NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 284

THE COMPARATIVE PERFORMANCE OF ROOTS TYPE AIRCRAFT ENGINE SUPERCHARGERS AS AFFECTED BY CHANGE IN IMPELLER SPEED AND DISPLACEMENT

By MARSDEN WARE and ERNEST E. WILSON

REPRINT OF REPORT No. 284, ORIGINALLY PUBLISHED APRIL, 1928

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AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Symbol	Unit	Symbol
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	sec	second (or hour)	sec. (or hr.)
Force	F	weight of one kilogram	kg	weight of one pound	lb.
Power	P	kg/m/sec		horsepower	HP.
Speed		km/hr		mi./hr	M. P. H.
		m/sec		ft./sec	f. p. s.

2. GENERAL SYMBOLS, ETC.

W, Weight, $=mg$

g, Standard acceleration of gravity $=9.80665$ m/sec.$^2=32.1740$ ft./sec.^{2}

m, Mass, $=\frac{W}{g}$

ρ, Density (mass per unit volume).

Standard density of dry air, 0.12497 (kg-m^{-4} sec.^{2}) at 15° C and 760 mm $=0.002378$ (lb.-ft.$^{-4}$ sec.^{2}).

Specific weight of "standard" air, 1.2255 kg/m$^3=0.07651$ lb./ft.^{3}

mk^2, Moment of inertia (indicate axis of the radius of gyration, k, by proper subscript).

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord length.

b/c, Aspect ratio.

f, Distance from $c.\ g.$ to elevator hinge.

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed.

q, Dynamic (or impact) pressure $=\frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L=\frac{L}{qS}$

D, Drag, absolute coefficient $C_D=\frac{D}{qS}$

C, Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

R, Resultant force. (Note that these coefficients are twice as large as the old coefficients L_C, D_C.)

i_w Angle of setting of wings (relative to thrust line).

i_t, Angle of stabilizer setting with reference to thrust line.

γ, Dihedral angle.

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension.

e. g., for a model airfoil 3 in. chord, 100 mi./hr. normal pressure, 0° C: 255,000 and at 15° C., 230,000;

or for a model of 10 cm chord 40 m/sec, corresponding numbers are 299,000 and 270,000.

C_p, Center of pressure coefficient (ratio of distance of $C.\ P.$ from leading edge to chord length).

β, Angle of stabilizer setting with reference to lower wing, $=(i_t-i_w)$.

α, Angle of attack.

ϵ, Angle of downwash.

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Langley Memorial Aeronautical Laboratory

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NAVY BUILDING, WASHINGTON, D. C.

(An independent Government establishment, created by act of Congress approved March 3, 1915, for the supervision and direction of the scientific study of the problems of flight. It consists of 15 members who are appointed by the President, all of whom serve as such without compensation.)

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SUMMARY

This report presents the results of tests made by the National Advisory Committee for Aeronautics on three sizes of Roots type aircraft engine superchargers. The impeller contours and diameters of these machines were the same, but the lengths were 11, 8¼, and 4 inches, giving displacements of 0.509, 0.382, and 0.185 cubic foot per impeller revolution. The information obtained serves as a basis for the examination of the individual effects of impeller speed and displacement on performance and of the comparative performance when speed and displacement are altered simultaneously to meet definite service requirements.

According to simple theory, when assuming no losses, the air weight handled and the power required for a given pressure difference are directly proportional to the speed and the displacement. These simple relations are altered considerably by the losses.

In estimating the effect of speed on performance it is of interest to note that:

(1) The difference between the actual power and the theoretical power was found to vary with the speed raised to the 2.5 power. The theoretical power was obtained by multiplying the pressure difference by the displacement and speed and dividing by the horsepower constant.

(2) The volumetric efficiency of the actual machine remains nearly constant over a large part of the interesting speed range, the decrease in volumetric efficiency at a speed of 6,000 R. P. M. being less than 2 per cent.

(3) The ratio of the discharge air temperature to the inlet temperature was found to depend on speed. This effect of speed is represented by the coefficient "C" in the relation

$$\frac{T_2}{T_1}=C\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}},$$

which has a value of 1 at zero R. P. M. increasing to 1.04 at 6,500 R. P. M.

With regard to the effect of displacement on performance, the following points are of interest:

(1) The power loss was found to increase with displacement.

(2) The maximum volumetric efficiency increased somewhat with increase in displacement.

(3) The relation between the inlet and discharge temperatures and pressures as represented by the exponent "n" in the above equation was found to increase from 1.36 to 1.53 with increase in impeller length from 4 to 11 inches.

When comparing the performance of different sizes of machines whose impeller speeds are so related that the same service requirements are met, it is found that the individual effects of speed and displacement are canceled to a large extent and the only considerable difference is the difference in the power losses which decrease with increase in the displacement and the accompanying decrease in speed. This difference is small in relation to the net power of the engine supercharger unit, so that a supercharger with short impellers may be used in those applications where the space available is very limited without any considerable sacrifice in performance.

INTRODUCTION

The general performance of the Roots type aircraft engine supercharger has been discussed in Technical Report No. 230 (Reference 1) and a brief comparison made with some of the important characteristics of other types of compressors that are used as superchargers. This comparison showed that the Roots type compressor has several features which make attractive its use as an aircraft engine supercharger. Of these features, its adaptability to a simple method of control involving a minimum of power loss and its good efficiency are especially noteworthy.

In determining the proportions of a Roots supercharger for a particular application there are two variables that are primarily concerned, namely, the displacement per revolution and the rotative speed of the impellers. The action of a Roots supercharger is to transfer a fixed volume of air at intake density from the inlet side to the discharge side where it is compressed to the discharge pressure by the back flow of high pressure air (Reference 1). The theoretical delivery in weight per unit time, assuming no clearance and no losses, is, then, the product of the displacement in unit time and the density of the inlet air. Since the displacement in unit time is directly proportional to the product of displacement per revolution and revolutions per unit time, and the size and weight are to a large extent proportional to the displacement per revolution, it is evident that a great saving in space occupied and weight can be made by operating a small machine at high impeller speeds. The theoretical power required with no losses is given by the equation

$$HP=\frac{DN\ (P_2-P_1)}{33000}$$

where

D = Displacement per revolution

N = R. P. M.

P_2-P_1 = Pressure difference.

The theoretical power is, therefore, directly proportional to the speed, and the power per unit of air delivered in unit time, assuming no losses, is the same regardless of speed or size.

Certain losses enter, however, to alter these simple relations and a knowledge of the effects of speed and displacement per revolution becomes important in the application of this type of supercharger.

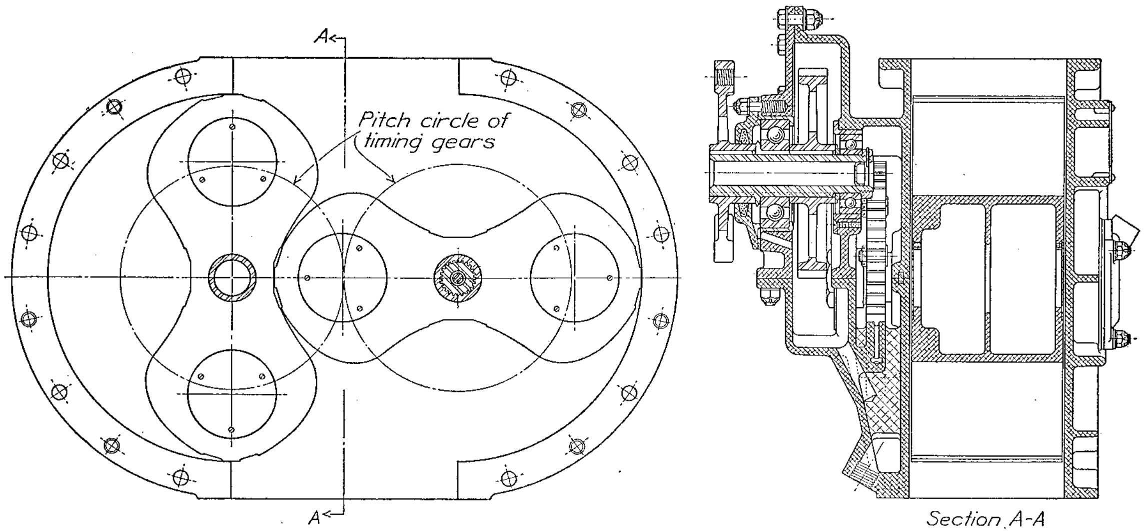

FIG. 1.—N. A. C. A. Roots type supercharger with gear end plate removed and supercharger cross section showing 4-inch impellers

Tests covering a large range of impeller speeds have been made at the Langley Memorial Aeronautical Laboratory on three sizes of Roots type superchargers. These three machines have the same impeller contour and diameter so that change in displacement and delivery with no losses is proportional to the change in impeller length. The displacements per revolution are 0.509, 0.382, and 0.185 cubic foot and the impeller lengths are 11, 8¼, and 4 inches.

The machine with the 11-inch impellers has been described in detail in Technical Report No. 230 and, except for changes tending for better mechanical conditions, the type of construction of all three machines is essentially that given therein. Figure 1 shows the constructional details of the machine with 4-inch impellers.

The purpose of this report is to present the performances of these three machines on a comparative basis and point out the effects of speed and displacement on performance.

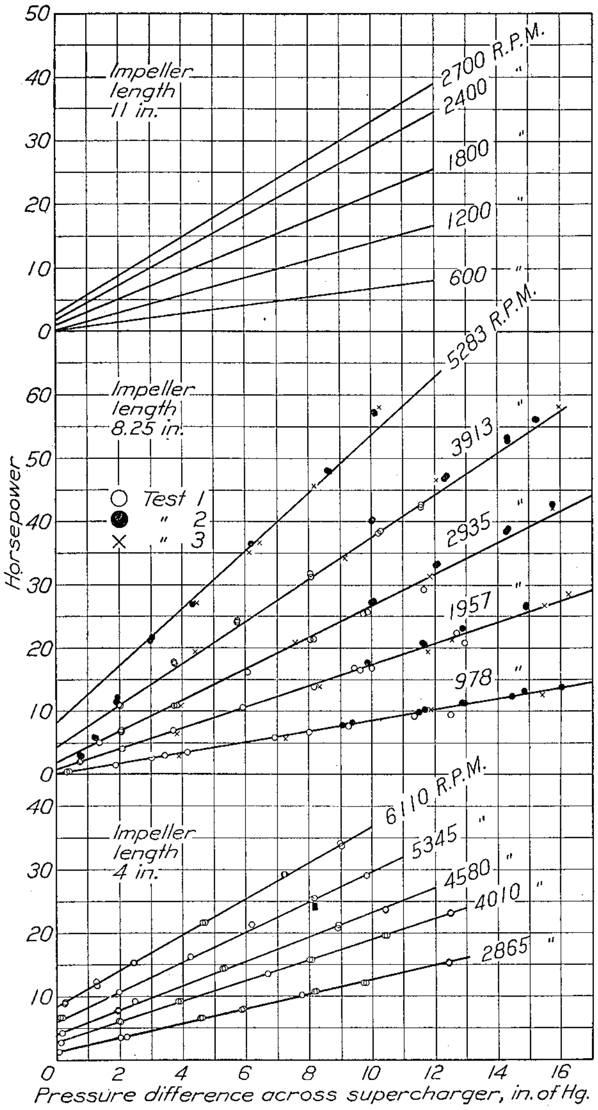

FIG. 2.—Power requirements as affected by impeller displacement, speed, and pressure difference

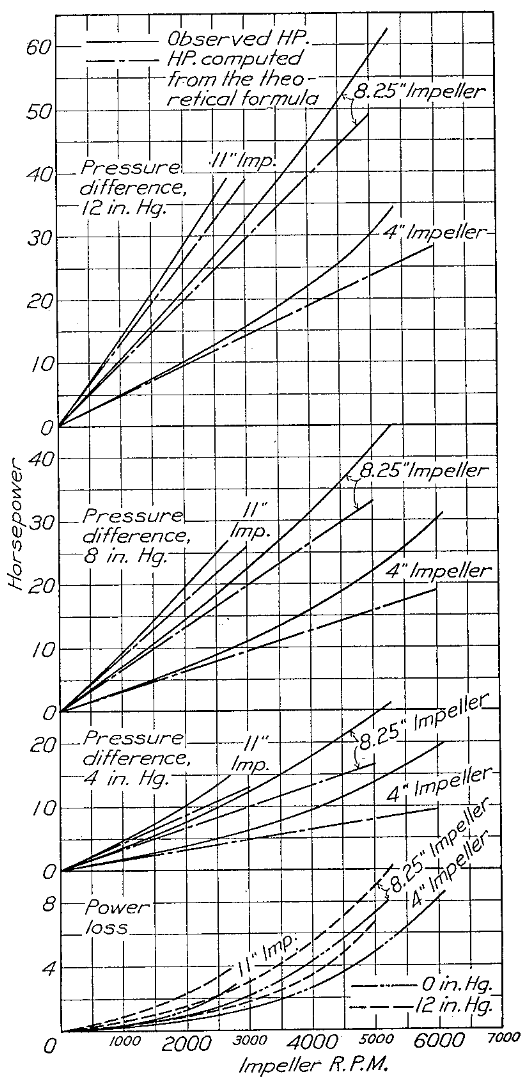

FIG. 3.—Power and power losses as affected by impeller displacement, speed, and pressure difference

TEST RESULTS

The performances of the superchargers were obtained from tests made by throttling their inlet ports and driving them at speeds up to 2,700 R. P. M. for the 11-inch machine, 5,283 R. P. M. for the 8¼-inch machine, and 6,110 R. P. M. for the 4-inch machine. The air was discharged at atmospheric pressure. The quantity of air delivered was measured by a Durley Orifice Box, the power required to drive the superchargers was measured by an electric dynamometer and the inlet and discharge temperatures and pressures were measured by mercury thermometers and manometers. Experimental data for the tests of the 8¼-inch supercharger are shown in Tables I to V, inclusive. Since the temperatures of the air varied somewhat while the tests were in progress, the delivered air weights were corrected to a temperature of 59° F. in order to provide comparable data. The apparatus used and the methods of computation were, in general, the same as given in Technical Report No. 230.

Figure 2 shows the brake power for the three superchargers. The data for the 8¼ and 4 inch superchargers were obtained by operating them at fixed speeds, but those for the 11-inch supercharger were obtained by maintaining the delivered air weight constant over a range of pressure differences. It was necessary, therefore, to cross plot the original data for the 11-inch supercharger to find the relation shown in this figure; hence, data points are not shown for this machine.

Three distinct series of tests were made to obtain the data shown for the 8¼-inch supercharger. The range of pressure differences used in the first series was extended in the second and third series, although these latter included data within the range of the first series. There appeared to be some contacting between the rotors at the higher pressure differences in the second series which probably accounts for the fact that the power was highest for this series.

A brief analysis of power is shown in Figure 3. The brake power shown in this figure was obtained by cross plotting from Figure 2. The theoretical power was obtained from the theoretical equations given in the introduction and explained in Technical Report No. 230. The differences between these two powers represent the power losses.

Figure 4 shows the weight of air delivered; the curves are cross plots of the original data, which gave definite relations.

The ratios of the discharge air temperature to the inlet air temperature plotted against the ratios of the discharge pressure to the inlet air pressure on a logarithmic basis are shown in Figure 5. It may be noted that, for the 8¼ and 4 inch superchargers the intercept of straight lines representing the data with the temperature ratio axis increases with increase in speed. The tests of the 11-inch supercharger were not carried to those speeds where a definite speed effect is apparent. The data for the 8¼-inch supercharger appears to give two straight lines of different slopes, intersecting at a pressure ratio of about 1.5. Although some of the points were obtained in the second series of tests where some contacting had been noted, the few points obtained in the third series show the same effect.

Measurements were also made of slip speed, i. e., that speed required to maintain definite pressure differences with no air delivery. These tests were made by blocking off the inlet to the supercharger. The results of these measurements are given in Figure 6. The lower part of this figure shows the effect of a change in impeller end clearance from 0.015 to 0.020 inch. The dotted lines shown in this part of the figure indicate the manner in which the slip speed changes with temperatures.

ANALYSIS OF THE PERFORMANCES OF THE THREE SUPERCHARGERS

In making a comparison of the performances of these superchargers the test results used should apply to that condition of each supercharger necessary for the most efficient operation under ordinary service conditions. Since the performance of a Roots supercharger is affected by the clearances between the two impellers and between the impellers and the parts composing the compression chamber, the comparison must be made for comparative clearances. The clearances that should obtain for a fair comparison depend on the tolerances used and on the materials and details of construction. The tolerances and freedom in the bearings and the method of locating them prohibit the use of clearances proportional to the impeller length, although such a proportion might have been possible from a consideration of the relative amount of expansion with increased temperature. A definite comparison was obtained by reducing all performances for the three machines to the same clearances that obtained in the tests of the 4-inch supercharger −0.007 inch between the impellers and between the tips of the impellers and the curved sides of the compression chamber, and 0.010 inch between the ends of the impellers and the ends of the compression chamber.

A change in clearance does not affect the air handled which is the sum of the air delivered and that which slips back through the impeller-case clearances, but it does affect the ratio of these two components. The amount of air delivered decreases with increased clearance, as is shown in Figure 4. The amount of air that is lost in slip increases with the clearance since the slip speed increases with clearance, as shown by Figure 6.

The method used herein for correcting the air delivered assumes that it is proportional to the difference between the impeller speed and the slip speed. It is realized, however, that the

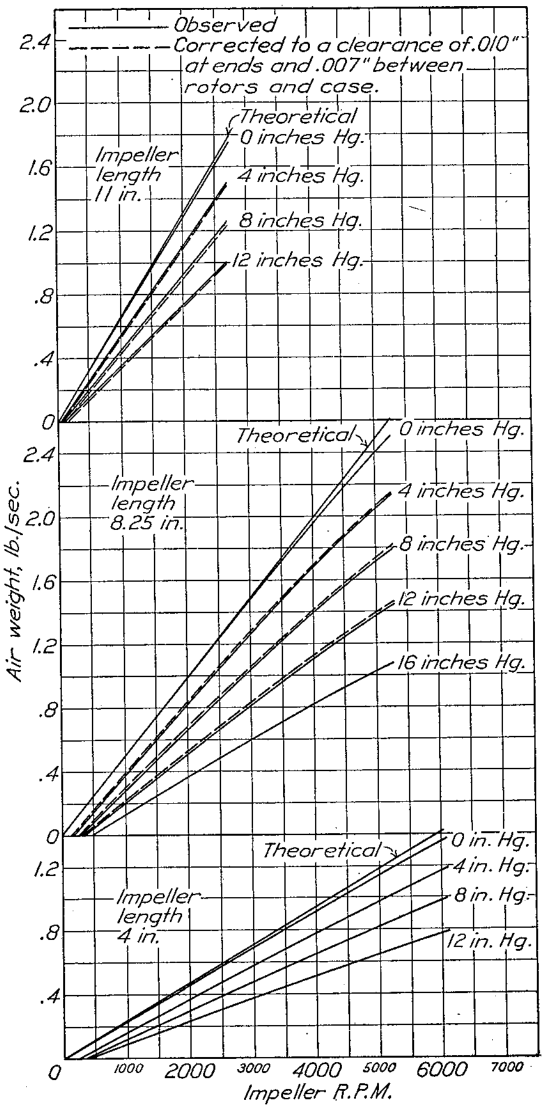

FIG. 4.—Rate of air delivery as affected by impeller displacement, speed, pressure difference, and clearance

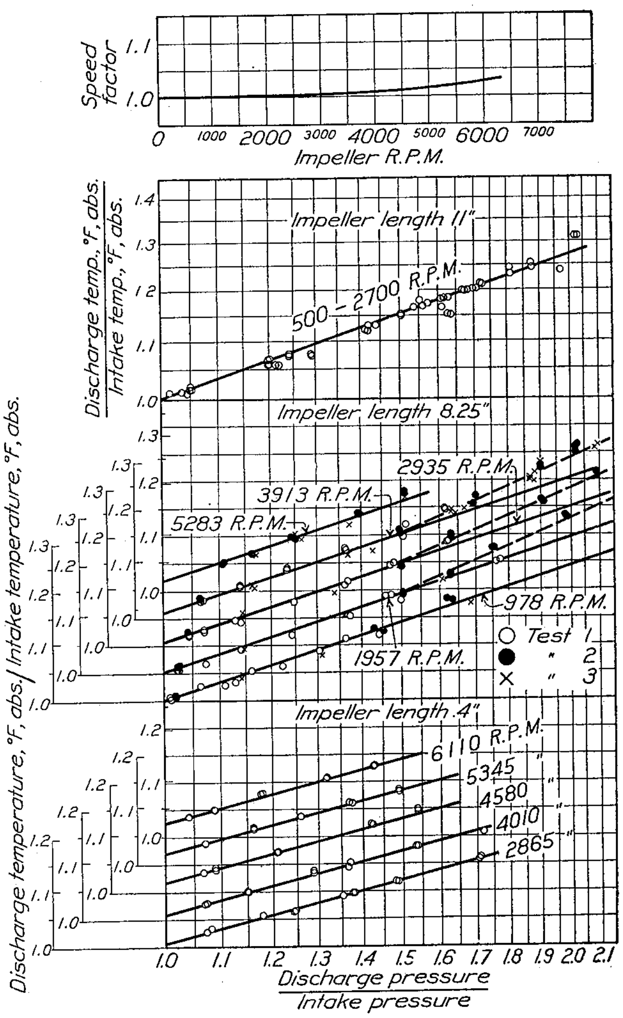

FIG. 5.—Temperature-pressure relations as affected by impeller displacement and speed. Plotted on a logarithmic scale

slip, i. e., that air which slips back through the impeller-case clearances, measured at a given pressure difference with no delivery, as obtained by blocking off the inlet, may be in error when used at the same pressure difference for high impeller speeds during air delivery. Since the corrections made are for the same impeller speeds, the relative errors resulting from the use of slip at no delivery are small. Slip speeds for the three machines reduced to the same clearances by rational processes are shown on Figure 6. Plots of air delivered corrected by this method are shown as dotted lines in Figure 4. Volumetric efficiencies as computed from these air weights are shown by Figure 7. The power required to drive the supercharger, being mainly a function of speed and pressure difference, is not affected very much by change in clearance.

The test results and the comparative volumetric efficiencies form the basis for an estimation of the comparative performance for definite service requirements. This will be preceded by consideration of the independent effects of speed and displacement, without regard to service requirements, in order that the comparison may be more readily appreciated.

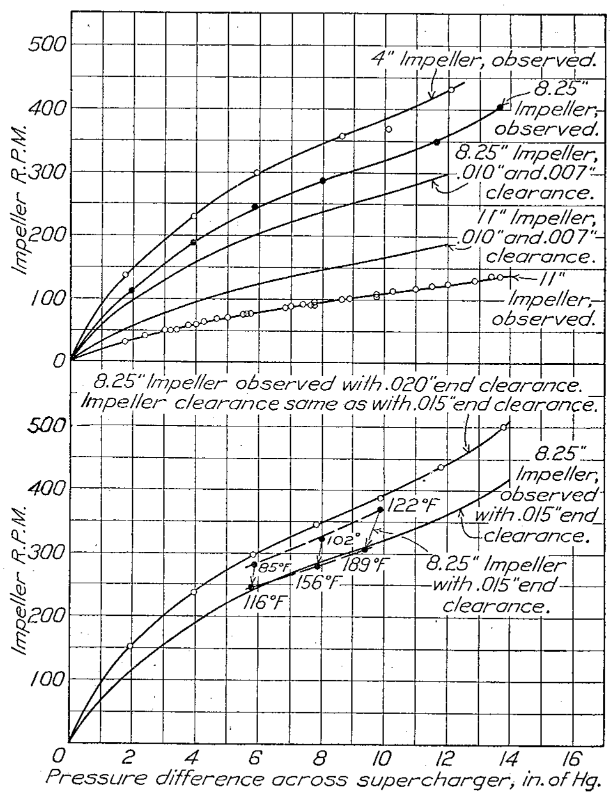

FIG. 6.—Slip speed as affected by impeller displacement, pressure difference, clearance, and temperature

THE EFFECT OF SPEED ON PERFORMANCE: Since simple theory, when assuming no losses, shows that the air delivered depends only on the displacement per revolution and the revolutions per minute while the power required depends on the air delivered and the pressure difference, consideration of the effect of speed on performance in the actual machine depends on consideration of the losses occurring in the supercharger, their kind and effect on performance, and the effect of speed on their magnitude. The one item of loss that causes the greatest departure from the no-loss performance is that due to the air leaking from the delivery side to the inlet side through the clearance spaces. Other losses entering are the power lost in gears and bearings, the power due to air friction, and an apparent loss in power and air delivery that will be termed pressure loss. This apparent loss is due to the fact that at the high speeds encountered the pressure within the displacement volume before compression will be less than that measured at the inlet to the machine, and after compression it will be greater than that measured at the discharge side, thus increasing the power required to drive the supercharger and decreasing the air delivered beyond that computed from observed pressures.

The effect of these losses on the relations of air delivered and volumetric efficiency to speed will be considered first. On Figure 4 the theoretical air delivery, assuming no losses, is plotted together with the measured deliveries. The difference between the air weight delivered at zero pressure difference and the theoretical value shows the effect of speed which is made up of the effect of pressure loss and the effect of the loss due to air friction. The displacement of the other curves is due partially to the reduced inlet density and partially to the slip. For the condition of no losses the volumetric efficiency is 100 per cent regardless of speed. At the lower impeller speeds, loss of air through the impeller-case clearances reduces

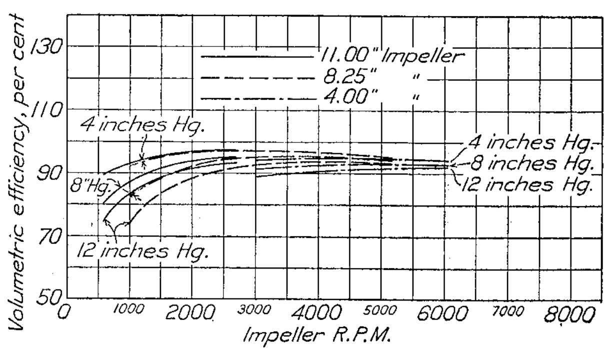

FIG. 7.—Volumetric efficiency as affected by impeller displacement, pressure difference, and speed

the volumetric efficiency below 100 per cent, having less effect as the speed increases. If this loss were the only loss, volumetric efficiency would approach 100 per cent at infinite speed. Actual tests, however, show that the pressure loss serves to reduce the volumetric efficiency within a practical speed range, but the reduction is quite gradual with increase in speed.

The effect of speed on power losses is shown graphically by Figure 3, from which it may be seen that the departure of the measured power from theoretical power increases with speed. The power losses, at zero pressure difference, as given by differences of the theoretical and actual power, are exponential functions of the speed, showing a variation with speed raised to the 2.5 power. The increases in the power losses with pressure difference, as shown on Figure 3, are largely caused by the increased gear and bearing friction.

The power losses given by these differences are composed of gear and bearing friction, pressure losses, and air friction. Since the power depends on the geometrical displacement and not on the air delivered, the effect of slip does not enter.

Speed will also have an effect on the temperature-pressure relations, tending to increase the temperature ratio for a given pressure ratio because of the fact that the radiating surface remains constant while the total amount of heat generated in the compression of an increased amount of air increases with speed. Counteracting this effect is the loss of air throught the clearance spaces. Assuming that the amount of air that returns from the pressure side of the supercharger to the inlet side depends primarily on the pressure difference, then the proportion of heated air that is returned and recompressed with further increase in temperature decreases as the speed is increased, thus resulting in a lower temperature for the delivered air. The fact that the temperature-pressure relation plotted on a log basis, Figure 5, shows a definite temperature increase with increase in speed for a discharge-inlet air-pressure ratio equal to 1 indicates that the radiation condition controls. This speed effect may be represented by inserting a coefficient "C" in the usual relation between temperature and pressure, giving

$$\frac{T_2}{T_1} = C\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$$

The value of "C" is taken from the speed-curve intercepts on the temperature axis, and is plotted against speed at the top of Figure 5. The increase in temperature ratio due to increase in speed is seen to be less than 5 per cent for speeds up to 6,500 R. P. M.

It was noted previously that the data for the 8¼-inch supercharger shows a definite change in slope in the temperature-pressure relation at a pressure ratio of approximately 1.5. It appears from rational processes of reasoning that this effect is independent of speed.

THE EFFECT OF DISPLACEMENT ON PERFORMANCE:

In view of the fact that the theoretical equation, omitting the influence of losses, shows that the power required and air weight delivered are directly proportional to displacement, an analysis of the effect of displacement on performance is reduced to analyses of the effects of the losses on the simple relations as in the discussion of the effects of speed on performance. Slip has the greatest influence on the difference between the simple theoretical and the actual performances. Since slip speed at a given pressure difference is directly proportional to the clearance area and inversely proportional to the displacement, it is necessary to know the relative change in displacement and clearance area with a change in dimension. The displacement varies with the length of the supercharger, but since there are fixed clearance areas at the ends of the impellers which are not changed by an increase in length the total clearance will not vary as rapidly as the length. For example, doubling the length of the impellers doubles the displacement but does not double the clearance area. The slip, therefore, will be less for the machine with greater displacement, as is evident from Figure 6.

The influence of slip on the air delivery can be seen from Figure 7. If all three superchargers had the same slip, volumetric efficiency curves for the three superchargers would be approximately superimposed when the pressure difference is the same. The displacement of the curves which show higher volumetric efficiencies for the longer superchargers indicates the extent to which slip enters into the consideration of the effect of displacement and air weight delivered.

Since the power required depends upon the work done on the air handled by the supercharger and this work is the same regardless of the proportion of the air handled that returns to the intake side, slip has no effect on the relation between displacement and power unless the power for a given weight of air is considered.

The magnitude of the effect of displacement on the other losses—namely, the pressure, mechanical and air friction losses—is shown at the bottom of Figure 3.

A pronounced effect of change in displacement is its influence on the temperature-pressure relations. The heat radiation surface of a Roots supercharger is composed of the two ends and two sides of the compression chamber. When a change in size is obtained by a change in length the heat generated in unit time will increase in proportion with the increase in length for a given pressure difference and speed. The increase in radiating surface with an increase in length, however, is less than the proportional increase in length; consequently, the compression exponent will increase with increase in displacement. It may be noted that for the two larger superchargers the compression exponent is greater than the theoretical adiabatic exponent of 1.41. This is due to the magnitude of the power losses, which are such that the additional heat generated by these losses is not completely radiated by the supercharger case. Under the conditions of the laboratory tests, the compression exponent "n" in the equation

$$\frac{T_2}{T_1}=C\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$$

varies with the size in the following manner:

11 in. supercharger; $n=1.53$
8¼ in. supercharger; $n=1.48$
4 in. supercharger; $n=1.36$

COMPARATIVE PERFORMANCE FOR GIVEN REQUIREMENTS:

While the individual effects of speed and displacement have been discussed in the preceding paragraphs, speed and displacement must be considered simultaneously in the usual case of selection of a supercharger for a specific purpose, entailing, as it does, a definite weight of air delivered.

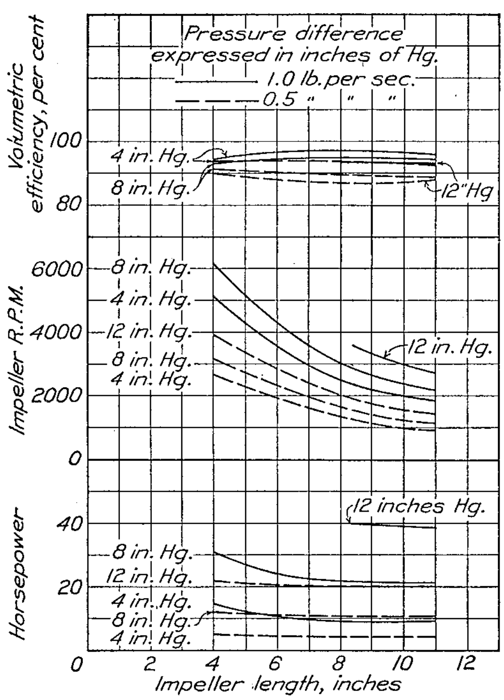

FIG. 8.—Comparative performances of three superchargers for definite rates of air delivery and variable impeller length

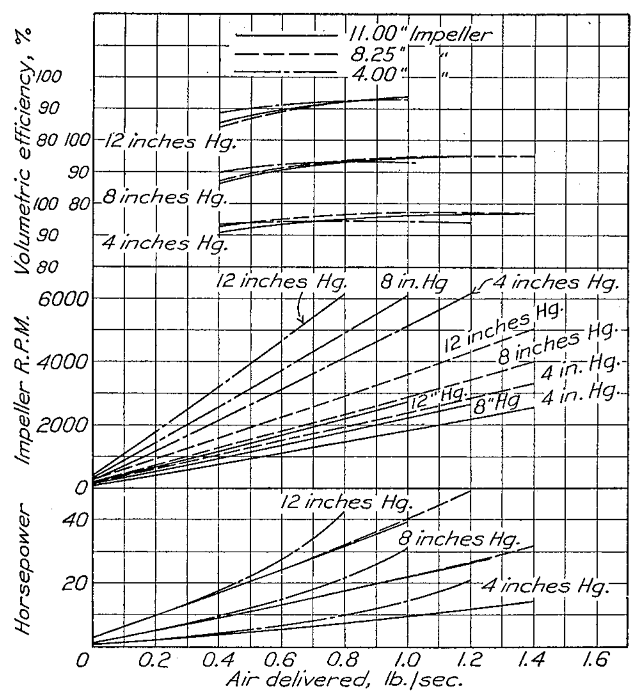

FIG. 9.—Comparative performances for three superchargers for definite impeller length and variable rate of air delivery

In Figure 8 several performance factors are plotted against impeller length for constant rates of air delivery of 1 and 0.5 pound per second. These values were selected because they approximate the air requirements of the two most popular sizes of engines in use to-day—engines of 400 to 450 and 200 to 220 HP., respectively.

It will be noted that the volumetric efficiency remains at a satisfactorily high value, regardless of length; hence, there is very little choice between different lengths from this viewpoint. This is accounted for by the fact that the tendency for reduced volumetric efficiency caused by higher slip for the smaller machines is counteracted by the tendency for increased volumetric efficiency caused by the increased speed at which the smaller machine must be operated. The rapid increase in impeller speed with reduction in length results in an increase in power required for the shortest supercharger, as discussed heretofore. While the percentage increase may seem considerable in a reduction of length from 11 to 4 inches, the actual difference may not be considered prohibitive, since at a pressure difference of 8 inches of mercury and a delivery rate of 1 pound per second the difference of 9 HP. is small in relation to the net power of the engine-supercharger unit. It is well to point out, however, that very high speeds may cause a considerable increase in power due to the exponential nature of the power losses. Figure 9 shows the same information plotted against air delivered.

With regard to the temperature-pressure relations which were shown to be influenced by a change in displacement and speed, it should be noted that the independent effects of each are practically canceled at speeds that are of interest in the supercharger application when considering simultaneous changes in speed and displacement to meet a specific requirement.

With this information as a basis, the actual selection may be made more intelligently, but, since the performance is, in general, improved somewhat by increasing the size of the machine, the selection will be governed to a large extent by the space requirements of the particular application.

THE REDUCTION OF LABORATORY PERFORMANCE TO ALTITUDE PERFORMANCE

The pressure conditions in these tests are comparable to actual service conditions where the supercharger is used to maintain sea-level pressure at the carburetor as the altitude of operation is increased because they were created by throttling the inlet to the supercharger with free discharge into the atmosphere. The intake temperature was nearly constant for all pressure differences while in service the temperature decreases considerably with increase in pressure difference caused by increase in altitude of operation. In using the test data in this report for the estimation of altitude performance of the supercharger it is necessary, therefore, to take into account this difference in temperature conditions.

The chief effect of the difference in temperature is to change the density of the inlet air and, therefore, the weight of air handled in unit time. A simple method of finding the air weight that would be handled at altitude consists in multiplying the air weight given herein for the pressure corresponding to the altitude under consideration by the ratio of the absolute temperature of these tests (519° F.) to the absolute temperature of the altitude. The power required will be sensibly that given herein, since power for a given machine is dependent on the pressure difference and the speed.

No attempt is made to consider here the agreement of flight results with laboratory results; it is intended merely to point out the importance of the difference in laboratory and flight intake air temperatures. While the different temperature conditions give some difference in clearance and consequently some difference in the volumetric efficiency, the results that have been obtained by the use of this method in connection with actual flight work makes this effect appear inconsequential for most purposes.

CONCLUSION

It is evident from these tests that impeller speed and displacement have an appreciable effect on the performance characteristics of Roots superchargers aside from their effect as a result of a direct proportional relation. It may be concluded, however, that the speed of impeller operation may be increased to at least 6,000 R. P. M. without imposing any serious performance limitation—the volumetric efficiency is not seriously reduced and the power required per pound of air delivered is not increased excessively at this speed. The results obtained with the 4-inch supercharger indicate that good performance characteristics may be obtained with this relatively small machine, which lends itself to a compact type of construction so much desired in aircraft practice.

When the three sizes of machines are compared on a basis of the same rate of air delivery it is seen that the performance characteristics are the same in general, except that the power loss introduced by high speeds of operation result in somewhat greater power requirements for the smallest supercharger.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *December 23, 1927.*

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TABLE I

EXPERIMENTAL DATA USED TO DETERMINE THE EFFECTS OF IMPELLER SPEED AND DISPLACEMENT

[8.25-inch supercharger]

Run No.	Speed (impeller) (R. P. M.)	Horse-power	Air weight (lb. per sec.)	Pressure difference (In. Hg.)	Pressure ratio	Temper-ature ratio
			Test 1			
4	978	1.48	0.4165	1.86	1.067	1.024
5	978	3.39	.3615	4.14	1.162	1.050
6	978	5.81	.2970	6.93	1.304	1.085
7	978	9.46	.1890	12.51	1.728	[1] 1.177
8	978	.36	.5100	.35	1.010	1.002
9	978	2.91	.3465	3.43	1.131	1.030
10	978	2.48	.3955	3.00	1.111	1.025
11	978	3.32	.3334	5.56	1.227	1.059
12	978	7.60	.2555	9.26	1.446	1.115
13	978	6.65	.2775	8.00	1.363	1.108
14	978	9.26	.2255	11.35	1.607	1.167
15	978	.39	.4855	.36	1.012	1.006
			Test 2			
64	978	.19	.4935	.32	1.011	1.001
65	978	.17	.4950	.32	1.011	1.000
66	978	8.00	.2647	9.38	1.453	1.121
67	978	7.83	.2658	9.07	1.431	1.125
68	978	10.07	.2186	11.70	1.636	1.182
69	978	9.88	.2212	11.50	1.618	1.184
70	978	11.24	.1750	12.92	1.750	[1] 1.180
71	978	11.24	.1740	12.88	1.746	[1] 1.185
72	978	13.82	.1222	16.03	2.135	[1] 1.196
73	978	12.91	.1452	14.85	1.970	[1] 1.216
74	978	12.47	.1454	14.45	1.921	[1] 1.237
			Test 3			
208	978	3.16	.3570	3.75	1.143	1.040
209	978	5.90	.2680	7.06	1.307	1.078
210	978	10.31	.1712	12.18	1.684	[1] 1.127
211	978	12.68	.1276	14.81	1.974	[1] 1.183

[1] These points were not used in determining the temperature-pressure relations because the discharge temperatures had not reached a sufficiently constant condition.

TABLE II

EXPERIMENTAL DATA USED TO DETERMINE THE EFFECTS OF IMPELLER SPEED AND DISPLACEMENT

[8.25-inch supercharger]

Run No.	Speed (impeller) (R. P. M.)	Horse-power	Air weight (lb. per sec.)	Pressure difference (In. Hg.)	Pressure ratio	Temper-ature ratio
			Test 1			
16	1,957	1.95	0.9450	0.78	1.027	1.010
17	1,957	4.00	.8825	2.09	1.074	1.015
18	1,957	6.85	.8160	3.73	1.142	1.039
19	1,957	10.50	.7240	5.90	1.244	1.065
20	1,957	13.93	.6410	8.18	1.374	1.099
21	1,957	16.68	.5765	10.00	1.498	1.128
22	1,957	1.75	.9385	.74	1.025	1.009
23	1,957	1.73	.9330	.74	1.025	1.006
24	1,957	16.80	.5810	9.44	1.459	1.136
25	1,957	16.55	.5820	9.64	1.473	1.136
26	1,957	22.25	.4570	12.70	1.775	1.205
27	1,957	20.62	.4650	12.97	1.761	1.203
			Test 2			
75	1,957	3.00	.9275	.71	1.024	1.010
76	1,957	2.98	.9250	.74	1.025	1.010
77	1,957	17.85	.5775	9.87	1.489	1.138
78	1,957	17.63	.5800	9.87	1.488	1.143
79	1,957	20.75	.5088	11.63	1.631	1.176
80	1,957	20.58	.5090	11.63	1.631	1.180
81	1,958	23.05	.4585	12.90	1.750	1.230
82	1,957	23.02	.4620	12.90	1.750	1.230
83	1,957	26.68	.3955	14.92	1.986	1.296
84	1,957	26.50	.3952	14.90	1.981	1.298
			Test 3			
206	1,957	19.55	.5040	11.31	1.606	1.168
207	1,957	28.55	.3310	16.28	2.188	[1] 1.254
212	1,957	21.25	.4202	12.38	1.703	[1] 1.146
213	1,957	26.85	.3735	15.45	2.063	[1] 1.237
214	1,957	6.55	.7910	3.75	1.143	1.044
215	1,957	14.00	.6190	8.12	1.367	1.100

[1] These points were not used in determining the temperature-pressure relations because the discharge temperatures had not reached a sufficiently constant condition.

TABLE III

EXPERIMENTAL DATA USED TO DETERMINE THE EFFECTS OF IMPELLER SPEED AND DISPLACEMENT

[8.25-inch supercharger]

Run No.	Speed (impeller) (R. P. M.)	Horse-power	Air weight (lb. per sec.)	Pressure difference (In. Hg.)	Pressure ratio	Temper ature ratio
			Test 1			
28	2,935	4.94	1.360	1.35	1.047	1.018
29	2,935	4.94	1.352	1.35	1.047	1.018
30	2,935	6.81	1.327	2.05	1.073	1.023
31	2,935	6.66	1.319	2.05	1.073	1.026
32	2,935	10.76	1.215	3.75	1.141	1.043
33	2,935	10.71	1.236	3.79	1.143	1.039
34	2,935	16.13	1.105	6.07	1.251	1.076
35	2,935	16.13	1.102	6.07	1.251	1.076
36	2,935	21.26	1.006	8.07	1.363	1.105
37	2,935	21.46	1.002	8.16	1.368	1.112
38	2,935	25.51	.918	9.74	1.472	1.142
39	2,935	25.61	.915	9.85	1.481	1.148
40	2,935	29.14	.820	11.62	1.621	1.187
41	2,935	29.16	.817	11.65	1.625	1.191
			Test 2			
85	2,935	5.67	1.354	1.25	1.043	1.022
86	2,935	5.55	1.358	1.25	1.043	1.021
87	2,935	27.44	.886	10.05	1.500	1.138
88	2,935	27.14	.890	10.00	1.500	1.147
89	2,935	33.18	.784	12.10	1.668	1.197
90	2,935	33.30	.782	12.06	1.671	1.203
91	2,935	38.74	.669	14.34	1.908	1.268
92	2,935	38.67	.669	14.30	1.903	1.273
93	2,935	42.70	.593	15.75	2.095	1.324
94	2,935	42.70	.593	15.72	2.090	1.333
			Test 3			
202	2,935	10.87	1.212	3.86	1.148	1.052
203	2,935	20.82	1.032	7.56	1.337	1.093
204	2,935	31.50	.793	11.74	1.642	1.177
205	2,935	42.25	.590	15.65	2.090	[1] 1.288

[1] These points were not used in determining the temperature-pressure relations because the discharge temperatures had not reached a sufficiently constant condition.

TABLE IV

EXPERIMENTAL DATA USED TO DETERMINE THE EFFECTS OF IMPELLER SPEED AND DISPLACEMENT

[8.25-inch supercharger]

Run No.	Speed (impeller) (R. P. M.)	Horse-power	Air weight (lb. per sec.)	Pressure difference (In. Hg.)	Pressure ratio	Temperature ratio
			Test 1			
42	3,913	11.15	1.783	1.94	1.068	1.030
43	3,913	11.10	1.791	1.99	1.070	1.032
44	3,913	17.50	1.662	3.76	1.141	1.053
45	3,913	17.55	1.655	3.76	1.141	1.055
46	3,913	24.00	1.527	5.75	1.234	1.083
47	3,913	24.25	1.520	5.75	1.233	1.086
48	3,913	31.35	1.359	8.10	1.365	1.120
49	3,913	31.55	1.365	8.06	1.362	1.122
50	3,913	38.05	1.215	10.22	1.507	1.145
51	3,913	38.45	1.212	10.28	1.513	1.168
52	3,913	42.15	1.125	11.58	1.616	1.196
53	3,913	42.40	1.129	11.59	1.616	1.199
			Test 2			
95	3,913	12.05	1.782	1.98	1.068	1.032
96	3,913	11.40	1.778	1.88	1.066	1.032
97	3,913	40.05	1.209	10.06	1.498	1.149
98	3,913	40.00	1.212	10.03	1.496	1.158
99	3,913	46.93	1.038	12.37	1.696	1.209
100	3,913	47.25	1.041	12.42	1.701	1.225
101	3,913	52.75	.909	14.32	1.904	1.283
102	3,913	53.05	.902	14.32	1.904	1.288
103	3,913	56.20	.853	15.21	2.016	1.318
104	3,913	-------	.840	15.21	2.016	1.329
105	3,913	56.05	.833	15.25	2.021	1.333
			Test 3			
164	3,913	(1)	(1)	13.98	1.865	1.261
165	3,913	(1)	(1)	13.98	1.865	1.262
166	3,913	(1)	(1)	14.00	1.877	1.257
167	3,913	(1)	(1)	14.05	1.880	1.276
168	3,913	(1)	(1)	14.20	1.898	1.294
192	3,913	(1)	(1)	1.91	1.080	1.050
193	3,913	(1)	(1)	4.17	1.172	1.057
194	3,913	(1)	(1)	7.79	1.365	1.116
195	3,913	(1)	(1)	11.71	1.657	1.192
196	3,913	(1)	(1)	11.66	1.646	1.194
197	3,913	(1)	(1)	11.70	1.651	1.198
198	3,913	(1)	(1)	15.72	2.110	1.328
199	3,913	(1)	(1)	15.76	2.115	1.338
200	3,913	46.60	1.074	12.07	1.670	1.200
201	3,913	58.00	.827	15.85	2.170	1.299
216	3,913	19.50	1.620	4.32	1.168	1.053
217	3,913	34.20	1.286	9.08	1.429	1.119

[1] These values were not computed since these runs were made for purposes other than the determination of power and air delivery.

TABLE V

EXPERIMENTAL DATA USED FOR DETERMINING THE EFFECTS OF IMPELLER SPEED AND DISPLACEMENT

[8.25-inch supercharger]

Run No.	Speed (impeller) (R. P. M.)	Horse-power	Air weight (lb. per sec.)	Pressure difference (In. Hg.)	Pressure ratio	Temperature ratio
			Test 1			
No runs made at 5,283 impeller R.P.M.				----------	----------	----------
			Test 2			
115	5,283	21.06	2.225	2.96	1.109	1.047
116	5,283	21.60	2.220	3.00	1.110	1.050
117	5,283	26.87	2.133	4.30	1.164	1.063
118	5,283	26.87	2.125	4.30	1.164	1.063
119	5,283	36.45	1.953	6.17	1.255	1.090
120	5,283	36.38	1.933	6.17	1.245	1.094
121	5,283	48.05	1.738	8.60	1.394	1.136
122	5,283	48.00	1.751	8.64	1.397	1.137
123	5,283	57.48	1.596	10.20	1.508	1.177
124	5,283	57.24	1.595	10.20	1.508	1.178
			Test 3			
222	5,283	27.15	2.106	4.42	1.169	1.066
223	5,283	36.70	1.837	6.43	1.267	1.091
224	5,283	45.37	1.797	8.24	1.372	1.116
225	5,283	58.20	1.648	10.23	1.510	1.167
226	5,283	35.45	1.973	6.10	1.251	1.100

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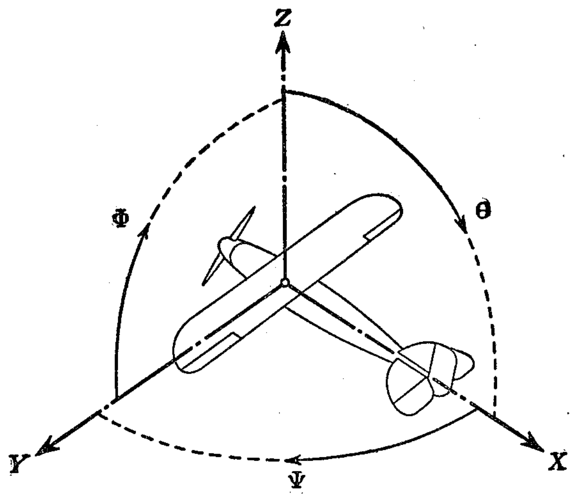

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	rolling	L	$Y \longrightarrow Z$	roll	Φ	u	p
Lateral	Y	Y	pitching	M	$Z \longrightarrow X$	pitch	Θ	v	q
Normal	Z	Z	yawing	N	$X \longrightarrow Y$	yaw	Ψ	w	r

Absolute coefficients of moment

$$C_L=\frac{L}{qbS}\quad C_M=\frac{M}{qcS}\quad C_N=\frac{N}{qfS}$$

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter.
p_e, Effective pitch
p_g, Mean geometric pitch.
p_s, Standard pitch.
p_v, Zero thrust.
p_a, Zero torque.
p/D, Pitch ratio.
V', Inflow velocity.
V_s, Slip stream velocity.

T, Thrust.
Q, Torque.
P, Power.
(If "coefficients" are introduced all units used must be consistent.)
η, Efficiency $= T\,V/P$.
n, Revolutions per sec., r. p. s.
N, Revolutions per minute., R. P. M.
Φ, Effective helix angle $=\tan^{-1}\left(\frac{V}{2\pi rn}\right)$

5. NUMERICAL RELATIONS

1 HP = 76.04 kg/m/sec. = 550 lb./ft./sec.
1 kg/m/sec. = 0.01315 HP.
1 mi./hr. = 0.44704 m/sec.
1 m/sec. = 2.23693 mi./hr.

1 lb. = 0.4535924277 kg.
1 kg = 2.2046224 lb.
1 mi. = 1609.35 m = 5280 ft.
1 m = 3.2808333 ft.