CCC ENGINEERING REPORT 541

HOT GAS FLOW SYSTEM
NASA CONTRACT NAS 8-11951

FLOW TEST ON MOCKED-UP CIRCUIT

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TABLE OF CONTENTS

OBJECT

An expedient mock up of the Hot Gas Flow System air circuit design per CCC Drawing TE 1900 was built and tested to determine the characteristics and configuration necessary to meet the design objective of 50 feet per second air flow velocity in the central test section.

The action of the novel impeller and the pressure loss in the 180° annular turning section were of particular interest.

SUMMARY

Air velocities in the test section and differential pressures in various areas were measured with the impeller rotating at the maximum design speed of 3000 RPM. Velocity measurements were also obtained at several impeller speeds.

The air velocity profile across the 4.5 inch diameter test section obtained with two pitot tubes spaced 90° apart shows that, while the velocity at the center was greater than 50 FPS, the profile is not as flat as desired. The reduced velocities on either side of the center are due to the vena contracta effect produced by the sharp edged entrance from the 180° turning section.

The mock-up is to be modified to incorporate curved turning vanes of different radii in the turning section. Also an inducer at the impeller entrance, a diffuser at the impeller exit and an entrance section into the test section will be tried. It is anticipated that one or a combination of these modifications will produce a more satisfactory velocity profile and improve the efficiency of the air flow circuit.

RESULTS

The maximum air velocities measured were 66.0 and 58.5 feet per second with the large and small pitot tubes respectively in the center of the flow test area. These velocities were obtained under stable temperature conditions of 116°F with an impeller speed of 3012 RPM. The average velocity within the measured zone (3.18 in. dia.) of the test section was 45 and 42 feet per second. Rotation of the small pitot tube indicated there was a small rotary component of the flow. The shape of the velocity profiles shows that a stabilized turbulent velocity profile expected for an average Reynolds number of 78,600 has not had time to develop. This effect is due to the vena contracta formed by the sharp edge entrance from the 180° turning section and the short length of the central flow test cylinder.

Figure No.9 shows the expected horsepower versus temperature relationship based on the present test data. Improvements in the impeller entrance and exit section as well as the 180 degree end turn will reduce the losses and thereby reduce the horsepower requirements.

DESCRIPTION OF TEST

The flow test mock-up was constructed of sheet metal inner and outer cylinders and a cast aluminum impeller. The cross tubes, 180° turning section and heaters were made of wood. The impeller was belt driven by a 1/4 horsepower mechanical variable speed drive. The impeller speed was measured by a two pole tachometer mounted on the driven shaft and connected to a 10 second gate electronic counter.

Two pitot tubes were mounted in the inner test section cylinder 90° apart to measure the air velocity. Refer to figures 4, 5 and 6. The pitot tubes were capable of rotary and axial movement. Ten static pressure measurement taps were provided. Two of these points were centrally located 180° apart in the test flow section and together with the static connection to the pitot tubes permitted static pressure measurements at four positions 90° apart. Four static connections were provided approximately 2 inches below the impeller and 2 inches above the 180° turning section. These eight taps were placed in line with the cross cylinders and 90° to the cylinders. Gage and differential pressure measurements were made with inclined manometers calibrated in inches of water. The air temperature was measured by inserting a dial type bi-metallic thermometer through one of the static taps into the annular flow area at the turning section end.

The impeller was first operated at the maximum speed to stabilize the air temperature at 116°F. It was not possible to attain 3000 RPM until the air had warmed up from room temperature (approximately 72°F) because of the power limitation. When stable operating conditions were obtained air velocity measurements were made at the center and five equal area points in the insertion direction and two or three points in the withdrawal direction with each pitot tube. The traverse in the withdrawal (-) direction was limited because of the bend radius of the pitot tubes. Velocity measurements were also made when the small pitot tube was rotated through angles up to 20° to sense swirl or rotation of the velocity vector.

Differential pressures were measured between the static and total pressures of both pitot tubes as well as between the various static pressure taps.

THEORY

Formulas:

$$d_a = \frac{P}{RT}$$

$$V_a = \sqrt{\frac{2gdw}{12\ d_a}} \times \sqrt{hva}$$

$$Q = A\ V_a$$

$$W_a = A\ V_a\ d_a$$

$$H = \frac{P_2 - P_1}{d_a} + \frac{V_2^2 - V_1^2}{2g}$$

$$T = \frac{Q\ d_a}{g} (V_{t_1}\ 1 - V_{t_2}\ 2)$$

$$V_t = \pi ND$$

$$\text{Air HP} = \frac{W_a\ H}{550} = \frac{QHtd_w}{6600}$$

$$Q \sim D^3N$$

$$P \sim D^2N^2$$

$$HP \sim D^5N^3$$

$$HP \sim P$$

$$HP \sim d_a$$

$$e = \frac{100\ (\text{Air Horsepower})}{\text{Brake Horsepower}}$$

Symbols:

d_a	= Air density - lb. per cu. ft.
d_w	= Water density = 62.4 lb. per cu. ft.
P	= Pressure - lb. per sq. ft.
R	= Gas Constant = 53.3 ft. - lb. per lb. °R
T	= Absolute Temperature - °R = 460 + °F
V_a	= Average Air Velocity - ft. per sec.
g	= Acceleration of Gravity = 32.17 ft. per sec.^{2}
h_{va}	= Average Pressure induct-in. of water
Q	= Flow Volume - cu. ft. per sec.
A	= Area - Sq. Ft.
W_a	= Weight Flow of Air - lb. per sec.
H	= Total Head - ft. of air.
P_1	= Pressure at inlet - lb. per sq. ft.
P_2	= Pressure at outlet - lb. per sq. ft.
V_1	= Velocity at inlet - ft. per sec.
V_2	= Velocity at outlet - ft. per sec.
T	= Torque - ft. - lb.
V_t	= Tangential component of absolute velocity - ft. per sec.
r	= radius arm - ft.
N	= Impeller speed - RPM

D = Impeller diameter - ft.

V_o = Radial Velocity - ft. per sec.

w = Angular Velocity - radions per sec.

HP = Horsepower - 550 ft - lb. per sec.

ö = Mechanical Efficiency - %

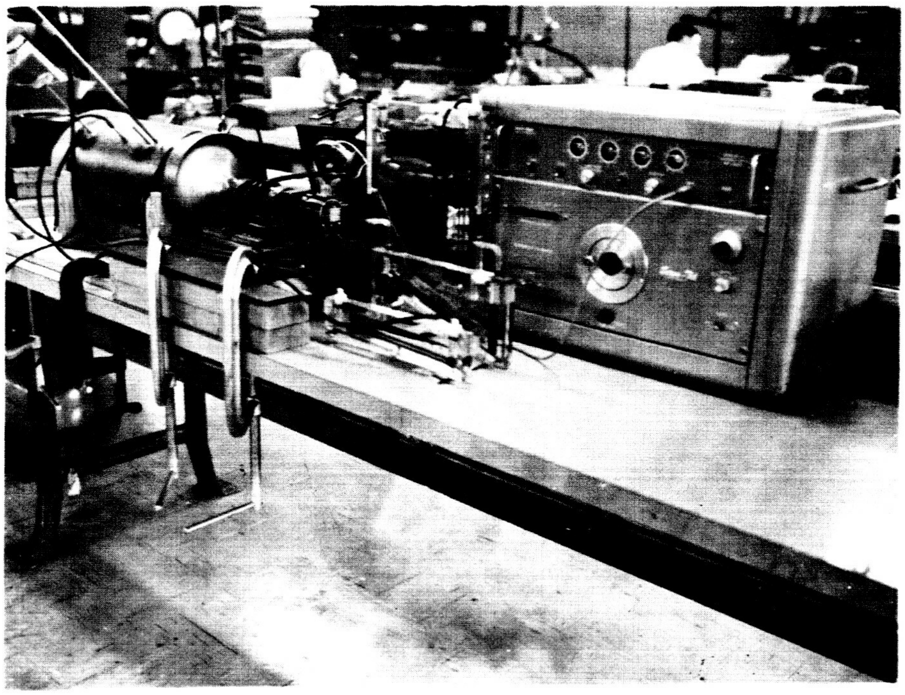


FIGURE 1
Flow Test Mock-Up.
Pressure and Velocity Gages in Center.
RPM Counter on Right.

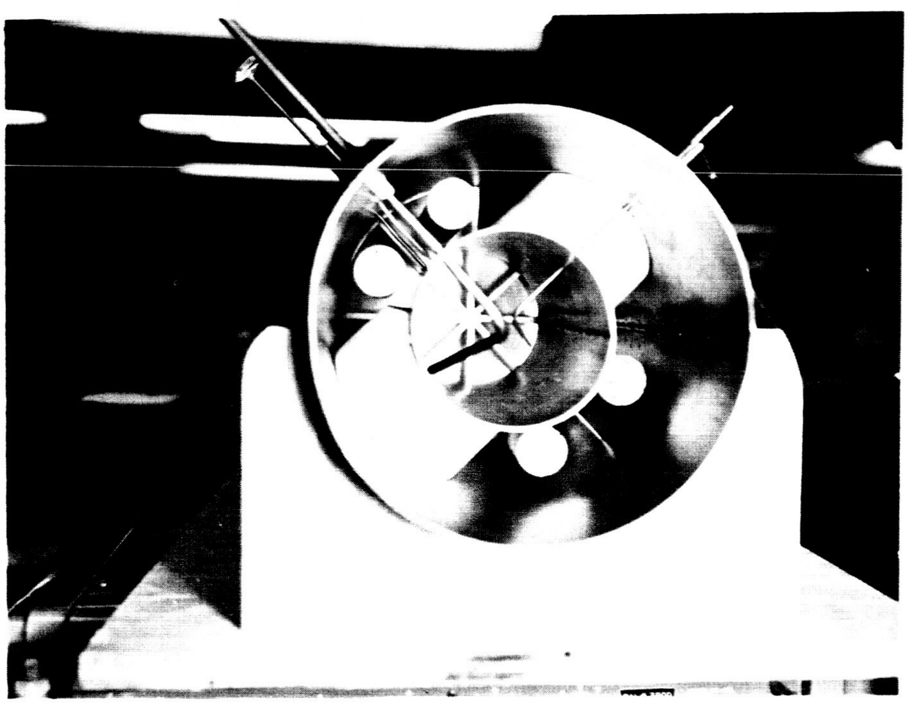


FIGURE 2
Flow Test Mock-Up with Impeller Removed.
Both Pitot Tubes in Place.

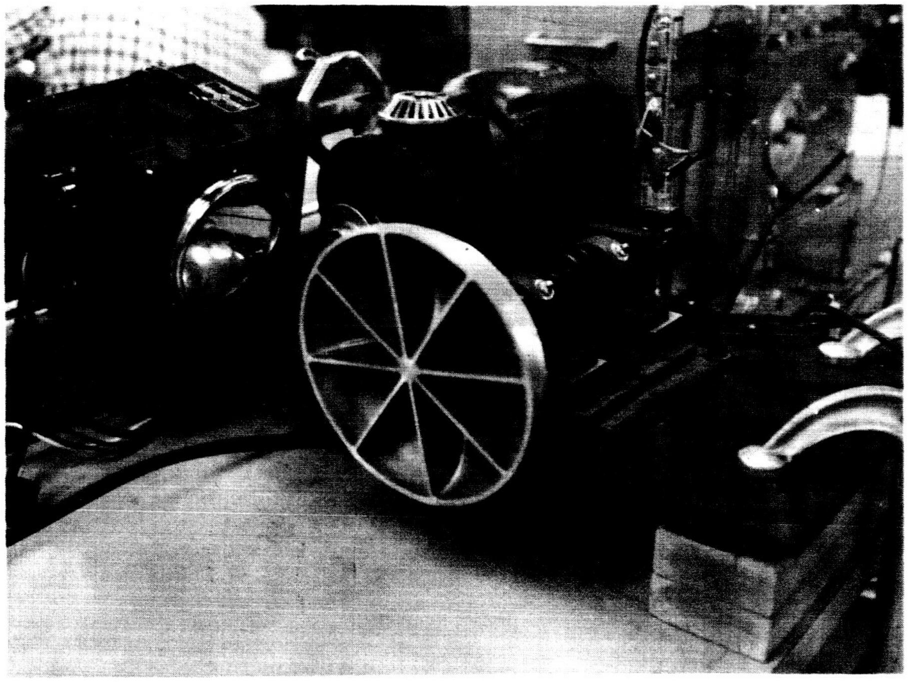
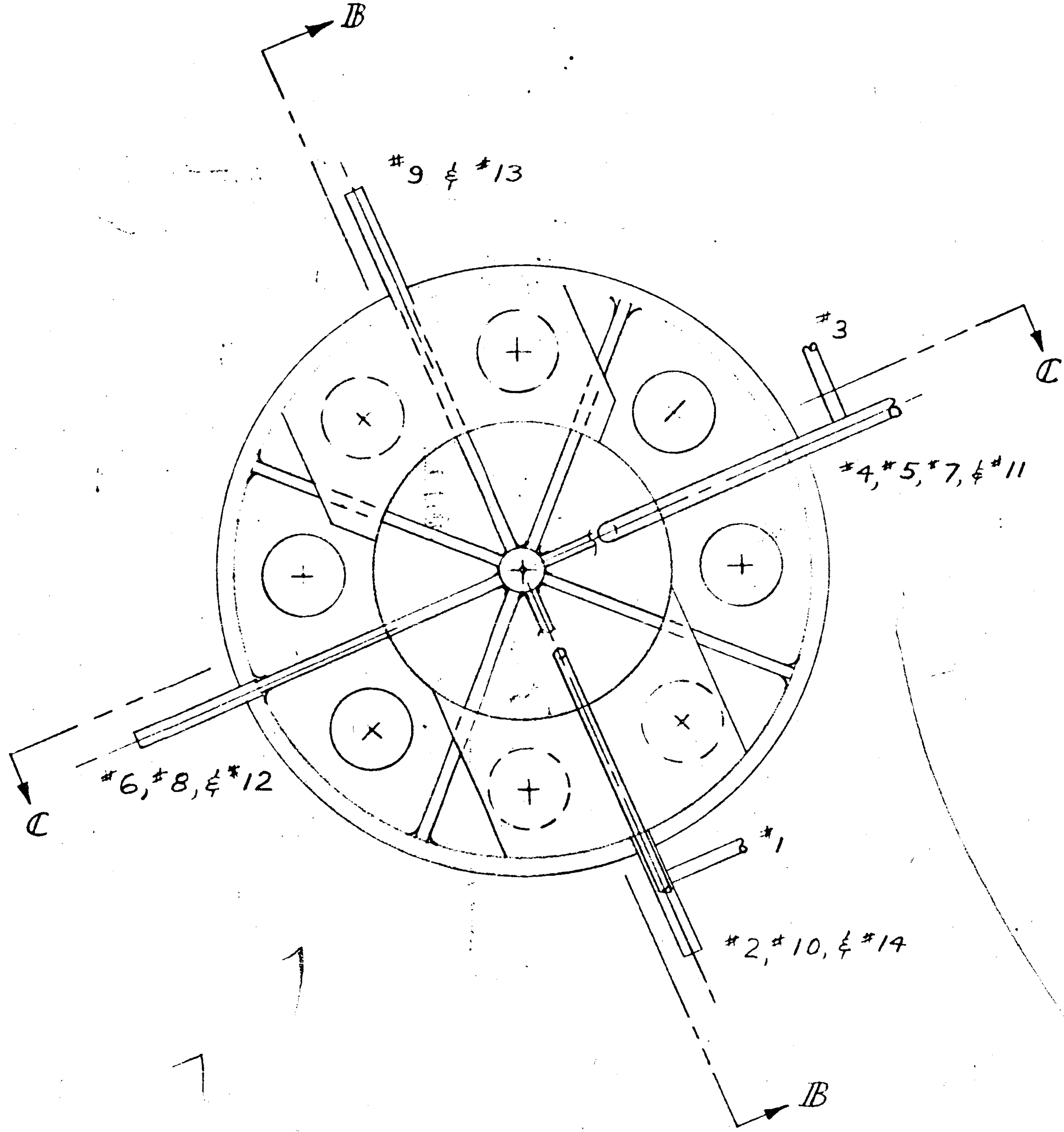
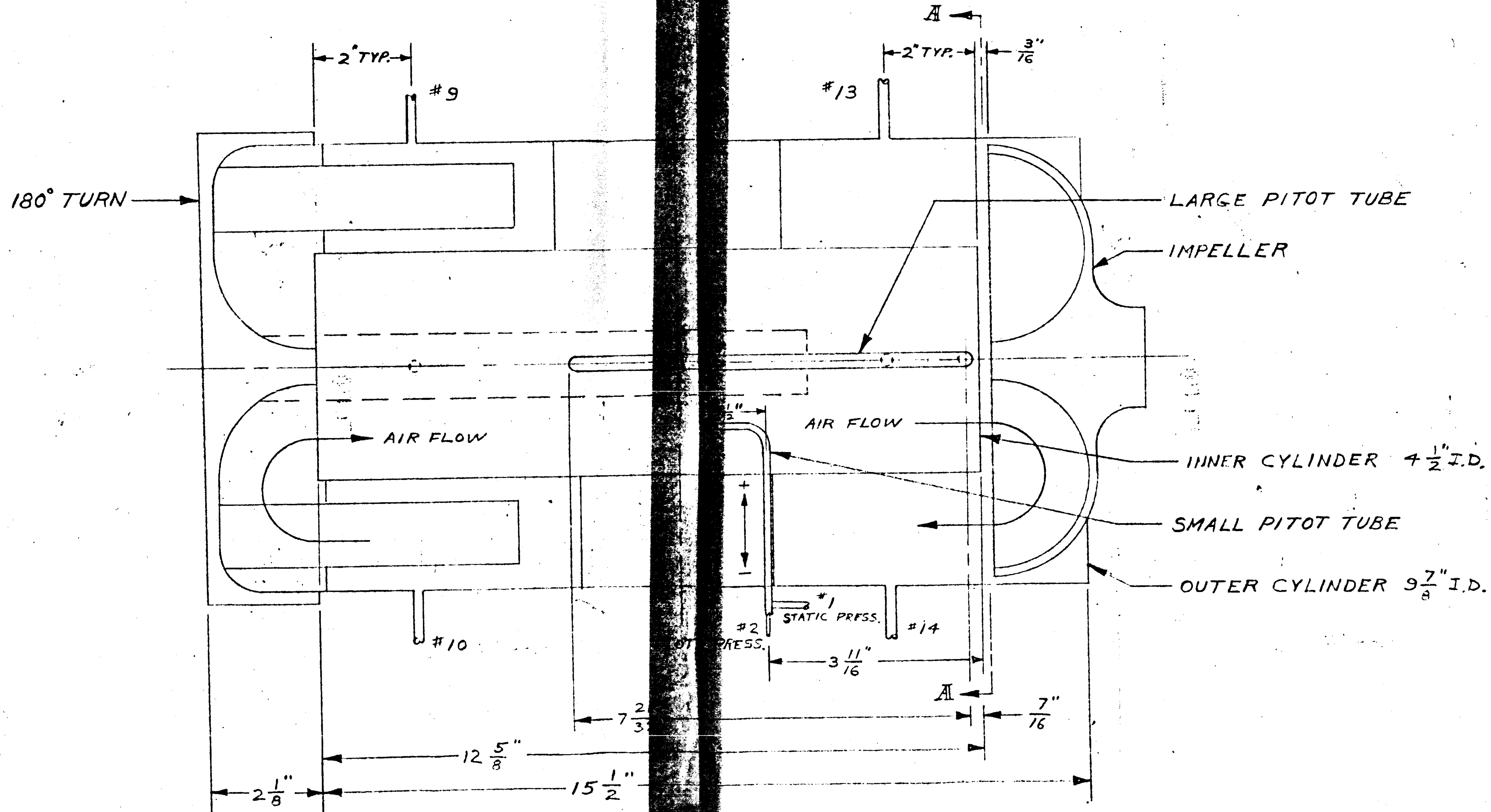


FIGURE 3
Cast Aluminum Impeller Stroboscope,
Variable Speed Drive and Tachometer.



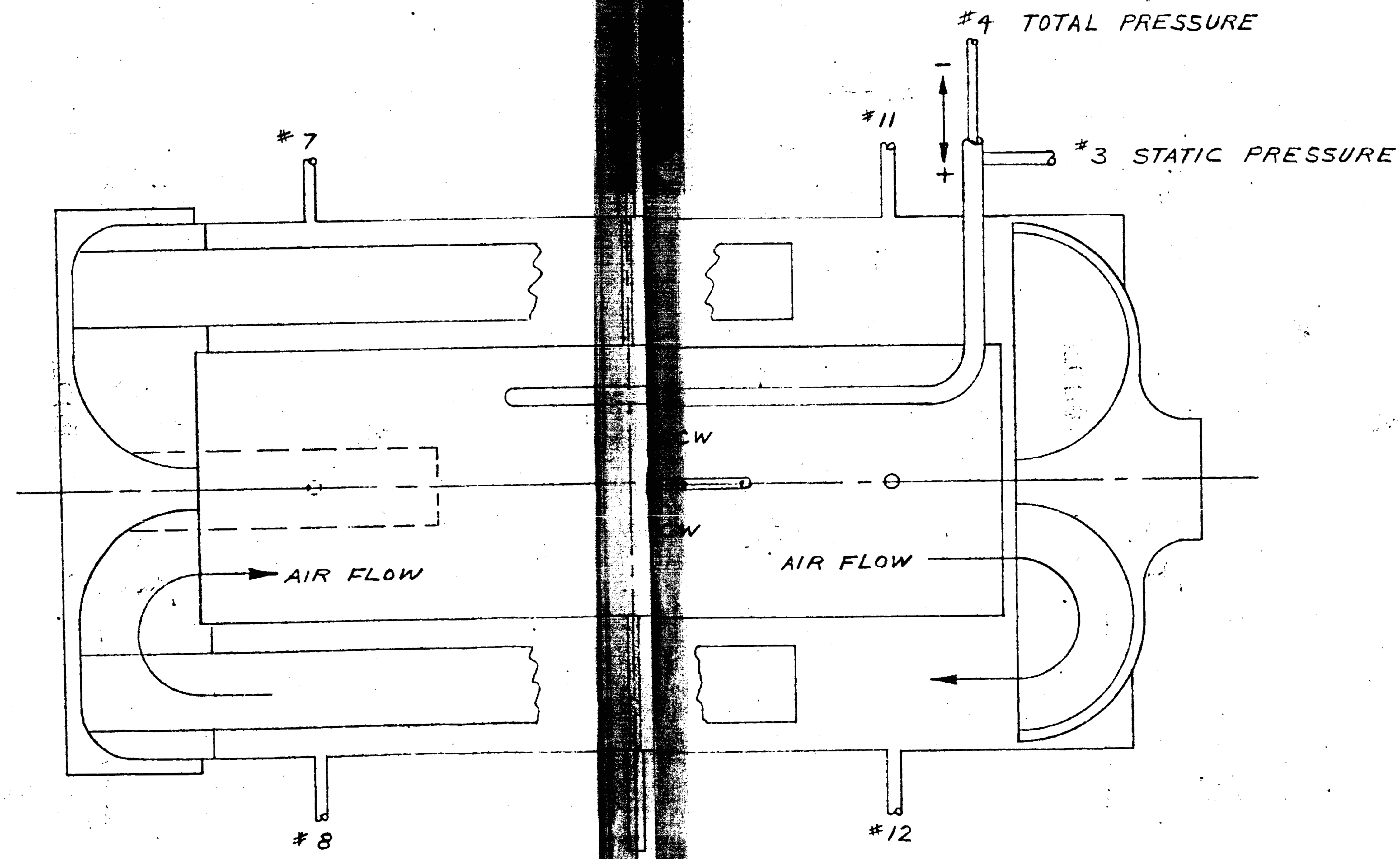
SECTION A - A

FIG. 4



SECTION B-B

FIG. 5



SECTION C-C

FIG. 6

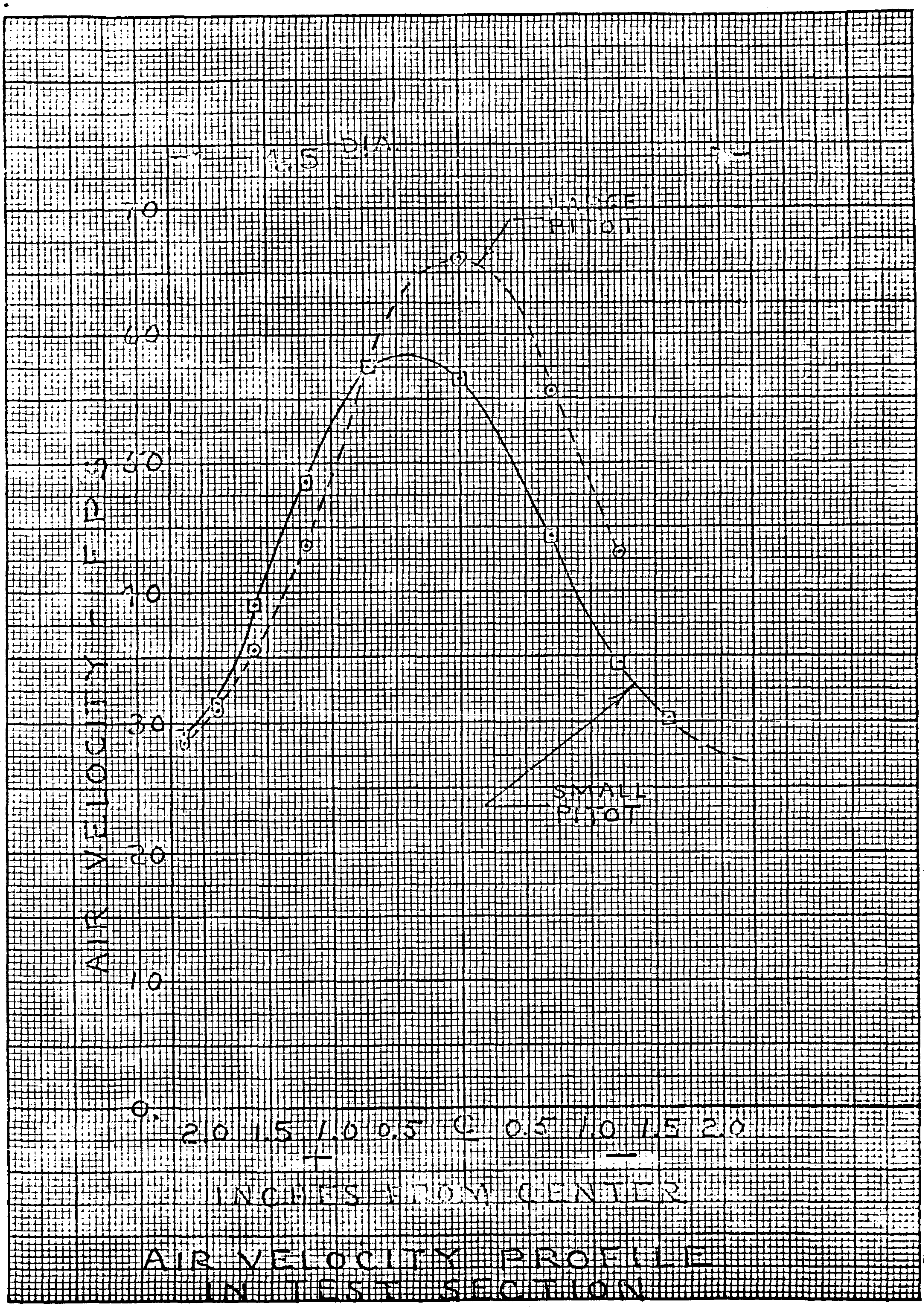

1.5 DIA.
LARGE PITOT
SMALL PITOT
AIR VELOCITY - FPS
2.0 1.5 1.0 0.5 ℄ 0.5 1.0 1.5 2.0
INCHES FROM CENTER
AIR VELOCITY PROFILE
IN TEST SECTION

Fig. 7

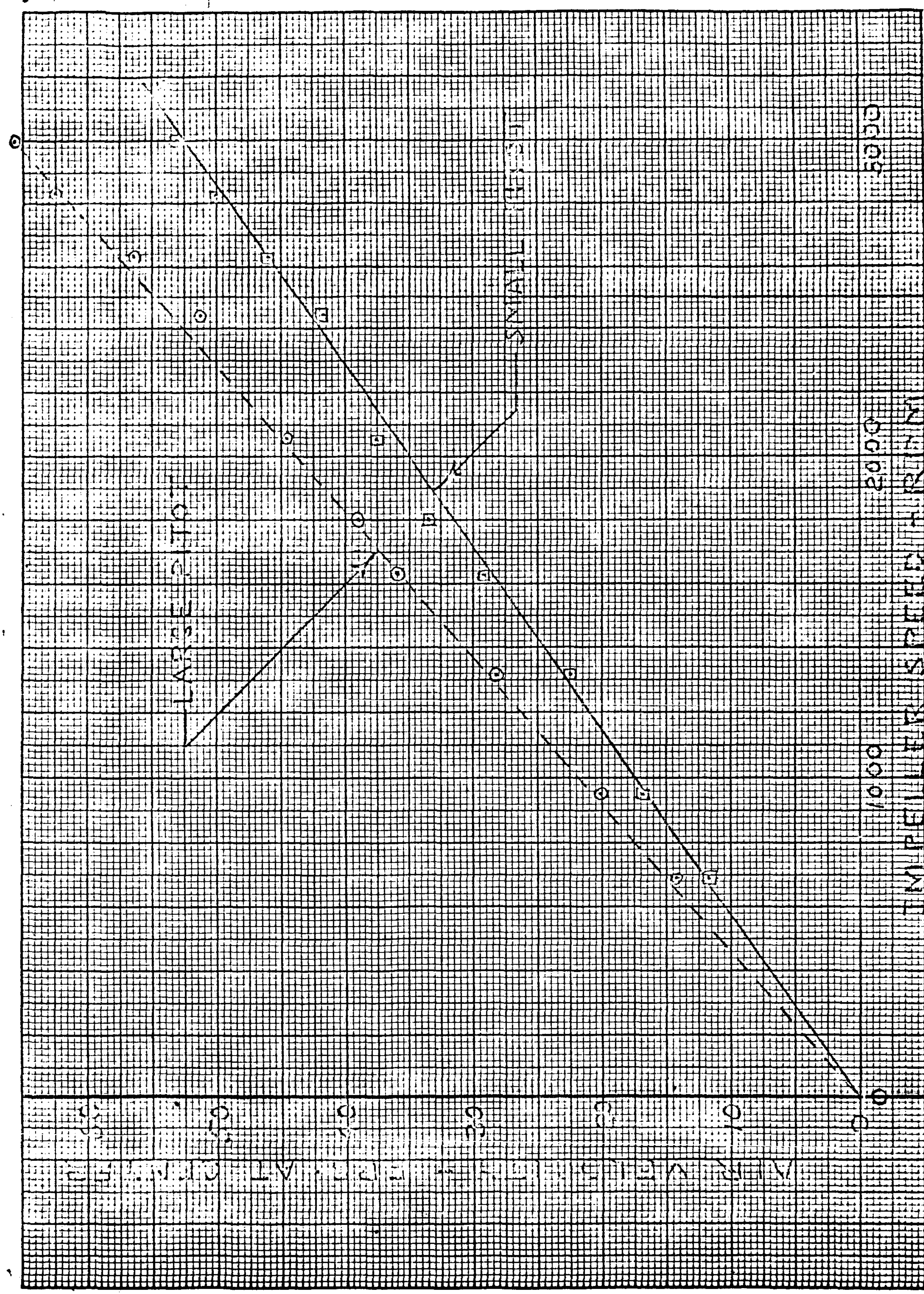


Fig 8

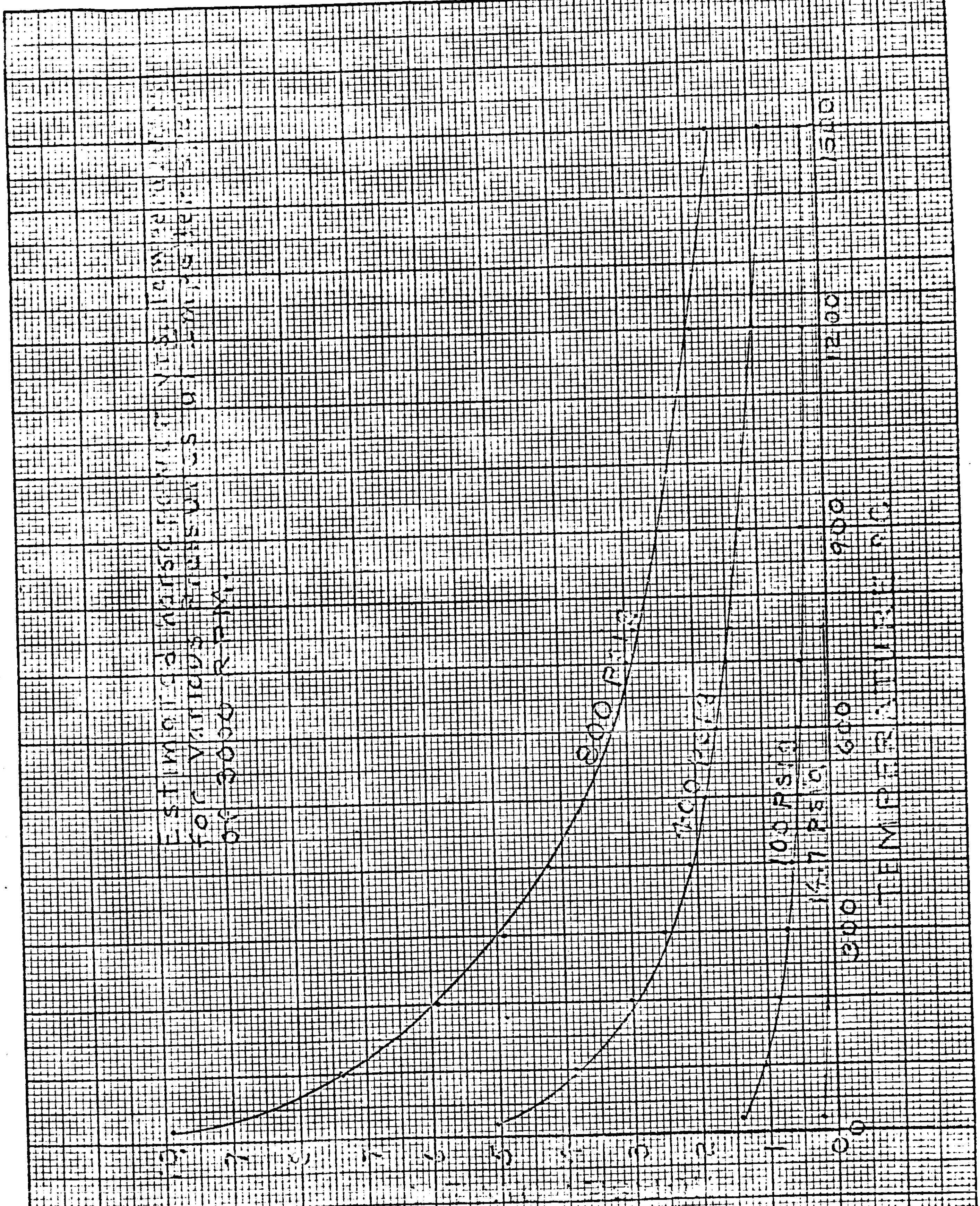


Fig. 9

CALCULATIONS

$P = 29.40$ in. Hg. $= 14.44$ psia

$T = 116°F = 576°R$

$$d_a = \frac{P}{RT} = \frac{14.4(144)}{53.3(576)} = 0.067 \text{ lb/ft.}^3$$

$$h_{v_a} = \frac{0.66 + 0.47 + 0.3 + 0.205 + 0.17 + 0.39 + 0.24 + 0.182}{8}$$

$h_{v_a} = 0.336$ in. H_2O (From Data-Small Pitot)

$$V_a = \sqrt{\frac{2gd_w}{12d_a}}\left(\sqrt{h_{v_a}}\right) = \frac{2(32.17)(62.3)}{12(0.067)}\left(0.336\right)$$

$V_a = 70.7 (0.58) = 41.0$ f ps (Test Section)

$$Q = AV_a = \frac{15.904(41)}{144} = 4.53 \text{ ft.}^3\text{/sec.}$$

$W_a = AV_ad_a = 4.53 (0.067) = 0.304$ lb./sec.

Head Loss from 2 in. above 180° turn to test section area (b of T/c)

$$\text{Avg. } \Delta P = \frac{0.88 + 1.06 + 1.00 + 0.95}{4} = 0.96 \text{ in.} H_2O \text{ (From Data)}$$

Velocity at #7, #8, #9 and 10# $- V_2 = \frac{V_2A_1}{A_2}$

$V_2 = \frac{41(15.9)}{32.6} = 20$ fps

$V_1 = 41$ fps

$$H_1 = \frac{P_2 - P_1}{W_a} + \frac{V_2^2 - V_1^2}{2g}$$

$$H_1 = \frac{0.96(144)}{27.7(0.067)} + \frac{(41)^2 - (20)^2}{2(32.17)} = -74.5 + 20$$

$H_1 = -54.5$ ft. Air.

<u>Impeller Head = H_2</u>

$$\text{Avg. } P = \frac{1.24 + 1.20 + 0.90 + 0.76}{4} = 1.025 \text{ in. } H_2O$$

Velocity at #11, #12, #13 and #14 $= V_3 = \frac{V_a A_1}{A_3}$

$$V_3 = \frac{41(15.9)}{42.4} = 15.4 \text{ fps}$$

$$H_2 = \frac{1.025(144)}{27.7(0.067)} + \frac{(15.4)^2 - (41)^2}{2(32.17)} \quad 79.5 - 22.2$$

$H_2 = +57.3$ ft. Air.

$$\text{Air HP} = \frac{W_a H}{550} = \frac{0.304(57.3)}{550} = 0.0317$$

$$V_{t_1} = \pi N D = \frac{3000}{60} \quad \frac{8.625}{12} = 113 \text{ fps}$$

$$V_{t_2} = \frac{3000}{60\ (12)} (4.5) = 58.8 \text{ fps}$$

$$r_1 = \frac{8.625}{2} = 4.313 \text{ in.}$$

$$r_2 = \frac{4.5}{2} = 2.25 \text{ in.}$$

$$\Upsilon = \frac{0.304}{32.17} \quad 113(4.313) - 58.8(2.25)$$

$= 3.38$ in. - lb.

$$HP = \frac{2 \quad N}{33,000} = \frac{2 \quad (3000)(3.38)}{12 \; (33,000)} = 0.161$$

$$e = \frac{0.0317(100)}{0.161} = 19.7\%$$

Reynolds Number - $N_R = \frac{DV}{\nu}$

$$N_R = \frac{4.5(41)}{12(19.56 \times 10^{-5})} = 78,600 \text{ (Turbulent Flow)}$$

Horsepower Variation with pressure and temperature variations.

HP $d_a = \frac{P}{RT}$

$$HP1 = 0.161 \left(\frac{14.7}{14.44}\right)\left(\frac{46.7 + 273}{20 + 273}\right) = \underline{0.179} \text{ @ 14.7 psia and 20°C}$$

$$HP_2 = 0.179 \left(\frac{293}{1500 + 273}\right) = \underline{0.029} \text{ @ 14.7 psia and 1500°C}$$

$$HP3 = 0.179 \left(\frac{414.7}{14.7}\right) = \underline{5.05} \text{ @ 400 psig and 20°C}$$

$$HP_4 = 0.179 \left(\frac{414.7}{14.7}\right)\left(\frac{293}{1500 + 273}\right) = \underline{0.029} \text{ @ 14.7 psia and 1500°C}$$

$$HP3 = 0.179 \left(\frac{414.7}{14.7}\right) = \underline{5.05} \text{ @ 400 psig and 20°C}$$

$$HP_4 = 0.179\left(\frac{414.7}{14.7}\right)\left(\frac{293}{1793}\right) = \underline{0.825} \text{ @ 400 psig and 1500°C}$$

$$HP5 = 0.179 \left(\frac{814.7}{14.7}\right) = \underline{9.9} \text{ @ 800 psig and 20°C}$$

$$HP6 = 0.179 \left(\frac{814.7}{14.7}\right)\left(\frac{293}{1793}\right) = \underline{1.62} \text{ @ 800 psig and 1500°C}$$

DATA
FLOW TEST - MOCK-UP

			ΔP in. H_2O	Corrected Velocity FPS
Date	2-1-66			
Time	3:00PM			
Baro. Press.	29.40	in H_2O		
Relative Humidity	23	%		
Temp.	116	°F		
Impeller Speed	3012	RPM		
Air Velocity - Small Pitot				
Center #1 to #2			0.635	56.6
+0.71 in.			0.660	57.5
+1.23 in.			0.470	48.6
+1.59 in.			0.300	39.0
+1.88 in.			0.205	31.9
+2.14 in.			0.170	29.2
-0.71 in.			0.390	44.3
-1.23 in.			0.240	34.6
-1.59 in.			0.182	30.1
5° (CW)			0.585	54.2
5° (CCW)			0.660	57.5
10° (CW)			0.540	52.0
10° (CCW)			0.680	58.5
15° (CW)			0.490	49.5
15° (CCW)			0.655	57.4
Air Velocity - Large Pitot				
Center #1 to #2			0.870	66.0
+0.71 in.			0.660	57.5
+1.23 in.			0.380	43.5
+1.59 in.			0.250	35.4
+1.88 in.			0.190	31.0
+2.14 in.			0.160	28.4
-0.71 in.			0.610	55.2
-1.23 in.			0.370	42.9
Differential Pressures				
#1 to #3 (Static)			0.00	
#2 to #4 (Total)		-	0.25	
#5 to #6 (Static)		+	0.02	
#7 to #5 "		+	0.88	
#8 to #5		+	1.06	
#9 to #5		+	1.00	

DATA
FLOW TEST - MOCK-UP

Differential Pressures		in. H_2O
#10 to #5 (Static)	+	0.95
#11 to #5 "	+	1.24
#12 to #5 "	+	1.20
#13 to #5 "	+	0.90
#14 to #5 "	+	0.76
#7 to #11 "	+	0.14
#8 to #12 "	+	0.15
#9 to #13	+	0.15
#10 to #14	+	0.23
#11 to #13	+	0.36
#9 to #10	+	0.05

Pressure in. H_2O Gage		in. H_2O
#5	−	0.67
#6	−	0.79
#7	+	0.20
#8	+	0.37
#9	+	0.33
#10	+	0.26
#11	+	0.53
#12	+	0.48
#13	+	0.17
#14	+	0.08

Impeller Speed	Small Pitot		Large Pitot	
RPM	in. H_2O	FPS	in. H_2O	FPS
3186	0.585	54.0	0.94	68.5
3000	0.548	53.0	0.86	65.6
2832	0.500	50.0	0.78	62.5
2616	0.420	45.9	0.64	56.5
2418	0.345	41.6	0.55	52.5
2052	0.280	37.5	0.40	44.8
1800	0.220	33.3	0.30	39.0
1626	0.170	29.2	0.25	35.4
1308	0.125	25.0	0.16	28.2
942	0.055	16.7	0.08	20.0
690	0.027	11.7	0.04	14.2