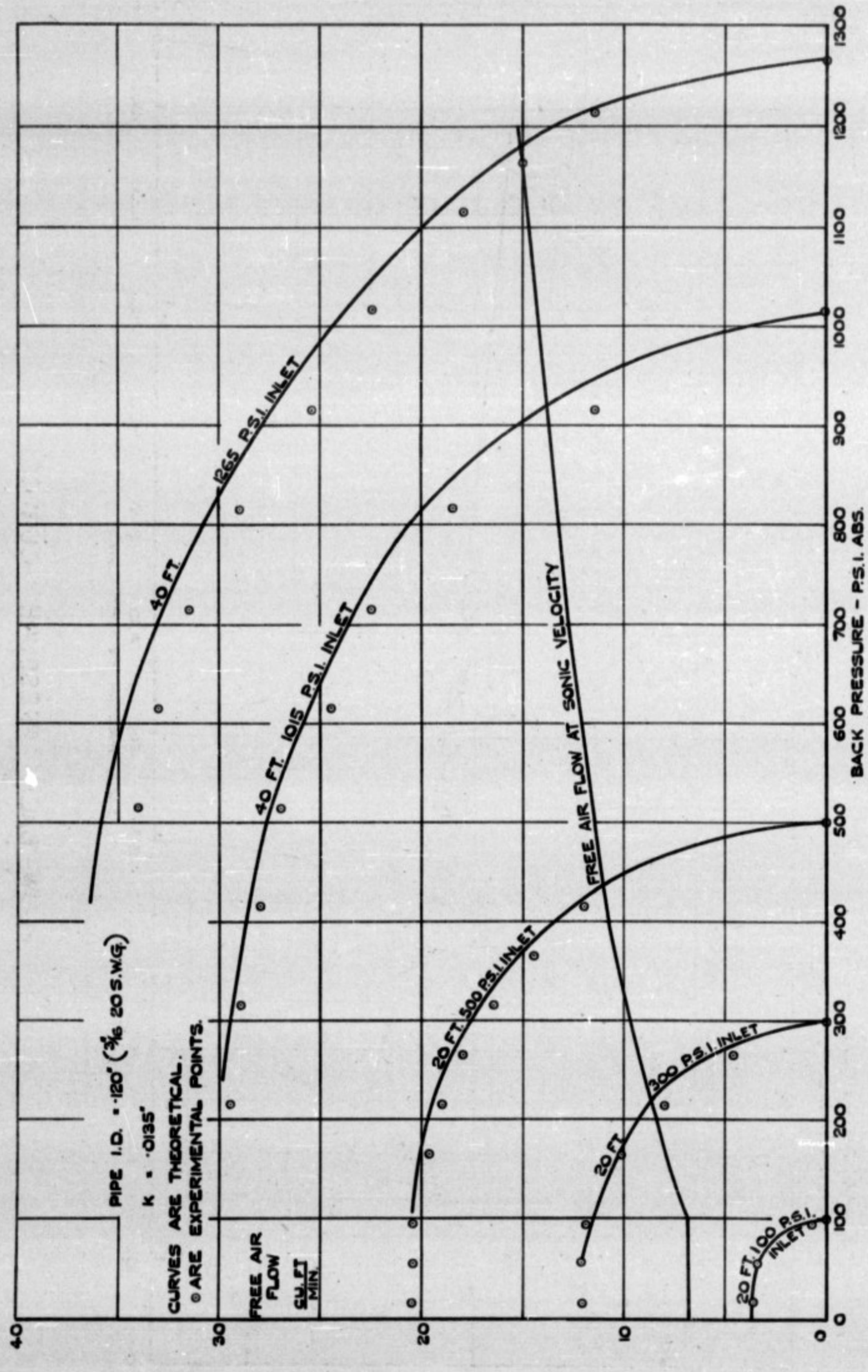
EFFECT OF VARIATION OF PIPE LENGTH AND DIAMETER.

FIG. 5



FLOW - BACK PRESSURE CURVES.

FIG. 6

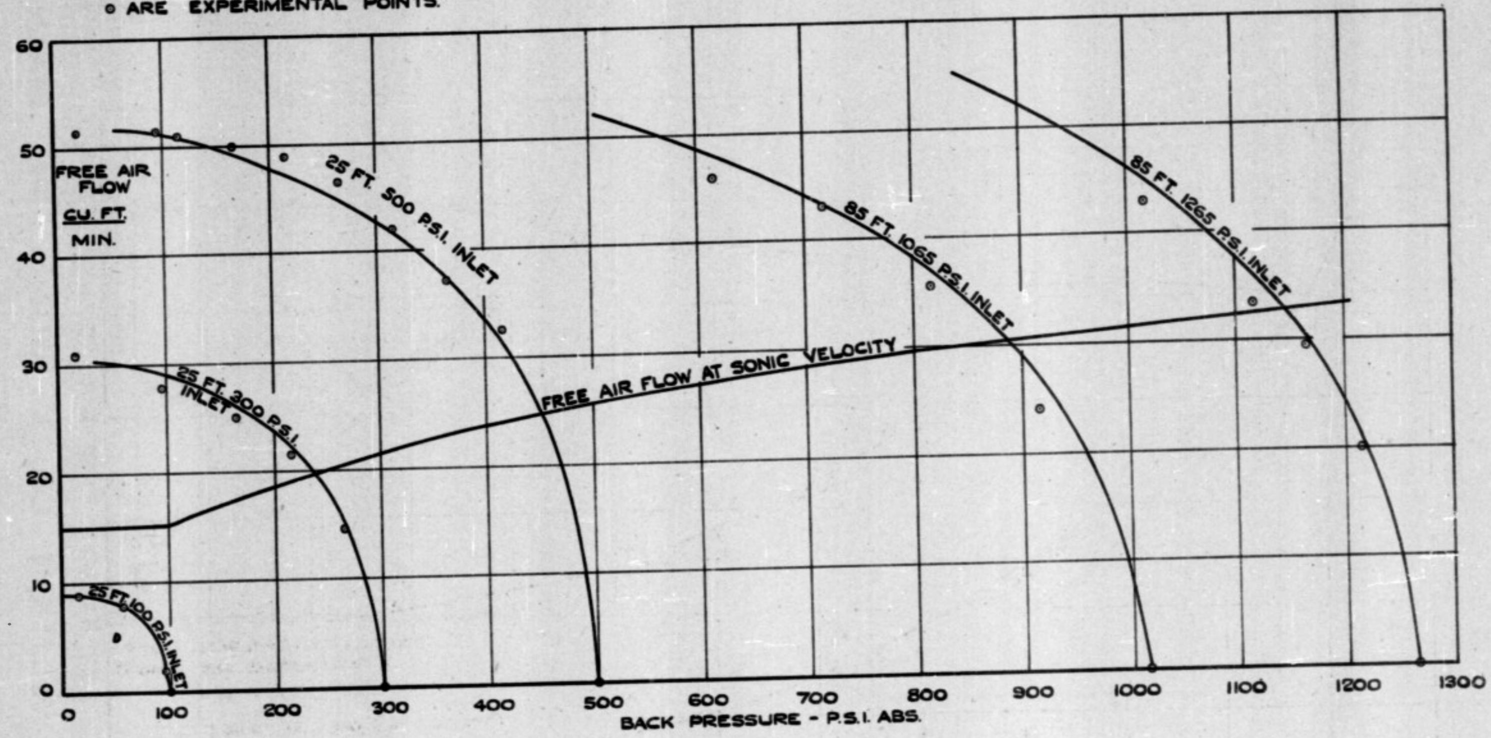


FLOW - BACK PRESSURE CURVES.

FIG. 7

PIPE I.D. = ·178" 1/4" 20 S.W.G.
K = ·0110".

CURVES ARE THEORETICAL.
o ARE EXPERIMENTAL POINTS.



FLOW- BACK PRESSURE CURVES.

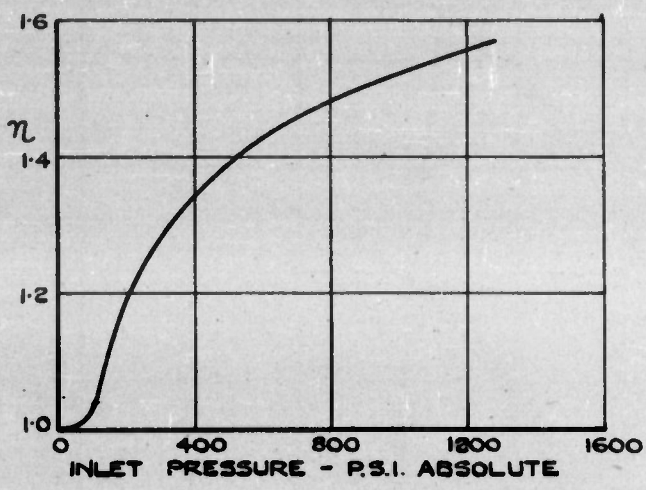


FIG. 8. VARIATION OF n WITH INLET PRESSURE.

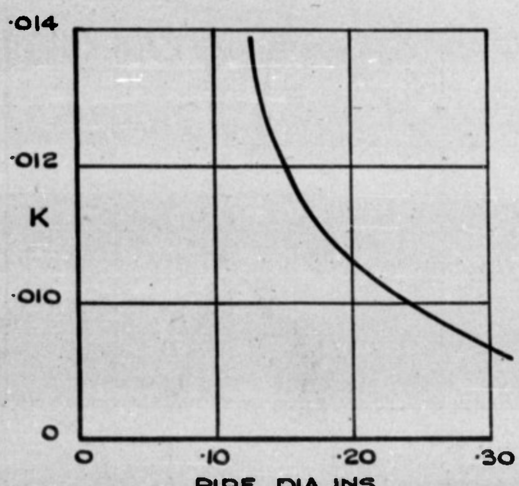


FIG. 9. VARIATION OF K WITH PIPE DIAMETER.

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