REPORT No. 645

CORRECTION OF TEMPERATURES OF AIR-COOLED ENGINE CYLINDERS FOR VARIATION IN ENGINE AND COOLING CONDITIONS

By Oscar W. Schey, Benjamin Pinkel, and Herman H. Ellerbrock, Jr.

SUMMARY

Factors are obtained from semiempirical equations for correcting engine-cylinder temperatures for variation in important engine and cooling conditions. The variation of engine temperatures with atmospheric temperature is treated in detail, and correction factors are obtained for various flight and test conditions, such as climb at constant indicated air speed, level flight, ground running, take-off, constant speed of cooling air, and constant mass flow of cooling air.

Seven conventional air-cooled engine cylinders enclosed in jackets and cooled by a blower were tested to determine the effect of cooling-air temperature and carburetor-air temperature on cylinder temperatures. The cooling-air temperature was varied from approximately 80° F. to 230° F. and the carburetor-air temperature from approximately 40° F. to 160° F. Tests were made over a large range of engine speeds, brake mean effective pressures, and pressure drops across the cylinder. The correction factors obtained experimentally are compared with those obtained from the semiempirical equations and a fair agreement is noted.

INTRODUCTION

In present-day air-cooled engines of high specific output, cooling is very often the factor that limits engine performance. As a result, several problems arise which require that cooling data obtained at one set of test conditions be converted to apply at another. Because of the strict limits set on maximum cylinder temperatures in acceptance tests and because of the difficulty of obtaining a standard set of test conditions both in flight and on the ground, a method is required for correcting the engine-cylinder temperatures to the standard conditions. It is very often necessary to predict cylinder temperatures at altitude from tests made on the ground and cylinder temperatures in the summer from tests made in the winter.

The correction of cylinder temperature for variation in atmospheric temperature is of particular interest to persons concerned with acceptance tests. In the past, several methods have been used for making this correction.

In May 1933 the Chief of the Bureau of Aeronautics, Navy Department, issued to the inspector of naval aircraft the following corrections to be applied to observed cylinder temperatures for change in strut air temperatures: "1.5° F. for every 1° F. strut air for the cylinder-head temperatures and 0.5° F. for every 1° F. strut air for the cylinder-base temperatures."

The Army Air Corps has issued the following instructions for correcting engine-cylinder temperatures: "In determining temperatures for satisfactory operation to be encountered with anticipated summer temperatures, a correction will be added to the actual recorded temperature and the corrected temperature will be the anticipated engine summer temperature. This correction is the difference between the actual air temperature and the anticipated summer air temperature for the particular altitude and it is added directly to all engine temperatures to determine the anticipated summer temperature in each case."

Campbell (reference 1) obtained a correction factor of 1; that is, for every degree rise in air temperature, there is a 1° F. rise in cylinder temperature for a constant-velocity condition. The Army and Navy methods did not specify the conditions for which the corrections applied and it is to be assumed that they were to be applied to all flight conditions.

Besides affecting the temperature of the cooling air, the variation in atmospheric temperature affects other factors that, in turn, influence the engine cooling; for example, the density of the cooling air, the speed of the airplane, the engine power, and the temperature of the mixture at the intake manifold. It is thus evident that the value of the correction factor for variation of cylinder temperature with atmospheric temperature will depend to some extent on the type of test to which it is to be applied.

An expression for the correction factor as a function of the test conditions will be obtained from equations for the rate of transfer of heat from the engine gas to the cylinder wall and from the cylinder wall to the cooling air. Under Application of Results, curves of this function will be presented and an explanation will be given of the procedure by which the correction factors may be readily determined without reference to the analysis. A table has been prepared covering correction factors for flight and ground conditions of: climb at a designated air speed, level flight at a given pressure altitude, stationary on ground at a given atmospheric pressure, constant airplane velocity, and constant mass flow of cooling air. From this table, a close estimate of the correction factor may be rapidly obtained. A discussion of the table is included later in the report.

In any maneuver of short duration in which there is a sudden increase of power or decrease of cooling-air velocity, the cylinder temperatures, because of the time required for temperatures to stabilize, will depend on the time necessary for the completion of the maneuver. In such cases, the correction factor for the variation of atmospheric temperature will depend on the effect of atmospheric temperature upon the time duration of the maneuver. An equation will be derived for the cylinder temperature as a function of the engine and the cooling conditions and the time. The effect of variation of atmospheric temperature upon cylinder temperature for the take-off and the climb condition will be discussed.

The results of tests made at the request of the Bureau of Aeronautics, Navy Department, by the N. A. C. A. at Langley Field, Va., during 1934, 1935, and 1936 to determine the effect of atmospheric temperature on cylinder temperatures for seven service cylinders at various operating conditions are given in this report.

DISCUSSION OF PROBLEM

Cylinder temperature as a function of engine and cooling conditions.—As a starting point in the analysis, the equations for the transfer of heat from the combustion gases to the engine cylinder and from the cylinder to the cooling air will be reviewed. It has been shown in reference 2 that the rate of heat transfer (B. t. u. per hr.) from the combustion gases to the cylinder head may be written, as a good first approximation,

$$H=\overline{B}a_1I^{n'}(T_g-T_h) \tag{1}$$

and the rate of heat transfer from the cylinder head to the cooling air may be written

$$H_1=Ka_0(\Delta p\rho/\rho_0)^m(T_h-T_a) \tag{2}$$

where H is the heat transferred per unit time from combustion gases to cylinder head, B. t. u. per hr.

$\overline{B}$ and K, constants.

a_1, internal area of head of cylinder, sq. in.

I, indicated horsepower of each cylinder.

n' and m, exponents.

T_g, effective gas temperature, °F.

T_h, average temperature over the cylinder-head surface when equilibrium is attained, °F.

H_1, heat transferred per unit time from cylinder head to cooling air, B. t. u. per hr.

a_0, outside wall area of head of cylinder, sq. in.

Δp, pressure drop across cylinder, in. of water (includes loss out exit of baffle).

ρ, average density of cooling air, lb. ft.$^{-4}$ sec.^{2}

ρ_0, density of air at 29.92 in. Hg and 70° F., lb. ft.$^{-4}$ sec.^{2}

T_a, inlet temperature of cooling air, °F. (temperature of atmosphere).

(For convenience, a complete list of the symbols used is given in an appendix.)

For equilibrium the rate of heat transfer to the cylinder head is equal to the rate of heat transfer away from the cylinder head and, solving equations (1) and (2) for T_h, the following equation is obtained

$$T_h=\frac{T_g-T_a}{\frac{Ka_0(\Delta p\rho/\rho_0)^m}{\overline{B}a_1I^{n'}}+1}+T_a \tag{3}$$

Equation (3) gives the average head temperature as a function of the important engine and cooling variables. A set of equations similar to (1), (2), and (3) may be written for the barrel. In the following discussion, wherever an equation is derived for the head, it is to be remembered that a parallel equation applies for the barrel. The values for Ka_0, $\overline{B}a_1$, m, and n' were obtained from blower-cooling tests on Pratt & Whitney cylinders 1340-H and 1535 (reference 2) and are given in the following table.

Cylinder	Ka_0		$\overline{B}a_1$		m		n'	
	Head	Barrel	Head	Barrel	Head	Barrel	Head	Barrel
1340-H	78.1	33.0	5.22	2.77	0.34	0.34	0.64	0.64
1535	34.5	17.1	2.71	--------	.35	.31	.68	--------

The values for $\overline{B}a_1$, m, and n' should be about the same for a cowled engine under flight conditions and Ka_0 should be somewhat higher. The form of equation (3) was checked by flight tests on a Grumman Scout airplane equipped with a Pratt & Whitney 1535 engine (references 2 and 3).

It is also shown in reference 2 that the temperature of the combustion gases T_g is dependent on the air-fuel ratio, the compression ratio, the carburetor-air temperature, and the spark setting and, as a good first approximation, is independent of the engine speed and the brake mean effective pressure. Curves obtained from reference 2 showing the variation of T_g with air-fuel ratio, spark setting, and carburetor-air temperature for a Pratt & Whitney 1340–H cylinder and with air-fuel ratio for a Pratt & Whitney 1535 cylinder are reproduced in figure 1. In the range to the rich side of the theoretically correct mixture, T_g increases from approximately 1,100° F. at an air-fuel ratio of 10.5 to 1,150° F. at 12.5, and to 1,200° F. at 14.5. The foregoing values apply for a carburetor-air temperature of about 80° F. A 1° F. variation in the carburetor-air temperature produces approximately a ½° F. variation in T_g.

For the barrel, T_g has a value of about 600° F. at an air-fuel ratio of 12.5 and a carburetor-air temperature of 80° F. The effect of carburetor-air temperature on T_g for the barrel is about the same as for the head.

By a rearrangement of terms, equation (3) may also be written

$$\frac{T_g-T_h}{T_h-T_a}I^{n'}=\frac{Ka_0}{Ba_1}(\Delta p\rho/\rho_0)^m$$

Thus, for a given engine installed on a given airplane, a straight line is obtained when $\frac{T_g-T_h}{T_h-T_a}I^{n'}$ is plotted against $\Delta p\rho/\rho_0$ on logarithmic coordinates. The slope of the line will be equal to m and the intercept at $\Delta p\rho/\rho_0=1$ will be equal to Ka_0/Ba_1. All the temperature data for the given installation should fall on this curve provided, in each case, that the equilibrium temperature has been attained. It is evident that the temperature T_h corresponding to any desired set of test conditions within the useful range can be calculated from this curve. A curve of this type is shown in figure 12 of reference 2.

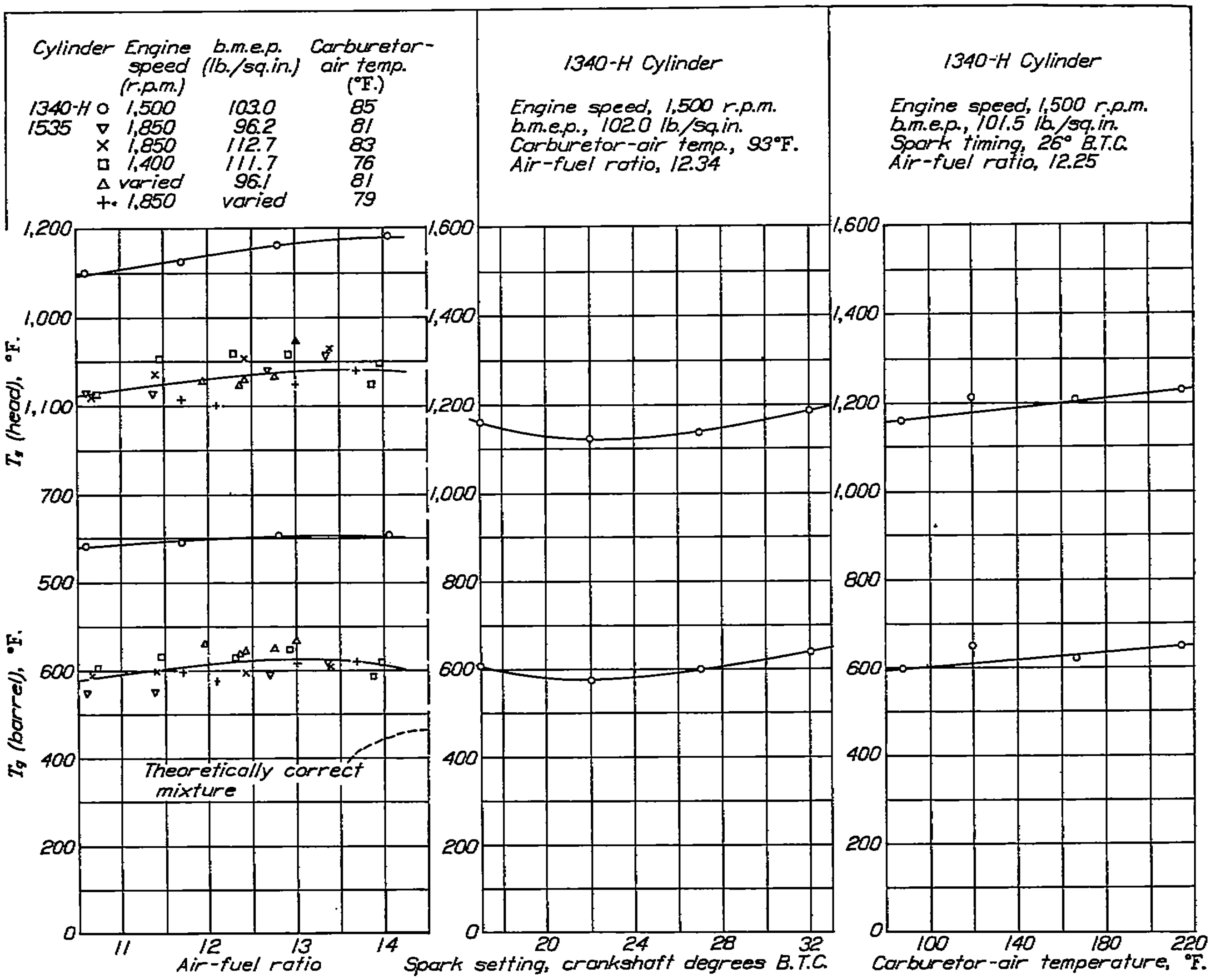


FIGURE 1.—Effect of air-fuel ratio, spark setting, and carburetor-air temperature on T_g (curves from reference 2).

Change in cylinder temperature with change in engine and cooling conditions.—For a constant mass flow, engine horsepower, and T_g, the variation of T_h with T_a is obtained by differentiating equation (3):

$$\alpha=\frac{\partial T_h}{\partial T_a}=\frac{\dfrac{Ka_0(\Delta p\rho/\rho_0)^m}{\bar{B}a_1I^{n'}}}{\dfrac{Ka_0(\Delta p\rho/\rho_0)^m}{\bar{B}a_1I^{n'}}+1}=\frac{T_g-T_h}{T_g-T_a} \qquad (4)$$

where α, which may be called the "basic temperature correction factor" is the change in cylinder-head temperature per degree change in cooling-air temperature. Figure 2 shows α for the head and the barrel plotted against the average head and barrel temperatures for various values of T_a and T_g.

If variations also occur in the density, the pressure drop, the indicated horsepower, and in T_g, then the increment in cylinder-head temperature for a small change in these factors is given by

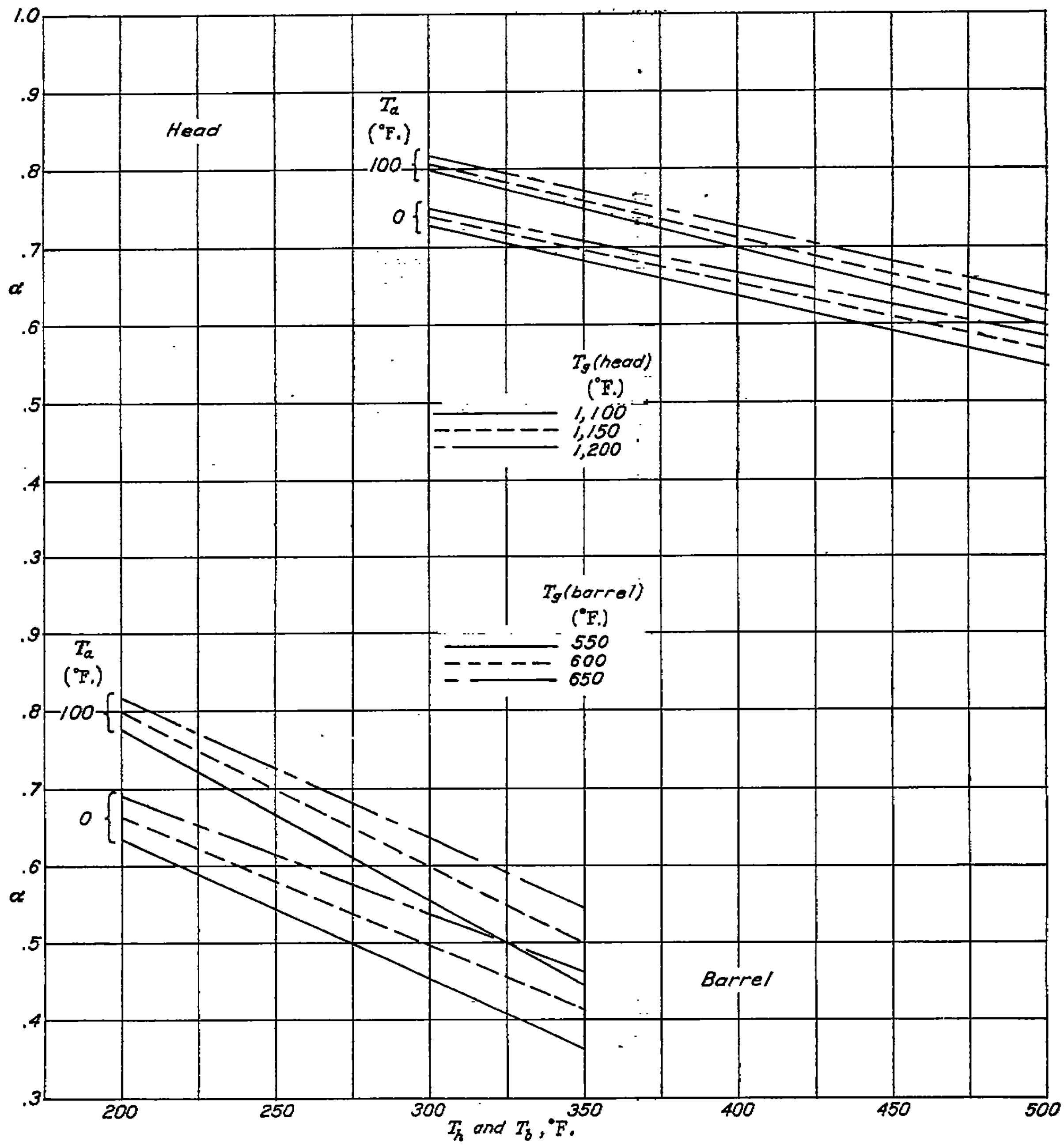


FIGURE 2.—Effect of cylinder temperature T_h or T_b on α at various values of T_a and T_g. Head, $\alpha=(T_g-T_h)/(T_g-T_a)$. Barrel, $\alpha=(T_g-T_b)/(T_g-T_a)$.

$$dT_h=\frac{\frac{Ka_0(\Delta p\rho/\rho_0)^m}{\overline{B}a_1I^{n'}}}{\frac{Ka_0(\Delta p\rho/\rho_0)^m}{\overline{B}a_1I^{n'}}+1}\left[dT_a-m(T_h-T_a)\frac{d(\Delta p\rho/\rho_0)}{\Delta p\rho/\rho_0}+n'(T_h-T_a)\frac{dI}{I}\right]+\frac{dT_g}{\frac{Ka_0(\Delta p\rho/\rho_0)^m}{\overline{B}a_1I^{n'}}+1}$$

With α as previously defined,

$$\frac{dT_h}{T_h-T_a}=\alpha\frac{dT_a}{T_h-T_a}+\frac{(1-\alpha)}{T_h-T_a}dT_g-m\alpha\frac{d(\Delta p\rho/\rho_0)}{\Delta p\rho/\rho_0}+n'\alpha\frac{dI}{I} \quad (5)$$

Thus, for small changes in the variables T_a, T_g, $\Delta p\rho/\rho_0$, and I, T_h is increased by the amounts αdT_a and $(1-\alpha)dT_g$ and a percentage change in T_h-T_a is effected equal to $-m\alpha$ times the percentage change in $\Delta p\rho/\rho_0$ and $n'\alpha$ times the percentage change in I. For example, with $\alpha=0.8$, $m=0.34$, and $n'=0.64$, a 10° F. increase in each of T_a and T_g causes an 8° F. and a 2° F. increase in T_h, respectively. A 10-percent change in each of $\Delta p\rho/\rho_0$ and I causes a -2.7-percent and a 5.2-percent change in T_h-T_a. Similar relations may be obtained for the barrel. The values of m and n' are about the same for the barrel as for the head but, as seen from figure 2, α is slightly lower for the barrel.

From equation (4)

$$T_h-T_a=(1-\alpha)\ (T_g-T_a) \quad (6)$$

and equation (5) may be written

$$dT_h=\alpha dT_a+(1-\alpha)dT_g-m\alpha(1-\alpha)(T_g-T_a)\frac{d(\Delta p\rho/\rho_0)}{\Delta p\rho/\rho_0}+n'\alpha(1-\alpha)(T_g-T_a)\frac{dI}{I} \quad (7)$$

It is evident from equations (4), (5), and (7) that, when the values of T_g or α are known, the variation in cylinder temperature with engine and cooling conditions can be determined for any test condition.

The present tests of seven service cylinders were made to determine the values of α and T_g for a range of engine conditions. Tests were also made to obtain the effect of carburetor-air temperature on T_g and cylinder temperature.

Effect of variation in atmospheric temperature on cylinder temperature at constant pressure altitude.—For tests in which atmospheric temperature is changed, in addition to changes in T_a, there are generally introduced changes in T_g, $\Delta p\rho/\rho_0$, and I. These changes depend on the specific tests under consideration.

As the pressure drop across the cylinder in a given flight condition depends on the atmospheric density and the airplane velocity, and the velocity depends on the engine power, the assumption will be made that $\rho\Delta p$ is proportional to ρ^xI^y. From this relation between $\rho\Delta p$ and ρ^xI^y, there is obtained

$$\frac{d(\Delta p\rho/\rho_0)}{\Delta p\rho/\rho_0}=x\frac{d\rho}{\rho}+y\frac{dI}{I}$$

Since ρ varies inversely as the absolute atmospheric temperature,

$$\frac{d\rho}{\rho}=-\frac{dT_a}{T_a+460}$$

With regard to carburetor-air temperature T_c, two conditions will be considered, one in which the carburetor-air temperature is equal to the atmospheric temperature, and the other in which it is held constant by means of a carburetor-air heater. The relation between the carburetor-air temperature and the atmospheric temperature for these two cases may then be expressed by

$$dT_c=zdT_a$$

where $z=1$ for the first case mentioned and $z=0$ for the second case. Then, as the indicated horsepower for a constant manifold pressure varies inversely as the square root of the absolute carburetor temperature,

$$\frac{dI}{I}=\frac{d(T_c+460)^{-1/2}}{(T_c+460)^{-1/2}}=-z\frac{dT_a}{2(T_a+460)}$$

Let

$$b=\frac{dT_g}{dT_c}$$

Then

$$dT_g=\frac{dT_g}{dT_c}\frac{dT_c}{dT_a}dT_a=bzdT_a$$

Inserting the foregoing quantities in equation (7) and combining

$$\frac{dT_h}{dT_a}=\alpha_\lambda=\alpha\left[1+0.34\lambda\frac{(1-\alpha)(T_g-T_a)}{T_a+460}\right]+zb(1-\alpha) \quad (8)$$

where

$$\lambda=\frac{m}{0.34}\left[x+\frac{z}{2}\left(y-\frac{n'}{m}\right)\right] \quad (9)$$

The correction factor α_λ is the change in cylinder temperature per degree change in atmospheric temperature at a constant pressure altitude. The effect of both atmospheric pressure and temperature on cylinder temperatures can be obtained from equation (3).

The last term in equation (8) is a small correction for variation in T_g. When the carburetor-air temperature is held constant, $z=0$ and this term is zero. When the carburetor-air temperature is allowed to vary with the atmospheric temperature, $z=1$ and this term becomes $(1-\alpha)b$. The value of b, as stated in the results, will be taken equal to 0.50 for both the head and the barrel. In figure 3, the remaining term in α_λ is plotted as α_λ against λ for various values of α, T_g, and T_a. The curves pass through $\alpha_\lambda=\alpha$ at $\lambda=0$. It is noticed that, for a given value of α, the value of α_λ does not depend appreciably on the value of T_g used.

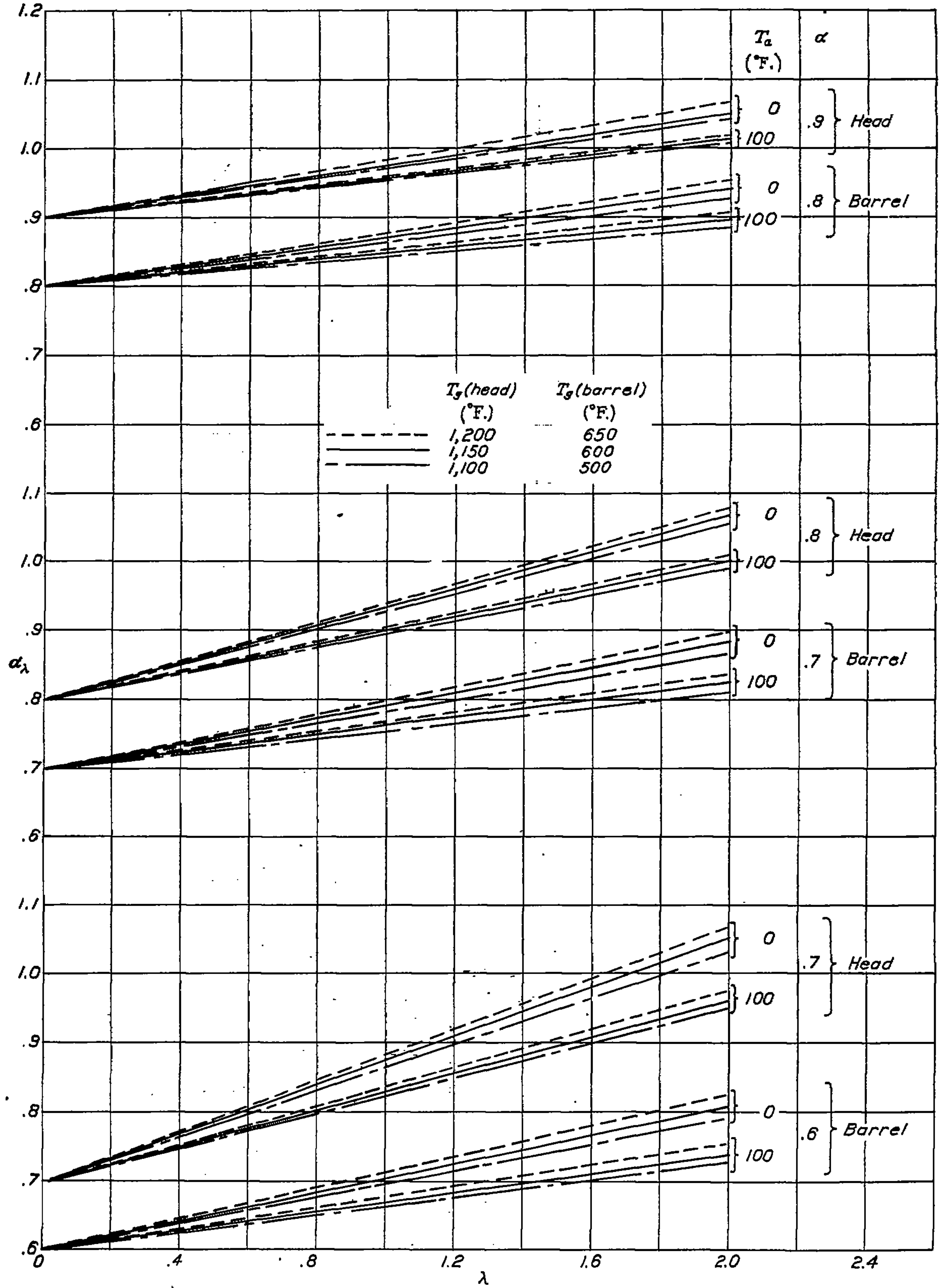


FIGURE 3.—Variation of correction factor α_λ with λ when carburetor-air temperature is constant, for various values of α, T_g, and T_a.

From figures 1, 2, and 3, it is apparent that the value of α_λ for any given average cylinder-head temperature and cooling-air temperature may be obtained, provided that the value of λ for the flight or the test condition is known. It will also be noticed that, for large temperature variations, the value of α_λ varies slightly in going from the initial to the final value of T_a and it is necessary to choose an average value for the range covered. As an added refinement after the first approximation, a corrected value of α_λ may be obtained by averaging the values at the initial and the final conditions. A number of test conditions including those of climb, level flight, ground running, and constant velocity will be considered in a later section on Application of Results.

Equation for cylinder temperature for varying operating conditions.—When the power and the cooling conditions of an engine change, time is required for the cylinder temperatures to reach their equilibrium values. For short maneuvers or for maneuvers in which the conditions are varying, the time required to complete the maneuver must be considered in the determination of the effect of atmospheric temperature on cylinder temperature.

The rate H at which heat is carried from the gas to the cylinder head is equal to the sum of the rate at which the cylinder absorbs heat and the rate H_1 at which heat is transferred to the cooling air:

$$H=cM\frac{dT_h}{dt}+H_1$$

where c is the specific heat of the head.

M, the weight of the head.

t, the time.

Substituting from equations (1) and (2) for H and H_1 respectively, there results

$$\overline{B}a_1I^{n'}(T_g-T_h)=cM\frac{dT_h}{dt}+Ka_0(\Delta p\rho/\rho_0)^m(T_h-T_a)$$

or

$$cM\frac{dT_h}{dt}+[Ka_0(\Delta p\rho/\rho_0)^m+\overline{B}a_1I^{n'}]T_h=\overline{B}a_1I^{n'}T_g+Ka_0(\Delta p\rho/\rho_0)^mT_a$$

For any given variation of Δp, ρ, I, T_g, and T_a with time, the solution for T_h is

$$T_h=e^{-\frac{1}{cM}\int_0^t Adt}\left[\int_0^t\frac{B}{cM}e^{\frac{1}{cM}\int_0^t Adt}dt+T_{h_0}\right] \qquad (10)$$

where

$$A=Ka_0(\Delta p\rho/\rho_0)^m+\overline{B}a_1I^{n'}$$
$$B=\overline{B}a_1I^{n'}T_g+Ka_0(\Delta p\rho/\rho_0)^mT_a$$

and T_{h_0} is the average temperature of the head at $t=0$.

For the case where A and B change at the time $t=0$ and thereafter remain substantially constant, equation (10) reduces to

$$T_{h_t}=T_h-(T_h-T_{h_0})e^{-\frac{At}{cM}} \qquad (11)$$

where T_h is the final average temperature that the head will reach when equilibrium is attained and is given by equation (3), and T_{h_t} is the average temperature of the head at time t. Equation (11) may be used for cases in which small variations in A occur after the initial change at $t=0$. In such cases an average of the values of A should be used.

Variation of cylinder temperature with atmospheric temperature for a maneuver of short duration.—With t now taken as equal to the time of completion of the maneuver, T_{h_t} is the temperature at the completion of the maneuver. The effect of T_a on cylinder temperature will be obtained for the case where the carburetor-air temperature and the engine power are assumed to be held constant. From equation (11), for a change in atmospheric temperature of dT_a for the pressure altitude at which the maneuver is completed and of dT_0 for the pressure altitude at which the maneuver is started, the change in T_h is given by

$$dT_{h_t}=\alpha_\lambda dT_a+(T_h-T_{h_0})\frac{tA}{cM}\left(\frac{dA}{A}+\frac{dt}{t}\right)e^{-\frac{At}{cM}}-(\alpha_\lambda dT_a-\alpha_{\lambda_0}dT_0)e^{-\frac{At}{cM}}$$

where α_{λ_0} is the correction factor, and T_0 is the temperature of the atmosphere at time $t=0$.

$$\frac{dA}{A}=\frac{mKa_0(\Delta p\rho/\rho_0)^m}{[Ka_0(\Delta p\rho/\rho_0)^m+\overline{B}a_1I^{n'}]}\frac{d(\Delta p\rho/\rho_0)}{\Delta p\rho/\rho_0}=\frac{m\alpha d(\Delta p\rho/\rho_0)}{\Delta p\rho/\rho_0}$$

As I is held constant, $\Delta p\rho/\rho_0$ may be assumed to be proportional to ρ^x and t proportional to ρ^u or to $(T+460)^{-u}$ where T is the average temperature of the atmosphere during the maneuver; then

$$\frac{dA}{A}+\frac{dt}{t}=(m\alpha x+u)\frac{d\rho}{\rho}$$

Since ρ is inversely proportional to $T+460$

$$\frac{d\rho}{\rho}=-\frac{dT}{T+460}$$

and the equation for dT_{h_t} becomes

$$dT_{h_t}=\alpha_\lambda dT_a-(T_h-T_{h_0})e^{-\frac{At}{cM}}\frac{tA}{cM}(m\alpha x+u)\frac{dT}{T+460}-(\alpha_\lambda dT_a-\alpha_{\lambda_0}dT_0)e^{-\frac{At}{cM}}$$

From equation (11)

$$e^{-\frac{At}{cM}}=\frac{T_h-T_{h_t}}{T_h-T_{h_0}}$$

and

$$\frac{At}{cM}=\log_e\frac{T_h-T_{h_0}}{T_h-T_{h_t}}$$

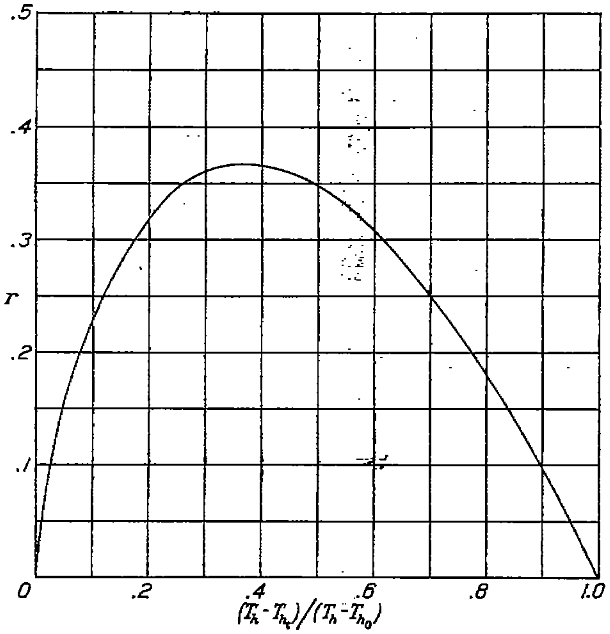


FIGURE 4.—Curve showing effect of $(T_h-T_{h_t})/(T_h-T_{h_0})$ on r.

$$r=\frac{T_h-T_{h_t}}{T_h-T_{h_0}}\log_e\frac{T_h-T_{h_0}}{T_h-T_{h_t}}$$

The quantity r is shown plotted in figure 4 against $(T_h-T_{h_t})/(T_h-T_{h_0})$. When T_{h_t} is equal to T_h, r is equal to zero and dT_{h_t} is equal to $\alpha_\lambda dT_a$. For $T_{h_t}=T_{h_0}$, r is again zero and $dT_{h_t}=\alpha_{\lambda_0}dT_0$. It is thus evident that, for very short maneuvers, the change in T_{h_t} depends, as may be expected, more on the change in T_{h_0} than on the change in T_h with atmospheric temperature. The conditions of climb to critical altitude and take-off will be considered in a later section.

APPARATUS

The apparatus consisted of a single-cylinder air-cooled engine, a supercharger for boosting carburetor-intake pressures, an electric dynamometer, a cooling system, heaters for varying the temperatures of the cooling and the carburetor air, a refrigerating system for cooling the carburetor air, and the necessary instruments to measure the factors involved. A diagrammatic sketch of the set-up is shown in figure 5 and a photograph of the engine with the cylinder enclosed in the cooling jacket is shown in figure 6.

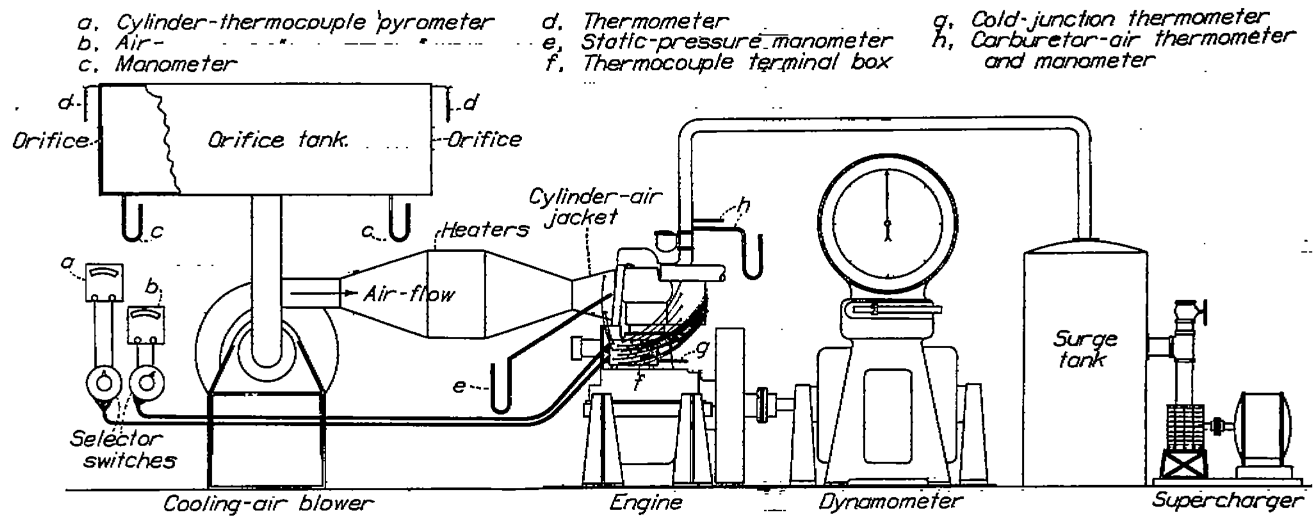


FIGURE 5.—Diagrammatic sketch of equipment.

and the equation for dT_{h_t} finally becomes

$$dT_{h_t}=\alpha_\lambda dT_a-\frac{T_h-T_{h_0}}{T+460}(max+u)rdT-(\alpha_\lambda dT_a-\alpha_{\lambda_0}dT_0)\frac{T_h-T_{h_t}}{T_h-T_{h_0}} \tag{12}$$

where
$$r=\frac{T_h-T_{h_t}}{T_h-T_{h_0}}\log_e\frac{T_h-T_{h_0}}{T_h-T_{h_t}}$$

AIR-COOLED CYLINDERS

The seven air-cooled cylinders (fig. 7) used in these tests were from the following engines: Pratt & Whitney 1340-H, 1535, 1830, and 1690 engines; and Wright 1820-F, 1820-G, and 1510 engines. They were adapted to the base of a universal test engine (reference 4). The valve movements and the timing of the single-cylinder engines were approximately the same as of the multicylinder engines. Slight changes in stroke were made on the single-cylinder engines as compared with the multicylinder engines to permit the use of available crankshafts. The bore, the stroke, and the compression ratio of the cylinders mounted on the single-cylinder test stand are given in the following table.

Cylinder	Bore (in.)	Stroke (in.)	Compression ratio
Pratt & Whitney:			
1340-H	5¾	6	5.52
1535	5³⁄₁₆	5½	6.73
1830	5½	5½	6.15
1690	6⅛	6	5.65
Wright:			
1820-F	6⅛	7	6.64
1820-G	6⅛	7	7.40
1510	5	5½	6.20

area of the exit of the jackets to the clear area between the fins for the 1340-H, 1820-F, 1690, 1820-G, and 1510 cylinders was approximately 2; for the 1535 and 1830 cylinders, the ratio was approximately 3.

TEST EQUIPMENT

An N. A. C. A. Roots supercharger was used to increase the carburetor-intake pressure during tests with manifold pressures greater than atmospheric. A tank was placed in the air duct between the supercharger and the engine to reduce pressure pulsations caused by these units. An electric dynamometer absorbed the power and measured the torque of the engine.

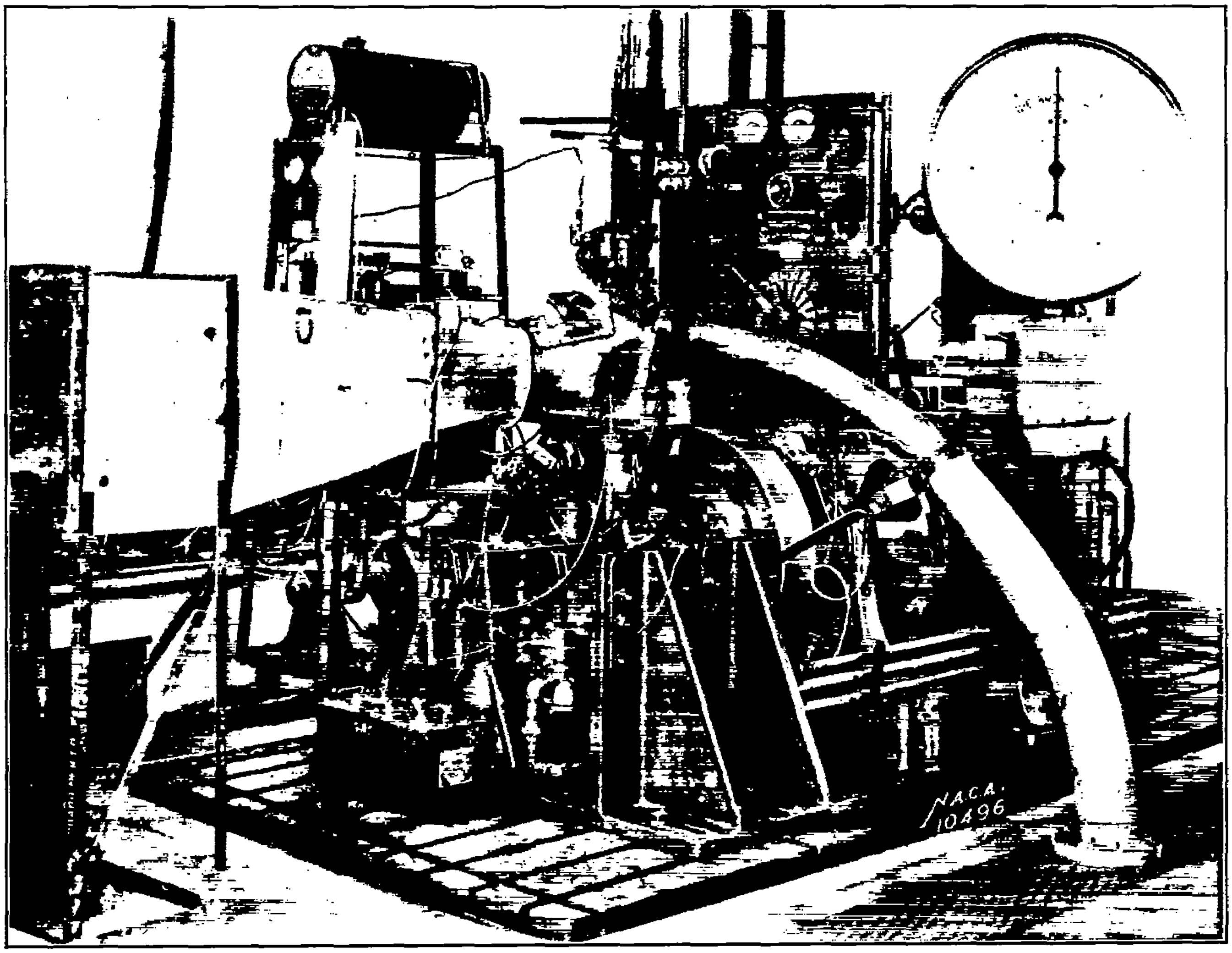


Figure 6.—Set-up of single-cylinder air-cooled engine showing jacket and air duct.

CYLINDER JACKETS

In each test, the cylinder was enclosed in a sheet-metal jacket open at front and rear. The jacket had a wide entrance section giving a low velocity of approach of the cooling air to the front half of the cylinder and fitted closely against the fins over the rear half, resulting in a high air velocity in this region. The ratio of the

The cooling system consisted of a blower to supply the cooling air, an orifice tank to measure the quantity of air, and an air duct between the blower and the jacket enclosing the cylinder. Baffles and screens were located in the air duct to insure a uniform temperature and velocity distribution.

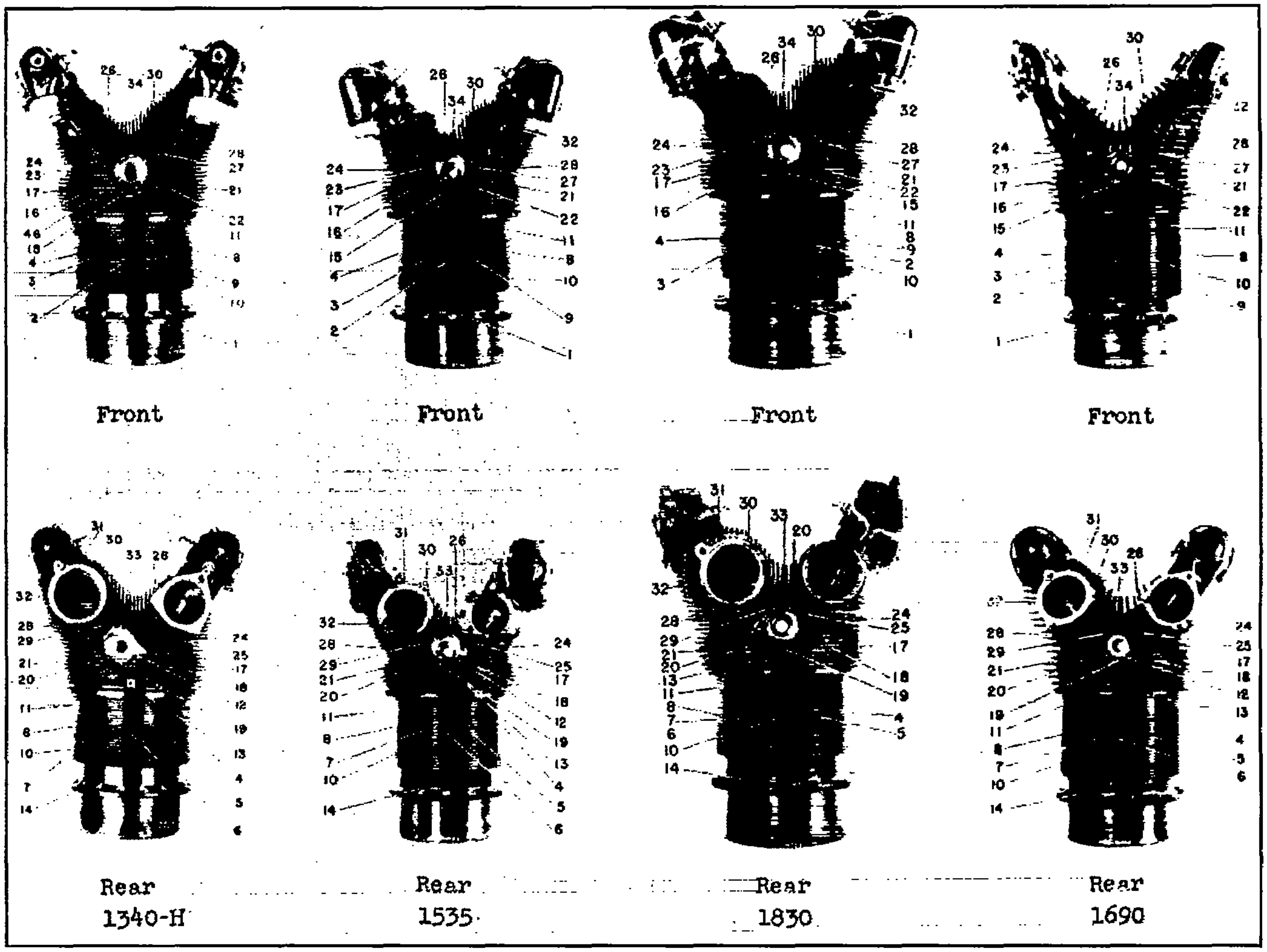


FIGURE 7 (a).—Front and rear views of cylinders from Pratt & Whitney engines showing location of thermocouples.

A 60-kilowatt heater consisting of four groups of separately controlled heating elements located in the air duct between the blower and the jacket was used for varying the temperature of the cooling air. In the tests in which the carburetor-air temperature was varied, temperatures higher than those of the room were obtained by heating the air with electric heaters placed in the intake-air line. For temperatures lower than atmospheric, the air to the carburetor was passed through a radiator submerged in a bath of kerosene into which carbon dioxide was expanded.

The standard test-engine equipment was used for measuring the engine speed and the fuel consumption.

INSTRUMENTS

Iron-constantan thermocouples and a direct-reading portable pyrometer were used to measure the cylinder temperatures. The thermocouples were made of 0.016-inch-diameter wire and were peened to the cylinder head and spot-welded to the barrel. The temperatures were measured on all cylinders by 22 thermocouples on the head, 10 on the barrel, and 2 on the flange, located as shown in figure 7. Thermocouple 12 was a standard Navy gasket-type thermocouple placed under the rear spark plug. The temperature of the cooling air at the inlet of the jacket was measured near the cylinder by 2 thermocouples connected to a sensitive galvanometer. The temperature of the cooling air at the outlet of the jacket was measured by 10 iron-constantan thermocouples. The cold junctions of all the thermocouples were placed in an insulated box. Liquid thermometers were used to measure the temperature of the air entering the orifice tank, of the cold-junction box, and of the carburetor intake.

The pressure drop across the cylinder was measured by a static tube located in the space ahead of the cylinder where the velocity head was negligible. This static tube was connected to a water manometer. A water manometer was used to measure the pressure in the orifice tank and a mercury manometer was used to measure the carburetor-intake pressure.

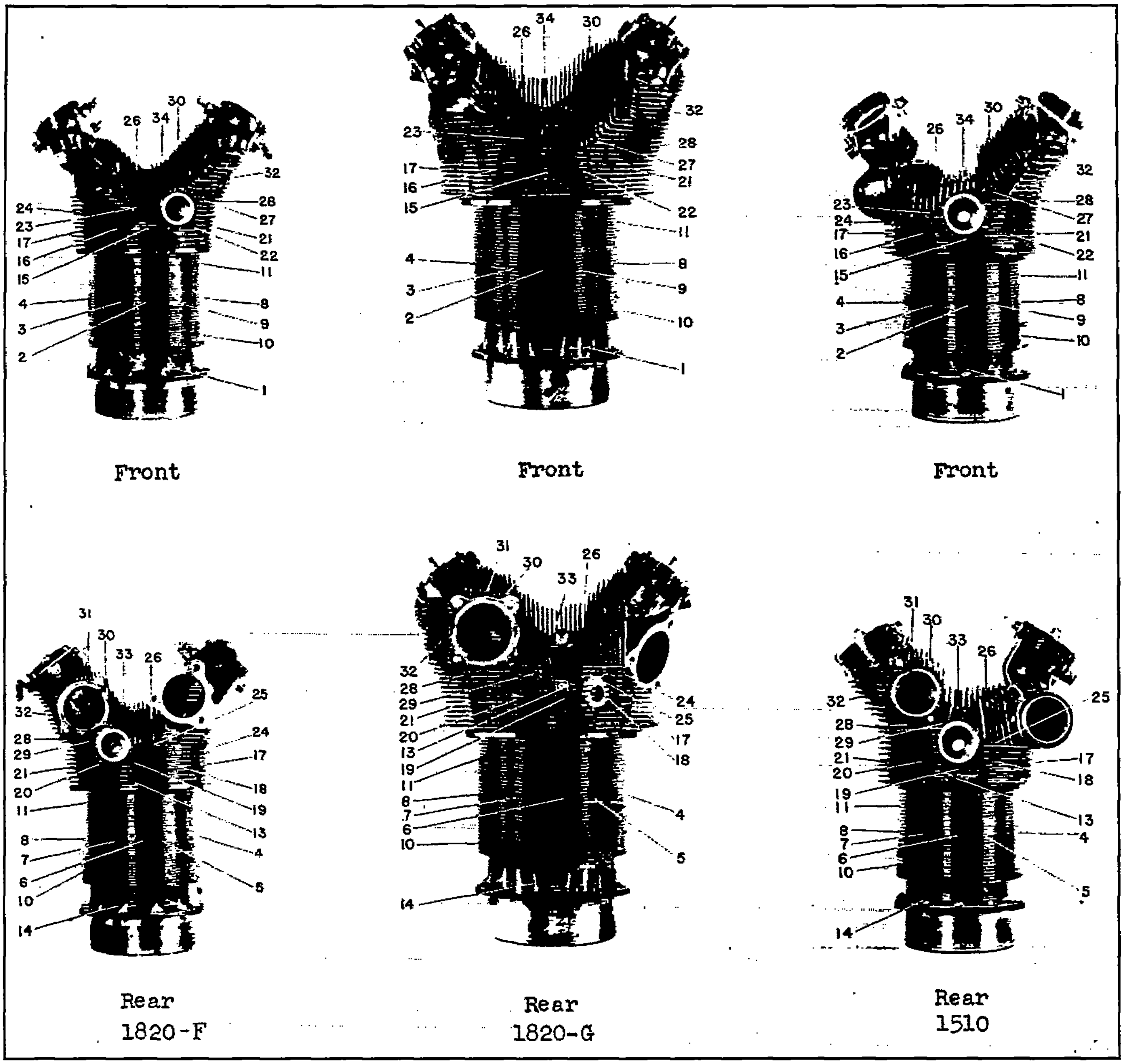


FIGURE 7 (b).—Front and rear views of cylinders from Wright engines showing location of thermocouples.

TESTS

Tests were made of the seven cylinders to determine the values of α and T_s at various engine speeds, indicated horsepowers, and mass flows of the cooling air. A list of the test conditions covered is given in table I. In each test the engine power, the engine speed, the air-fuel ratio, the carburetor-air temperature, the oil temperature, the spark timing, and the mass flow of the cooling air were held constant and the cooling-air temperature was varied. The range of the cooling-air temperatures in most of the tests was from 80° F. to 230° F. The α in a given test for each of the 34 thermocouples was determined by plotting the temperature measured by the thermocouple against the cooling-air temperature and obtaining the slope of the resulting straight line.

From equation (1) it is evident that, with engine conditions held constant, H is zero when T_h is equal to T_s; and from equation (2) it is apparent that at equilibrium, for a constant value of the mass flow, H is proportional to $T_h - T_a$.

Thus, in the foregoing tests when the average temperature difference between the cylinder head and the cooling air is plotted against the average head temperature, the value of T_h at which $T_h - T_a$ is zero is equal to T_g. The value of T_g for the barrel may be obtained in a similar manner. The procedure is illustrated in figure 8. A straight line is drawn through the points

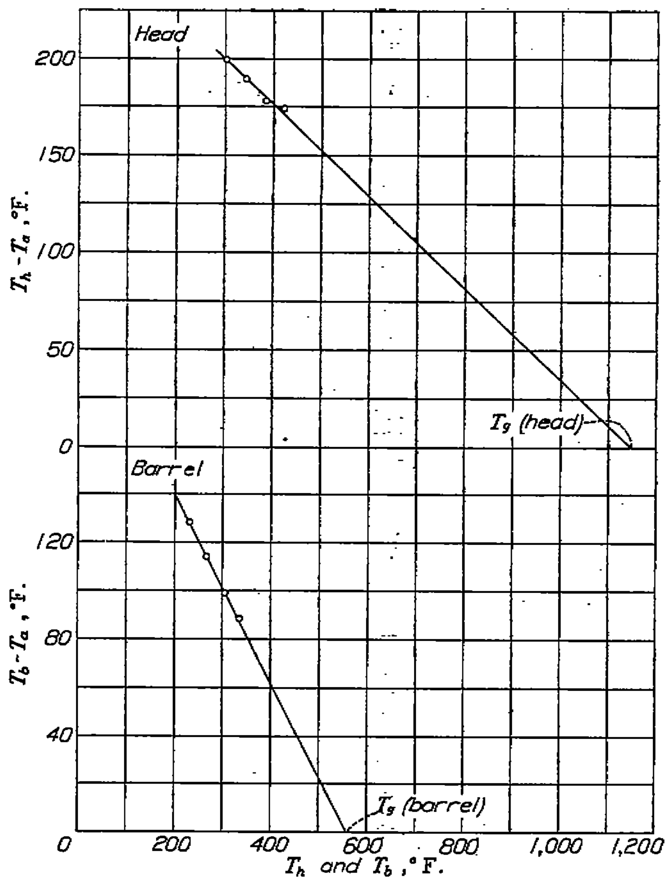


FIGURE 8.—Values of T_g for head and barrel of 1830 cylinder:

Series	4′
Engine speed, r. p. m.	1,518
Indicated horsepower	28.57
Indicated mean effective pressure, lb./sq. in.	114.1
$\Delta p \rho/\rho_0$, in. of water	15.27
Carburetor-air temperature, °F	94
Fuel consumption, lb./i. hp./hr	0.486

and extrapolated to the horizontal axis. Because of the large range through which the extrapolation is made, the value so obtained is approximate.

Additional tests were made of the 1340–H, 1535, 1820–F, 1830, and 1510 cylinders, for which the cooling conditions and the engine power were held constant and the carburetor-air temperature was varied. It was necessary to readjust the throttle setting at each new carburetor-air temperature to maintain constant power.

From equation (7) it is evident that for this case

$$aT_h = (1-\alpha)dT_g$$

or

$$dT_g = \frac{T_g - T_a}{T_h - T_a} dT_h$$

The quantity b is then given by the following expression:

$$b = \frac{dT_g}{dT_c} = \frac{T_g - T_a}{T_h - T_a} \frac{dT_h}{dT_c}$$

The value of b was obtained as indicated by plotting T_h against T_c, obtaining the slope, and multiplying by $(T_g - T_a)/(T_h - T_a)$, where the values of T_g and T_h were taken corresponding to a carburetor-air temperature equal to atmospheric temperature. The value of b obtained in this manner is approximate but, since the effect of variation of T_g on T_h is small, an accurate value is not required.

During each test, observations were made of the engine torque, the engine speed, the fuel consumed, the carburetor-intake pressure and temperature, the spark setting, the temperature of the air entering the orifice tank, the temperature of the cooling air entering and leaving the jacket, the cylinder temperatures, the pressure drop across the orifice tank, the pressure at the entrance of the jacket, and the barometric pressure.

The weight of the cooling air was controlled by varying the speed of the blower. The carburetor-intake pressures were varied either by throttling the intake or by boosting with the supercharger.

Gasoline conforming to Army Specification Y–3557 and having an octane number of 87 was used for most tests. For the most severe conditions, ethyl fluid was added to the gasoline in a sufficient amount to suppress audible knock.

COMPUTATIONS

The engine horsepowers given in this report are all observed values and were calculated from the corrected dynamometer-scale reading and the engine speed. The method of computing the cooling-air weight is given in detail in reference 5.

The cylinder temperatures, the inlet cooling-air temperatures, and the outlet cooling-air temperatures were corrected for instrument calibration and cold-junction temperature.

The specific fuel consumption was calculated from the observed weight of fuel used, the time required to use this fuel, and the indicated horsepower.

The pressure drop obtained from the static tube placed in front of the cylinder included both the drop across the cylinder and the loss out the exit of the jacket. It is denoted by the symbol Δp in this report and is given in inches of water.

RESULTS

Experimental values of α.—The experimental values of α for the various points on the cylinder showed no consistent trend with either the location or the temperature of the points, except that the values on the head grouped about a common value and the values on the barrel grouped about another value. It was also found that thermocouple locations on the cylinder which had higher than average α's in some tests had lower than average α's in others and, again, no consistent trend could be detected. It was, therefore, considered expedient to average the values of α for the head and the barrel separately and to present these values in this paper as the correction factors. The values of α are shown in table II.

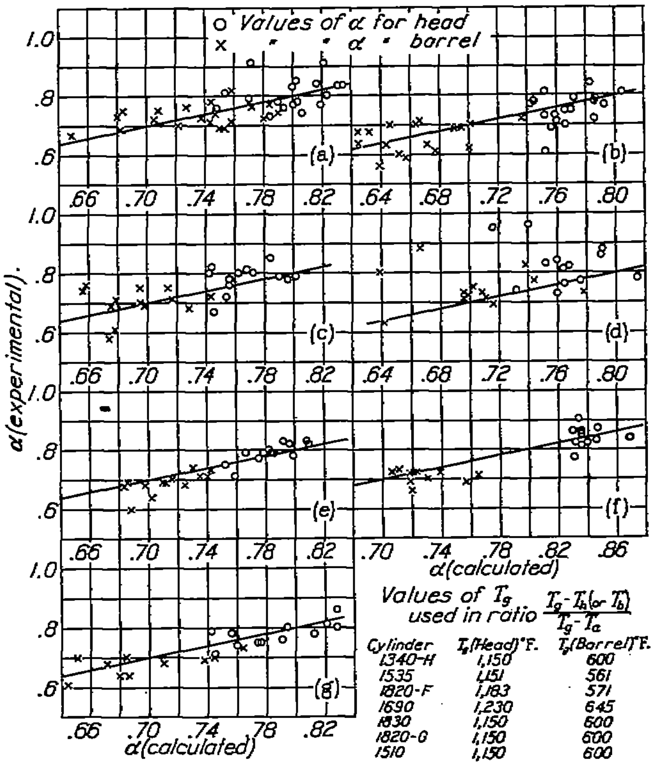
Effective gas temperature T_g.—The values of T_g were obtained in the manner previously described and are listed in table I. An average value of T_g was obtained as representative of the cylinder for average test conditions and is listed at the bottom of the column in table I. Most of the average values for the head and the barrel were close to 1,150° F. and 600° F., respectively. The largest deviation from these values occurred for the 1690 and 1820–F cylinders and for the barrel of the 1535 cylinder. As shown in figure 1, the values of T_g vary with the spark timing, the air-fuel ratio, and the carburetor-air temperature. The foregoing values hold for a normal spark timing, a carburetor-air temperature of approximately 80° F., and an air-fuel ratio of approximately 12.5 and agree fairly well with the values given in figure 1.

Calculated values of α.—The values of α for the various test conditions were calculated, making use of equation (4), and are shown in table II. The values of T_g used (see table II) were 1,150° F. for the head and 600° F. for the barrel except for the 1690, 1820–F, and 1535 cylinders, for which the average values of T_g shown in table I were used. The values of T_h, T_b, and T_a used correspond to the condition in which no heat was added to the cooling air by the electric heaters. The values of α were calculated for the 1510 cylinder, using the values of T_a, T_b, and T_h corresponding to maximum cooling-air temperature and are shown in table III. Comparison of these values with the calculated values shown in table II for the 1510 cylinder shows very little difference, as is to be expected.

The experimental values of α are plotted in figure 9 against the calculated values. A line is drawn in each figure for a 1:1 correspondence between the calculated and the experimental values. The points fall about each line and, although the scatter is wide, the same general trend is indicated.

Experimental values of b.—The values of b, the ratio of increase of T_g with increase of carburetor-air temperature, were obtained in the manner already described. The variation of cylinder temperature with carburetor temperature was small, of the order of 15° F. increase in cylinder temperature per 100° F. rise in carburetor-air temperature. It is apparent that small extraneous variations in cylinder temperature due to variation in other conditions would introduce a large percentage error in the value of b; however, because of the small effect of variation of T_g on cylinder temperature, the value of b need not be very accurately known. The values of b obtained from several tests of the various cylinders are listed in table IV.

As there is no apparent reason for a large difference between the values of b for the various cylinders, an average was taken of all the available values. An average value of 0.38 is obtained as compared with the



(a) 1340–H cylinder.
(b) 1535 cylinder.
(c) 1820–F cylinder.
(d) 1690 cylinder.
(e) 1830 cylinder.
(f) 1820–G cylinder.
(g) 1510 cylinder.

FIGURE 9.—Experimental against calculated values of α.

value of 0.58 obtained from figure 1. In the present report a value of $b=0.5$ will be used in making the computations. The term containing b in equation (8) occurs only in cases where the carburetor-air temperature is allowed to vary with the atmospheric temperature and, for these cases, an uncertainty in the computed value of α_λ equal to 50 percent of $b(1-\alpha)$ will exist when the foregoing value of b is used. In most cases, this uncertainty will be a small percentage of α_λ.

APPLICATION OF RESULTS

The correction factors for the variation of cylinder temperature with atmospheric temperature will be considered for the following cases:

A. Constant carburetor-air temperature and engine power.
   1. Climb at constant indicated air speed to a given pressure altitude.
   2. Level flight at a given pressure altitude.
   3. Stationary on ground at a given barometer.
   4. Constant airplane velocity.
   5. Constant mass flow.

B. Carburetor-air temperature equal to and varying with atmospheric temperature; engine power varying with carburetor-air temperature; constant manifold pressure; and constant engine speed.

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1. Climb at constant indicated air speed to a given pressure altitude.
2. Level flight at a given pressure altitude.
3. Stationary on ground at a given barometer.

C. Maneuvers of short time duration. Constant carburetor-air temperature and engine power.

1. Climb to critical altitude.
2. Take-off.

Cases A and B refer to equilibrium conditions and case C refers to varying conditions.

In the following calculations, the values given for the Pratt & Whitney 1340–H cylinder in the earlier Discussion of the Problem will be used for m and n'. The values of m and n' for other cylinders differ only by a slight amount from these values and will introduce only a small difference in α_λ.

Throughout the rest of the report, the problem will be simplified by taking the average density of the air flowing around the cylinder as equal to the atmospheric density. This assumption introduces no appreciable error as the two densities are practically proportional and it is only the percentage density change that is of consequence in the analysis.

CONSTANT CARBURETOR-AIR TEMPERATURE AND ENGINE POWER

From the relation given earlier, that $\rho\Delta p$ may be written proportional to $\rho^x I^y$, it is evident in the present case (constant engine power) that $y=0$. It has also been stated earlier that $z=0$ when the carburetor-air temperature is held constant. Thus, for the cases noted under A, the values of y and z in equations (8) and (9) are zero and $\lambda=x$. The value of x will be found for the various cases.

Climb at constant indicated air speed (A–1).—For climb at constant indicated air speed,

$$\rho V^2=\text{constant}$$

where V is the true velocity of the airplane.

As $\quad \Delta p=K_1\rho V^2$

then $\quad \rho\Delta p=\rho\times\text{constant}$

and, thus, $x=1$.

The correction factor α_λ may be obtained from figure 3 for $\lambda=1.0$ for various values of T_a and T_g; it applies for the case of slow climbs in which the final equilibrium temperature is very nearly reached. For fast-climbing airplanes, the cylinder temperature lags behind the equilibrium temperature and the effect of atmospheric temperature on the time of duration of the climb must also be considered in obtaining the correct factor. This case will be discussed later.

Level flight at a given pressure altitude (A–2).—At the level-flight condition

$$K_3 C_D \rho V^3=\text{t.hp.}$$

where K_3 is a constant and C_D is the drag coefficient. If it is assumed that the thrust horsepower remains constant for a constant engine power and that the drag coefficient is practically constant at the maximum-velocity condition in level flight, then

$$\rho V^3=\text{constant}$$

and, since $\Delta p=K_1\rho V^2$

$$\rho\Delta p=\rho^2\left(\frac{1}{\rho}\right)^{\frac{2}{3}}\times\text{constant}=\rho^{1.333}\times\text{constant}$$

For this case $x=\lambda=1.333$.

Stationary on ground at a given barometer (A–3).—From reference 6 a relation may be obtained between the nondimensional quantity $\sqrt{\Delta p}/\rho^{\frac{1}{2}}nD$ and the nondimensional power coefficient $P/\rho n^3D^5$ for a cowled engine stationary on the ground. This relation may be approximated by

$$\frac{\sqrt{\Delta p}}{\rho^{\frac{1}{2}}nD}=K_4\left(\frac{P}{\rho n^3D^5}\right)^{\frac{d}{2}}$$

where n, propeller speed.
P, propeller power.
D, propeller diameter.
K_4, a constant.
d, an exponent.

The exponent d may be taken as a constant for a given propeller and cowling combination and for a short range of variation of $P/\rho n^3D^5$. The values of d obtained from reference 6 were found to lie between ⅓ and ½. From the preceding relation for a given engine power, engine speed, and propeller, Δp is proportional to ρ^{1-d}, and $\rho\Delta p$ is proportional to ρ^{2-d}. The value of λ for this case lies between 1.50 and 1.666. As may be seen from figure 3, there is only a small difference between the values of α_λ for these two values of λ.

Constant airplane velocity (A–4).—The case of substantially constant airplane velocity with variations in atmospheric temperature occurs in level flight when the carburetor-air temperature and engine power are allowed to vary. This case will be taken up in section B. In some acceptance tests on a dynamometer stand, however, a constant air velocity is maintained irrespective of atmospheric temperature while carburetor-air temperature and engine power are held constant. The following factors apply in correcting the average head and barrel temperatures obtained in these tests to a standard cooling-air temperature.

$$V=\text{constant}$$
$$\rho\Delta p=K_1\rho^2V^2=\rho^2\times\text{constant}$$
$$\lambda=2$$

The correction factors for this case are the highest of those obtained. Campbell (reference 1) found that, for constant velocity, constant power, and constant carburetor-air temperature, α_λ was approximately 1.1 for the thermocouples on the head of the cylinder tested.

Corresponding to an air temperature of 70° F. (the mean of Campbell's temperatures), a value of T_g of 1,150° F., and an average of his cylinder temperatures on the head of 358° F., figure 2 gives a value of α of 0.73. With this α and a value of T_a of 70° F., figure 3 shows that, for constant velocity ($\lambda=2$), α_λ is approximately 1.0.

Constant mass flow (A–5).—It is advisable in acceptance tests conducted on the dynamometer stand, whenever possible, to maintain a standard mass flow, because then there is no correction necessary for variation of $\rho\Delta p$ since

$$\rho\Delta p=K_1\rho^2V^2=\text{constant}$$

$$\lambda=0 \text{ and } \alpha_\lambda=\alpha$$

CARBURETOR-AIR TEMPERATURE EQUAL TO AND VARYING WITH ATMOSPHERIC TEMPERATURE

Cases where the carburetor temperature is equal to and varies with the atmospheric temperature will now be considered. For these cases $z=1$.

Climb at constant indicated air speed to a given pressure altitude (B–1).—The angle of attack for optimum climb for an airplane equipped with a constant-speed propeller depends more on the angle of attack for minimum horsepower required than on the horsepower available. It may therefore be assumed that the slight variation in horsepower available due to temperature change will not appreciably affect the indicated air speed for optimum climb. As in the case of A–1

$$\rho V^2=\text{constant}$$

$$\rho\Delta p=K_1\rho^2V^2=\rho\times\text{constant}=\rho I^0\times\text{constant}$$

Thus $x=1$ and $y=0$

and from equation (9)

$$\lambda=\left[1+\frac{1}{2}\left(0-\frac{0.64}{0.34}\right)\right]=1-0.941=0.059$$

Level flight at a given pressure altitude (B–2).—In level flight at full open throttle, ρV^3 is approximately proportional to the thrust horsepower. If the thrust horsepower is assumed proportional to the indicated horsepower of the engine,

$$\rho V^3=K_5I$$

$$\rho\Delta p=K_1\rho^2V^2=\rho^{\frac{4}{3}}\,I^{\frac{2}{3}}\times\text{constant}$$

Thus

$$x=\frac{4}{3}\quad y=\frac{2}{3}$$

and

$$\lambda=\left[\frac{4}{3}+\frac{1}{2}\left(\frac{2}{3}-1.882\right)\right]=0.725$$

Stationary on ground at a given barometer (B–3).—As in case A–3,

$$\frac{\sqrt{\Delta p}}{\rho^{\frac{1}{2}}nD}=K_4\left(\frac{P}{\rho n^3D^5}\right)^{\frac{d}{2}}$$

On the assumption that the propeller power is proportional to the indicated horsepower and that the engine speed is held constant,

$$\rho\Delta p=K_6\frac{\rho^2I^d}{\rho^d}=K_6\rho^{2-d}I^d$$

Thus

$$x=2-d\quad y=d$$

and

$$\lambda=\left[2-d+\frac{1}{2}(d-1.882)\right]=1.059-\frac{d}{2}$$

When

$$d=\frac{1}{3}\quad \lambda=0.89$$

$$d=\frac{1}{2}\quad \lambda=0.81$$

The values of x, y, z, and λ for the various conditions considered are listed in table V. Calculated correction factors for the various conditions for several values of atmospheric and average head and barrel temperatures are also given in the table. The value of T_g in the computations was taken as 1,150° F. for the head and 600° F. for the barrel. The maximum cylinder-head temperature was assumed to be 125° F. higher than the average head temperature and the maximum cylinder-barrel temperature was assumed to be 30° F. higher than the average barrel temperature. Differences between the maximum and the average cylinder-head temperatures as low as 40° F. are being obtained on modern cylinders. For conditions B, in which the carburetor-air temperature was varied, the quantity $(1-\alpha)b$ was added to the value read from figure 3 to obtain the value of α_λ in the table.

MANEUVERS OF SHORT TIME DURATION

Climb to critical altitude (C–1).—The case of climb at constant indicated air speed from a pressure altitude of p_0 to a pressure altitude of p at constant indicated horsepower, engine speed, carburetor-air temperature, and air-fuel ratio will now be considered. The rate of climb or vertical ascent will be assumed to be practically independent of atmospheric temperature. The height of the climb in feet is given in reference 7 as

$$Z=122.9(T+460)\log_{10}\frac{p_0}{p}$$

Then the time of climb may be obtained by the equation

$$t=122.9\frac{T+460}{v_c\times 60}\log_{10}\frac{p_0}{p}$$

where v_c is the rate of climb, ft. per min.

From the equation for time of climb, it is evident that the value of u in equation (12) is -1. The present climb condition corresponds to the condition A–1, from which the value of $\lambda=x=1$ is obtained. If the last term of equation (12) is omitted as negligible, the increase in cylinder-head temperature with an increase in atmospheric temperature of dT_a at the pressure altitude p and an increase in the average atmospheric temperature of dT is given by

$$dT_{h_t}=\alpha_a dT_a+\alpha_t dT$$

where

$$\alpha_t=\frac{T_h-T_{h_0}}{T+460}(1-m\alpha)r$$

The magnitude of the factor α_t, which was introduced by the variation of the time of climb with the mean atmospheric temperature between the pressure altitude p_0 and p, will now be investigated. Figure 10

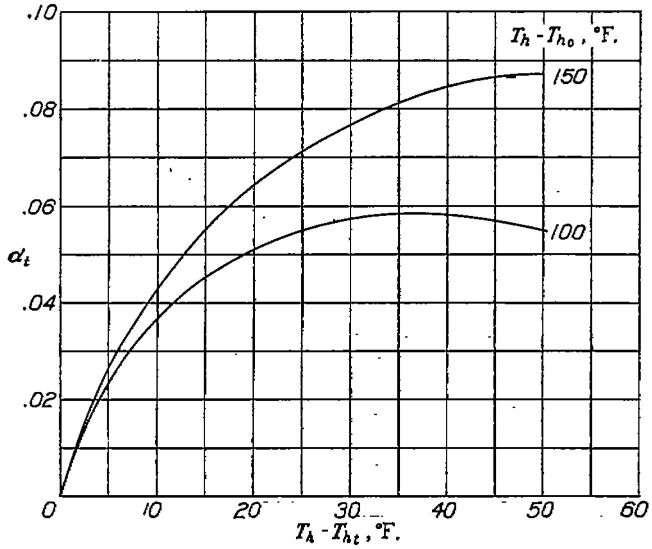

FIGURE 10.—Variation of correction factor α_t with $T_h-T_{h_t}$.

$$\alpha_t=\frac{T_h-T_{h_0}}{T+460}(1-m\alpha)r$$

shows α_t plotted against $T_h-T_{h_t}$. The values of α, m, and T were taken as 0.8, 0.336, and 0° F., respectively. Curves are given for values of $T_h-T_{h_0}$ of 100° F. and 150° F. It is seen that, when the cylinder temperature lacks only 10° F. of reaching its equilibrium value, the value of α_t is 0.04. When the equilibrium temperature is reached, as in a slow climb, $T_h-T_{h_t}=0$ and $\alpha_t=0$. This case reverts to the case A–1. The maximum value of α_t for $T_h-T_{h_0}=100$ is 0.06 and, for other values of $T_h-T_{h_0}$, is in the direct ratio of $T_h-T_{h_0}$ to 100. Although it is rarely known by what amount the cylinder temperature lags behind the equilibrium temperature in an actual climb test, figure 10 is of interest in showing the magnitude of the error that might be expected in neglecting α_t. In some cases, where the value of $T_h-T_{h_t}$ is known roughly, the value of α_t can be estimated.

A method of estimating $T_h-T_{h_t}$ in flight for a cowled engine provided with adjustable cowling flaps is to record the cylinder temperatures and the test conditions at the top of the climb and then to fly in level flight at the final altitude with the flaps adjusted to restrict the pressure drop across the cylinders to that obtained in the climb with the same engine conditions and again to record the cylinder temperatures. It should be borne in mind, however, that the two cooling conditions may not be entirely equivalent, as a difference in the turbulent air movement in front of the cylinder may be expected.

It is evident, from the foregoing considerations, that the cylinder temperatures at the end of a climb depend not only on the engine and cooling conditions prevailing at that time but also on their history during the climb. An ideal case was discussed in which the engine conditions were held constant during the climb. In climb tests as they are performed at present, the throttle is set at a definite stop at sea level and is adjusted to a new position at a prescribed altitude to bring the manifold pressure up. The mixture control and the carburetor-air temperature are set at sea level and are usually not again adjusted unless the engine functions improperly during the flight. It is known that the mixture becomes richer for a given control setting as the altitude is increased. The manifold pressure drops between the two altitudes at which it is adjusted. Even the maintenance of a constant manifold pressure does not insure constant power, as the charge to the engine depends also on the exhaust back pressure. Thus, until more complete control of the engine conditions can be maintained during the climb, good correlation of the temperature data for this flight condition cannot be expected. For an engine provided with cowling flaps, more accurate data can be obtained by flying the airplane in level flight at the critical altitude with the flaps adjusted to provide the same pressure drop as is obtained in climb. The temperatures obtained in this manner would be close to the equilibrium temperatures corresponding to the engine and cooling conditions in climb at the critical altitude.

The following example is given as an illustration of the variation of cylinder-head temperature in a climb. The airplane is assumed to be provided with a 9-cylinder Pratt & Whitney 1340–H engine operating at 550 horsepower. The climb is assumed to take place at a constant indicated air speed that provides a constant pressure drop Δp of 4.7 inches of water across the cylinders. The weight of the cylinder head is 18.86 pounds and the specific heat is 0.25 B. t. u. per lb. per °F. for aluminum. The average cylinder-head temperature just before entering into the climb is assumed to be 300° F. A climbing speed of 2,700 feet per minute is assumed. The temperatures and densities correspond to the standard altitude (reference 7). The foregoing values were substituted in equation (11). The values used for Ka_0, $\overline{B}a_1$, m, and n' are those obtained from the single-cylinder-engine tests. The value of K would probably be somewhat different for the cowled engine in flight. The calculated average cylinder-head temperature T_{h_t} at each 1,000 feet of altitude up to 7,000 feet is shown in the following table. The equilibrium temperature T_h that would be reached at each altitude, if the engine temperature responded instantaneously to a change in conditions, is also listed in the table.

Altitude (ft.)	T_h (°F.)	T_{h_t} (°F.)
0	450	300
1,000	450	337
2,000	450	363
3,000	450	384
4,000	450	400
5,000	450	412
6,000	451	421
7,000	451	428

It will be noticed that, for this case, the equilibrium temperature T_h is the same at sea level as at 7,000 feet, the effect of the decrease in density being compensated by the effect of the decrease in atmospheric temperature. The actual temperature T_{h_t} still lacks 23° F. of attaining equilibrium at 7,000 feet.

Take-off condition (C–2).—In the take-off, the engine is first warmed up until the oil reaches the desired temperature. The throttle is then opened to the manifold pressure for take-off and the airplane is put into motion. In general, the pressure drop available in take-off is not sufficient to cool the engine at the high power take-off rating. Because of the heat capacity of the cylinder material, however, the temperatures increase at a finite rate with time and the final temperature reached at the instant of take-off depends, other factors remaining constant, on the time of duration of the take-off run. The time duration of the take-off run for landplanes is usually in the neighborhood of 10 to 20 seconds and, in this short time, the cylinder temperatures are considerably less than the equilibrium temperature for the horsepower and the cooling-pressure drop involved.

As an illustration, consider an airplane equipped with a Pratt & Whitney 1340–H cylinder that, in being warmed up preparatory to take-off, has attained an average cylinder-head temperature of 300° F. The throttle is then opened to provide a power of 550 horsepower, or 61.1 horsepower per cylinder, at a propeller speed of 1,500 r. p. m. For a typical cowling and propeller combination, a value of 0.177 was obtained from reference 6 corresponding to the present value of $\sqrt{\Delta p}/n$ (n is in revolutions per second, and Δp is in pounds per square foot). Then

$$\Delta p = 3.75 \text{ in. of water.}$$

It is shown in reference 6 that, for low airplane speeds the pressure drop depends mainly on the propeller slipstream and that, as a good approximation, Δp can be assumed to remain constant up to the take-off velocity.

The average cylinder-head temperature for equilibrium at the given power and pressure drop may be obtained from equation (3). The value of T_g is taken as 1,150° F. and of T_a as 59° F.

$$T_h = \frac{T_g - T_a}{\dfrac{Ka_0(\Delta p\rho/\rho_0)^m}{\overline{B}a_1 I^{n'}}+1} + T_a = \frac{1{,}150-59}{\dfrac{78.1(3.75)^{0.34}}{5.22(61.1)^{0.64}}+1}+59$$
$$=469° \text{ F.}$$

Inasmuch as the engine and cooling conditions remain constant during the run, equation (11) may be used:

$$A = Ka_0(\Delta p\rho/\rho_0)^m + \overline{B}a_1 I^{n'}$$
$$=78.1(3.75)^{0.34}+5.22(61.1)^{0.64}=195$$

The weight of the head M is 18.86 pounds and the specific heat c for aluminum is 0.25 B. t. u. per lb. per °F. so that

$$\frac{A}{cM}=41.3\,\frac{1}{\text{hr.}}$$

$$T_{h_t}=469-(469-300)e^{-41.3t}=469-169e^{-41.3t}$$

where t is in hours.

On the assumption that the take-off run requires 10 seconds, the value of T_{h_t} over this period is given by

t (sec.)	0	2	4	6	8	10
T_{h_t} (°F.)	300	304	307	311	315	318

It is seen that, for this case, the average head temperature increases only 10.6 percent of the difference between the initial and the final equilibrium temperature.

The time required for take-off varies inversely as the square root of the atmospheric density and it is a simple matter to calculate the effect of variation of atmospheric conditions on the temperature rise of the cylinder during take-off. The cylinder temperature at the time of take-off depends mainly on the initial temperature of the engine and therefore depends on the instructions followed by the pilot in warming up the engine. For example, if the pilot is instructed to warm up the engine to the same temperature at the start of the take-off run irrespective of atmospheric temperature, then variation of atmospheric temperature will have only a small effect on the cylinder temperature at take-off.

As an illustration, refer to the case just considered of take-off at a given engine power, a given carburetor-air temperature, and a given engine speed. The increase in cylinder-head temperature is given by equation (12), where now $T_0=T_a=T$. Equation (12) becomes

$$\frac{dT_{h_t}}{dT_a}=\alpha_{\lambda_0}-\frac{T_h-T_{h_0}}{T+460}(m\alpha x+u)r+\left(\frac{T_{h_t}-T_{h_0}}{T_h-T_{h_0}}\right)(\alpha_\lambda-\alpha_{\lambda_0})$$

where α_{λ_0} is the variation of the initial head temperature T_{h_0} and α_λ is the variation of the final equilibrium head temperature T_h with atmospheric temperature. From the values of T_g, T_h, and T_a previously obtained, a value of $\alpha=0.63$ is calculated from equation (4). Since the pilot is assumed to warm up the engine to the same temperature prior to take-off independent of atmospheric temperature, α_{λ_0} is equal to zero. If the take-off occurs at a constant indicated air speed, as previously mentioned, the time for take-off is inversely proportional to the square root of the density

$$t \propto \rho^{-\frac{1}{2}}$$

from which there is obtained $u=-\frac{1}{2}$. (See development of equation (12).) The value of x as given by condition A–3 will be used because only a small change in $\sqrt{\Delta p}/n$ with airplane velocity in the take-off range is indicated in reference 6.

$$x=\lambda=0.5 \text{ to } 0.666$$

Using values of $x=0.5$, $\alpha=0.63$, $\alpha_{\lambda_0}=0$, $u=-\frac{1}{2}$, and $m=0.34$, the foregoing equation becomes

$$\frac{dT_{h_t}}{dT_a}=\frac{0.4(T_h-T_{h_0})r}{T_a+460}+\frac{T_{h_t}-T_{h_0}}{T_h-T_{h_0}}\alpha_\lambda$$

$$=\frac{0.4\times169r}{59+460}+0.106\alpha_\lambda$$

$$=0.13r+0.106\alpha_\lambda$$

The maximum value that r can have is $1/e$ and the maximum value of $0.13r$ is

$$\frac{0.13}{2.718}=0.05$$

For the present case, however,

$$\frac{T_h-T_{h_t}}{T_h-T_{h_0}}=1-0.106=0.894$$

and $r=0.10$ (fig. 4)

$$\frac{dT_{h_t}}{dT_a}=0.130\times0.10+0.106\alpha_\lambda=0.01+0.106\alpha_\lambda$$

The value of $\alpha_\lambda(\lambda=0.5,\ T_g=1{,}150,\ T_a=59,\ \alpha=0.63)$ as obtained from figure 3 is 0.72 and

$$\frac{dT_{h_t}}{dT_a}=0.08$$

It is evident that the effect of atmospheric temperature on the take-off temperature in the present case is small.

Attention is directed to the fact shown by the calculations that the power in take-off can be increased considerably and still not result in dangerous cylinder head and barrel temperatures if the temperatures of the cylinders just prior to take-off are low. Piston temperatures, however, will respond more rapidly to a sudden increase in engine power and may be the limiting factor.

SUMMARY OF METHOD OF DETERMINING CORRECTION FACTORS FOR VARIATION OF CYLINDER TEMPERATURE WITH ATMOSPHERIC TEMPERATURE

Reference to equation (8) or figure 3 shows that the correction factor α_λ (change in cylinder temperature per degree change in atmospheric temperature) may be determined when the values of T_g, T_a, α, and λ are known. As pointed out in the discussion following equation (8), the values given in figure 3 do not include the last term in equation (8), $zb(1-\alpha)$. When the carburetor-air temperature is held constant, z is equal to zero and this term reduces to zero. When the carburetor-air temperature is allowed to vary with the atmospheric temperature, $z=1$ and this term becomes $b(1-\alpha)$, where b may be taken equal to 0.5. This small correction must be added to the value of α_λ obtained from figure 3 for the case of $z=1$. When the exact value of T_g is not known, it is seen from figure 3 that a value of 1,150° F. for the head and of 600° F. for the barrel may be chosen without introducing appreciable error. The value of λ corresponding to the condition under consideration may be obtained from table V. It may also be determined from equation (9), as previously shown. The basic correction factor α (change in cylinder temperature per degree change in cooling-air temperature when mass flow of cooling air, engine power, and carburetor-air temperature are held constant) may be determined from equation (4) or figure 2 when T_g, T_a, T_h, and T_b are known; T_a is the atmospheric temperature, T_h the average head temperature, and T_b the average barrel temperature. As may be seen from figure 2, the assumed values for T_g may also be used for determining α without introducing an appreciable error.

In many practical cases only the maximum head and barrel temperatures and the atmospheric temperature are obtained in the tests. The difference between the average head temperature and the maximum cylinder temperature depends on the type of finning and baffling; the better the finning, of course, the smaller the difference. In the following table are given the approximate differences between the average head and the maximum cylinder temperatures for the cylinders tested.

Cylinder	Temperature difference (°F.)
Pratt & Whitney:	
1340-H	150
1535	50
1535 (flight)	100
1830	60
1690	90
Wright:	
1820-F	70
1820-G	40
1510	90

The average barrel temperature is of the order of only 30° F. lower than the maximum and can be quite closely estimated. From figure 2 it may be seen that an error of 25° F. in the estimated value of the average head temperature will cause an error in the value of α for the head of 0.03; an error of 10° F. in the estimated value of the average barrel temperature will cause an error in the value of α for the barrel of 0.02.

The preceding method is illustrated with the following example. An engine is tested in level flight and a maximum head temperature of 425° F. and a maximum barrel temperature of 250° F. are obtained at a cooling-air temperature of 20° F. The engine is provided with an air heater adapted to maintain a standard temperature at the carburetor of 70° F. It is desired to determine the value of the maximum cylinder temperatures if the cooling-air temperature were 70° F. at the same altitude and engine condition. If it is assumed that the average head and barrel temperatures are 125° F. and 30° F. lower than the respective maximum temperatures, the values of T_h and T_b are 300° F. and 220° F. Corresponding to these values of T_h and T_b and to a value of T_a of 20° F. and T_g of 1,150° F. and 600° F. for the head and the barrel, respectively, figure 2 shows a value of α for the head of 0.73 and for the barrel of 0.68. From table V, case A–2, a value of λ of 1.33 is obtained. The required correction factors α_λ corresponding to the values of λ, α, T_g, and T_a are read from figure 3. The values obtained are $\alpha_\lambda=0.93$ for the head and 0.80 for the barrel. The maximum cylinder head and barrel temperatures, corrected to a cooling-air temperature of 70° F., are then 472° F. and 290° F., respectively.

The correction factors for a number of test conditions are included in table V. For each condition, the factors were determined for average head temperatures of 350° F. and 275° F., average barrel temperatures of 300° F. and 225° F., and atmospheric temperatures of 100° F. and 0° F. These values bracket the usual operating range. For most test conditions, the variation of the correction factor over this range is small and an average value may be used. Where a large variation exists, the correction factors corresponding to a desired set of conditions may be obtained by interpolating between the values given in table V. In this connection it should be noted that a probable uncertainty of ± 5 percent exists in the values of the correction factors. Approximate maximum head and barrel temperatures are also listed in the table and were obtained by adding 125° F. to the average head temperature and 30° F. to the average barrel temperature.

GENERAL REMARKS

The dependence of cylinder temperatures on the engine power, the air-fuel ratio, the carburetor-air temperature, the pressure drop of cooling air across the cylinder, and the cooling-air temperature has been shown. It has also been shown that the correction factor for variation of cylinder temperature with atmospheric temperature depends on the type of flight or test to which it is to be applied. Correction factors have been obtained for several ideal cases. Various airplanes, however, have different refinements of equipment for controlling the engine and cooling factors and therefore present separate problems. These problems can be readily investigated by the methods illustrated.

Obviously, when cooling tests are made for accurate comparisons of cylinder temperatures, the factors that are not intentionally varied should be held as closely as possible to a standard and should be measured in order that corrections may be applied for small variations from the standard.

It is the practice at present to use the temperature of the rear spark-plug gasket as the index of the cooling of a cylinder. The temperature of the rear spark-plug gasket has been found to depend on the condition and construction of the plug, the cleanness of the plug, and the tightness with which it is inserted in the cylinder. For these reasons, the temperature of the rear spark-plug gasket may at times give incorrect indications of the cooling of a cylinder. The comparison of the cooling of a cylinder based on the reading of a single thermocouple may be misleading and it is recommended that the average of a number of thermocouples located at standard positions on the head and the barrel be used to obtain average head and barrel temperatures.

In a multicylinder engine, variations of as much as 50° F. occur between the maximum temperatures of the various cylinders. This fact tends to complicate the problem of correlating the temperature data obtained on such engines. An average of the maximum temperatures for all the cylinders would give the best correlation.

Although the methods in this paper apply for correcting the average head and barrel temperatures, the magnitude of variation of these temperatures indicates closely the magnitude of variation of the maximum cylinder temperatures to be expected.

In the computations, various additional refinements that might have been considered would have introduced small corrections. For example, it was found in the present tests that heating the cooling air tended to reduce the weight of the charge and the engine power even when the carburetor-air temperature and the manifold pressure were held constant.

In the consideration of the supercharged engine, the assumption was made that a 1° F. variation in carburetor-air temperature causes a 1° F. change in inlet manifold temperature. This assumption is only a rough approximation, as compression by the supercharger, cooling of the compressed charge, and evaporation of the gasoline would alter the relationship. The effect of carburetor-air temperature on cylinder temperature for a constant engine power is small, however, and it was not considered worth while to make a more accurate analysis.

Tests of one cylinder were made to determine the effect of oil temperature on cylinder temperature. It was found that a variation in oil-out temperature from 128° F. to 171° F. caused only a very small change in cylinder temperature. Although the majority of the thermocouples indicated a slight increase, some of the thermocouples showed a decrease. The quantity of oil circulated was found to have a greater effect.

The correction factors in the present report apply to the case where the engine is not detonating. When detonation occurs, the engine temperature changes more rapidly with atmospheric temperature because the intensity of detonation is also affected by the change in temperature.

CONCLUSIONS

1. The values of the cylinder-temperature correction factors for cooling-air temperature for constant engine conditions and constant mass flow calculated from semiempirical equations agree reasonably well with the experimental values.

2. The cylinder-temperature correction factors are lowest for the constant-mass-flow condition and highest for the constant-velocity condition.

3. The cylinder-temperature correction factors for a fast climb are slightly higher than those for a slow climb when the cylinder temperatures do not attain equilibrium in the fast climb.

4. A change in carburetor-air temperature affects the cylinder-temperature correction factors by changing the effective gas temperature, but the effect is small.

5. It is recommended that the average of a number of thermocouples on the cylinder head and barrel be used as a measure of the head and barrel temperatures. A single thermocouple, especially one located on the rear spark-plug gasket, may give misleading results.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *June 20, 1938.*

APPENDIX

SYMBOLS

a_0, outside wall area of head of cylinder, sq. in.
a_1, internal area of head of cylinder, sq. in.
A, $Ka_0(\Delta p\rho/\rho_0)^m+\overline{B}a_1I^{n'}$
b, ratio of change of effective gas temperature (T_g) to change of carburetor-air temperature (T_c).
B, $\overline{B}a_1I^{n'}T_g+Ka_0(\Delta p\rho/\rho_0)^mT_a$
$\overline{B}$, constant.
c, specific heat of metal in cylinder head, B. t. u. per lb. per °F.
C_D, drag coefficient.
d, exponent.
D, propeller diameter, ft.
H, heat transferred per unit time from combustion gases to cylinder head, B. t. u. per hr.
H_1, heat transferred per unit time from cylinder head to cooling air, B. t. u. per hr.
I, indicated horsepower of each cylinder.
K, K_1, K_3, K_4, K_5, K_6, constants.
m, exponent.
M, weight of cylinder head, lb.
n, propeller speed, r. p. s.
n', exponent.
p_0, pressure at initial altitude of climb, in. Hg.
p, pressure at final altitude of climb, in. Hg.
P, propeller power (brake horsepower), ft.-lb. per sec.
r, $\frac{T_h-T_{h_t}}{T_h-T_{h_0}}\log_e\frac{T_h-T_{h_0}}{T_h-T_{h_t}}$
t, time, hr.
T_a, inlet temperature of cooling air, °F. (temperature of atmosphere).
T_b, average temperature over the cylinder-barrel surface when equilibrium is attained, °F.
T_c, temperature of carburetor air, °F.
T_g, effective gas temperature, °F.
T_h, average temperature over the cylinder-head surface when equilibrium is attained, °F.
T, average temperature of atmosphere during maneuver, °F.
T_0, temperature of atmosphere at time $t=0$, °F.
T_{h_0}, average temperature of cylinder head at time $t=0$, °F.
T_{h_t} average temperature of cylinder head at time t, °F.
u, exponent.
v_c, rate of climb, ft. per min.
V, true velocity of airplane, m. p. h.
x, y, z, exponents.
Z, height of climb, ft.
α, basic temperature correction factor; change in cylinder temperature per degree change in cooling-air temperature; mass flow of cooling air, engine power, and carburetor-air temperature remaining constant.
α_λ, correction factor for any test condition when equilibrium is attained; change in cylinder temperature per degree change in atmospheric temperature.
α_{λ_0}, correction factor for any test condition at time $t=0$; change in cylinder temperature (T_{h0}) per degree change in cooling-air temperature (T_0).
α_t, correction factor during a climb; change in cylinder temperature per degree change in atmospheric temperature.
λ, $\frac{m}{0.34}\left[x+\frac{z}{2}\left(y-\frac{n'}{m}\right)\right]$
ρ, average density of cooling air, lb.-ft.$^{-4}$ sec.^{2} (average density of the air entering and leaving the fins).
ρ_0, density of air at 29.92 in. Hg and 70° F., lb.-ft.$^{-4}$ sec.^{2}
Δp, pressure drop across cylinder, in. of water (includes loss out exit of baffle).

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TABLE I.—TEST CONDITIONS FOR EFFECT OF COOLING-AIR TEMPERATURE ON CYLINDER TEMPERATURE

Cylinder	Series	Indicated horsepower	Indicated mean effective pressure (lb./sq. in.)	Engine speed (r. p. m.)	Indicated fuel consumption (lb./i. hp./hr.)	$\Delta p_\rho/\rho_0$ (in. of water)	Carburetor-air temperature (°F.)	T_e Head (°F.)	T_e Barrel (°F.)
1340-H	1	37.71	123.2	1,556	0.457	17.87	88	1,155	585
	2	41.25	133.6	1,569	.453	17.60	83	990	535
	3	29.70	97.7	1,545	.438	18.89	74	1,007	557
	4	56.50	137.6	2,082	.461	17.26	87	1,400	667
	4′	50.19	140.8	1,821	.458	17.24	92	1,113	679
	5	41.64	136.4	1,551	.461	16.35	86	1,373	631
	7	32.10	107.6	1,515	.439	18.03	72	1,150	580
	7′	40.40	134.9	1,521	.472	17.44	77	1,120	584
	8′	33.00	110.4	1,518	.442	12.71	77	1,150	592
	9	28.58	97.3	1,492	.420	9.73	72	1,040	563
	9′	27.87	97.2	1,456	.437	13.46	68	1,142	474
	10	40.00	137.0	1,480	.479	14.53	66	1,134	592
	11	44.95	150.6	1,515	.476	16.33	81	1,158	658
	11′	62.69	150.9	2,110	.464	18.01	62	1,273	622
	14	42.40	146.4	1,470	.471	17.49	64	1,142	599
	15	42.01	101.4	2,104	.469	17.94	66	1,069	563
	16	47.97	164.7	1,480	.501	18.18	73	1,139	592
	17	33.18	111.8	1,508	.508	15.20	93	1,065	635
	18	41.25	140.4	1,491	.548	13.77	92	905	657
	19	47.98	115.7	2,106	.412	14.49	80	1,180	601
							Average	1,136	598
1535	1	26.0	118.1	1,500	0.453	17.92	94	1,105	648
	2	26.1	118.0	1,503	.458	12.75	97	1,098	637
	3	26.2	118.8	1,501	.449	8.02	91	1,045	485
	3′	29.3	121.0	1,652	.443	16.47	97	1,100	465
	4	32.5	122.1	1,809	.434	16.14	85	1,060	540
	4′	36.8	125.2	2,001	.431	16.47	88	1,107	534
	5′	32.4	122.7	1,801	.431	15.90	92	1,126	500
	6	37.3	169.5	1,499	.490	15.26	109	1,300	558
	6′	31.9	144.35	1,508	.470	15.41	101	1,140	530
	7	24.3	110.6	1,497	.440	15.20	95	1,105	579
	7′	28.2	127.8	1,502	.455	15.65	90	1,175	572
	8	31.8	143.8	1,503	.475	15.63	105	1,095	469
	9	31.5	143.8	1,489	.475	15.39	103	1,304	580
	10	36.4	124.3	1,997	.445	15.57	91	1,303	575
	11	26.3	119.5	1,499	.451	12.58	97	1,168	611
	12	26.3	119.2	1,500	.458	7.77	87	1,178	646
	14	32.5	122.3	1,808	.444	15.60	83	1,174	620
	21	26.4	119.0	1,508	.455	15.30	82	1,140	545
							Average	1,151	561
1820-F	1	37.27	95.42	1,500	0.457	14.47	76	1,100	600
	2	37.21	95.40	1,498	.458	6.63	76	1,480	710
	3	37.33	95.44	1,502	.459	9.29	97	1,100	710
	4	37.13	95.29	1,497	.455	11.51	103	1,495	880
	5	49.22	99.23	1,905	.444	14.69	98	1,070	600
	6	43.32	97.42	1,708	.446	14.66	92	1,185	620
	7	31.79	93.64	1,304	.469	14.82	91	1,100	645
	8	51.86	132.68	1,501	.495	15.00	82	1,230	625
	9	44.65	114.16	1,502	.481	14.79	94	1,195	785
	10	30.02	76.65	1,504	.428	14.74	96	1,040	550
	11	49.00	99.06	1,900	.442	14.61	99	1,035	530
	13	57.45	147.36	1,497	.502	18.10	87	1,230	875
	14	47.44	98.58	1,848	.445	14.49	96	1,100	640
							Average	1,183	671
1600	1	35.06	104.6	1,493	0.481	11.15	92	1,320	735
	1′	35.16	104.6	1,505	.477	4.51	78	----	----
	2	35.02	104.6	1,499	.453	6.45	79	1,430	725
	2′	34.91	104.5	1,494	.481	8.55	79	1,100	605
	3	27.77	82.3	1,508	.453	11.19	87	1,170	590
	3′	35.03	104.2	1,505	.444	11.13	83	1,345	670
	4	40.83	121.0	1,510	.448	11.14	88	1,140	640
	5	35.13	104.4	1,506	.472	8.42	81	1,035	680
	6	34.87	104.1	1,499	.479	4.42	76	----	----
	7	----	----	2,012	----	11.10	88	1,320	500
	8	35.06	104.4	1,503	.471	4.88	80	1,140	630
	9	----	----	1,643	----	11.23	84	1,080	600
	9′	----	----	1,808	----	11.30	81	1,445	655
							Average	1,230	645
1830	1	32.41	130.6	1,504	0.479	17.88	86	1,125	600
	1′	32.33	130.8	1,498	.470	11.13	85	1,095	600
	2	32.34	129.4	1,514	.467	16.86	95	1,125	530
	3	32.34	129.5	1,514	.468	12.81	83	1,115	600
	3′	32.25	129.2	1,513	.465	9.80	86	1,165	600
	4	35.86	144.2	1,507	.491	15.53	100	1,110	620
	4′	28.57	114.1	1,518	.486	15.27	94	1,150	560
	5	32.01	129.2	1,501	.467	15.42	89	1,150	600
	5′	44.67	135.6	1,996	.452	15.78	85	1,105	575
	5″	40.18	133.4	1,825	.460	15.18	86	1,110	555
	5‴	35.80	131.7	1,647	.469	15.87	94	1,115	620
	6	44.61	135.6	1,904	.450	15.66	90	1,075	485
	8	36.06	144.3	1,514	.474	15.69	95	1,135	510
							Average	1,122	574
1820-G	12	37.59	96.0	1,504	0.428	9.89	74	1,135	590
	13	37.95	96.9	1,505	.426	8.82	78	1,155	610
	14	37.45	95.2	1,510	.424	7.61	78	1,140	615
	15	37.43	95.5	1,505	.424	9.22	77	1,135	610
	16	47.56	121.6	1,502	.443	9.48	73	1,200	600
	17	42.64	108.7	1,506	.429	9.41	75	1,120	625
	18	32.91	83.9	1,507	.397	9.58	69	930	515
	19	32.21	95.0	1,302	.422	9.58	76	1,100	550
	20	45.39	99.4	1,705	.410	9.59	73	1,210	640
	21	50.16	101.4	1,900	.396	9.48	71	1,125	595
	24	51.09	102.9	1,908	.390	9.55	74	875	475
	29	50.02	101.4	1,895	.396	8.14	72	1,160	585
							Average	1,107	580
1510	1	24.4	118.2	1,515	0.454	17.71	83	972	566
	2	24.3	118.0	1,510	.458	6.29	87	1,145	569
	3	28.8	117.7	1,490	.464	9.03	85	1,100	599
	4	24.3	118.0	1,506	.402	13.29	81	1,101	570
	6	37.1	129.0	2,106	.422	16.64	91	1,112	610
	7	28.4	122.5	1,699	.454	16.95	82	1,220	605
	8	32.4	125.0	1,897	.468	16.92	87	1,150	588
	9	27.2	132.1	1,510	.464	16.62	89	1,150	582
	10	21.2	103.5	1,499	.445	16.55	84	1,148	600
	11	33.8	165.0	1,499	.459	15.78	116	1,205	655
	13	21.2	103.0	1,505	.430	16.39	77	1,135	610
	14	24.2	118.1	1,504	.464	6.19	75	1,167	641
							Average	1,139	602
			Average T_e for all cylinders					1,153	604

TABLE II.—CALCULATED AND EXPERIMENTAL VALUES OF α

Cylinder	Series	T_a (°F.)	T_b (°F.)	T_h (°F.)	α (calculated) $\frac{T_g-T_b}{T_g-T_a}$ Barrel	α (calculated) $\frac{T_g-T_h}{T_g-T_a}$ Head	α (experimental) Barrel	α (experimental) Head	T_g Barrel (°F.)	T_g Head (°F.)
1340-H	1	92	208	271	0.772	0.831	0.76	0.83	600	1,150
	2	106	228	295	.753	.819	.69	.77	------	------
	3	87	195	243	.790	.853	.74	.80	------	------
	4	89	251	332	.682	.771	.69	.91	------	------
	4'	88	250	332	.684	.770	.75	.79	------	------
	5	91	214	280	.758	.821	.81	.91	------	------
	7	79	192	257	.784	.834	.77	.83	------	------
	7'	87	222	296	.737	.803	.72	.78	------	------
	8'	79	209	276	.750	.816	.69	.84	------	------
	9	68	.196	259	.758	.823	.71	.80	------	------
	9'	70	187	237	.780	.846	.72	.79	------	------
	10	67	204	277	.743	.806	.71	.74	------	------
	11	90	221	303	.744	.800	.78	.83	------	------
	11'	65	237	332	.680	.754	.73	.81	------	------
	14	65	214	289	.721	.794	.70	.76	------	------
	15	73	207	285	.747	.802	.74	.85	------	------
	16	70	226	297	.705	.790	.72	.78	------	------
	17	94	232	305	.727	.800	.76	.77	------	------
	18	86	236	316	.708	.784	.75	.78	------	------
	19	82	264	351	.648	.748	.67	.76	------	------
1585	1	108	227	311	.736	.805	.72	.81	561	1,151
	2	105	242	329	.700	.786	.62	.72	------	------
	3	90	254	353	.652	.752	.60	.73	------	------
	3'	106	247	329	.690	.786	.69	.78	------	------
	4	94	245	341	.677	.766	.61	.70	------	------
	4'	95	255	348	.657	.760	.58	.71	------	------
	5'	99	251	340	.671	.770	.63	.75	------	------
	6	102	274	361	.632	.752	.68	.81	------	------
	6'	98	265	354	.639	.756	.56	.69	------	------
	7	104	243	320	.695	.793	.69	.77	------	------
	7'	98	253	326	.664	.783	.70	.84	------	------
	8	106	258	365	.600	.752	.55	.61	------	------
	9	107	268	351	.646	.766	.70	.75	------	------
	10	100	273	369	.624	.744	.64	.78	------	------
	11	104	257	342	.666	.772	.71	.79	------	------
	12	88	266	362	.624	.742	.68	.77	------	------
	14	99	264	352	.648	.759	.63	.73	------	------
	21	93	233	318	.701	.787	.70	.79	------	------
1820-F	1	90	254	319	.717	.790	.71	.79	671	1,183
	2	84	285	365	.658	.744	.76	.82	------	------
	3	85	274	346	.678	.762	.71	.80	------	------
	4	98	262	332	714	.784	.75	.85	------	------
	5	95	280	363	.678	.754	.61	.72	------	------
	6	87	263	337	.698	.772	.69	.80	------	------
	7	88	237	305	.743	.801	.72	.79	------	------
	8	93	281	360	.675	.756	.69	.78	------	------
	9	96	271	346	.695	.768	.75	.81	------	------
	10	96	252	318	.728	.796	.68	.78	------	------
	11	91	280	370	.674	.745	.58	.67	------	------
	13	91	290	372	.656	.742	.74	.80	------	------
	14	93	269	359	.695	.756	.70	.76	------	------
1690	1	99	242	335	0.738	0.791	0.82	0.88	645	1,230
	1'	81	269	380	.666	.740	.88	.96	------	------
	2	84	251	354	.702	.764	.75	.81	------	------
	2'	87	245	343	.716	.776	.69	.77	------	------
	3	95	217	306	.778	.815	.73	.78	------	------
	3'	93	234	332	.744	.790	.77	.86	------	------
	4	98	258	370	.708	.760	.73	.73	------	------
	5	84	246	350	.711	.768	.71	.82	------	------
	6	78	283	405	.639	.716	.80	.95	------	------
	7	99	274	380	.679	.752	.72	.83	------	------
	8	82	284	390	.642	.732	.63	.74	------	------
	9	95	262	362	.696	.765	.73	.76	------	------
	9'	92	260	365	.696	.760	.71	.84	------	------
1830	1	99	229	301	.740	.808	.71	.83	600	1,150
	1'	92	252	330	.686	.775	.69	.77	------	------
	2	114	247	322	.725	.799	.68	.78	------	------
	3	92	239	321	.710	.782	.69	.80	------	------
	3'	90	252	337	.683	.766	.68	.79	------	------
	4	96	241	315	.712	.792	.69	.83	------	------
	4'	104	232	304	.742	.809	.73	.82	------	------
	5	99	232	313	.735	.796	.71	.82	------	------
	5'	97	249	358	.698	.752	.68	.75	------	------
	5''	102	243	335	.716	.778	.70	.79	------	------
	5'''	104	238	329	.730	.785	.74	.79	------	------
	6	105	259	357	.688	.759	.60	.71	------	------
	8	100	249	327	.702	.784	.64	.79	------	------
1820-G	12	94	236	263	.719	.840	.69	.82	600	1,150
	13	102	246	275	.711	.836	.73	.86	------	------
	14	91	224	254	.739	.846	.72	.83	------	------
	15	90	232	268	.721	.832	.72	.82	------	------
	16	97	245	277	.706	.830	.72	.86	------	------
	17	98	237	271	.723	.836	.72	.82	------	------
	18	93	212	231	.765	.869	.71	.84	------	------
	19	99	221	238	.757	.868	.69	.84	------	------
	20	93	230	255	.730	.847	.70	.87	------	------
	21	97	239	271	.718	.834	.72	.90	------	------
	24	104	251	281	.704	.831	.56	.77	------	------
	29	103	242	275	.720	.836	.66	.85	------	------
1510	1	99	230	296	.733	.812	.69	.78	600	1,150
	2	91	272	361	.644	.745	.61	.71	------	------
	3	96	255	334	.684	.774	.70	.75	------	------
	4	92	252	310	.686	.794	.64	.80	------	------
	6	108	280	358	.651	.760	.70	.74	------	------
	7	187	282	351	.764	.828	.73	.90	------	------
	8	101	265	336	.671	.776	.68	.75	------	------
	9	100	260	320	.680	.790	.64	.76	------	------
	10	96	225	277	.744	.828	.70	.86	------	------
	11	109	290	363	.631	.756	.73	.78	------	------
	13	91	239	283	.710	.821	.68	.81	------	------
	14	80	290	356	.597	.742	.70	.79	------	------

TABLE III.—VALUES OF α CALCULATED AT HIGHEST AIR TEMPERATURE

Cylinder	Series	T_a (°F.)	T_b (°F.)	T_h (°F.)	α(Calculated) $\frac{T_g-T_b}{T_g-T_a}$ Barrel	α(Calculated) $\frac{T_g-T_h}{T_g-T_a}$ Head	T_g Barrel (°F.)	T_g Head (°F.)
1510	1	236	325	398	0.756	0.822	600	1,150
	2	237	362	467	.655	.748	------	------
	3	219	340	427	.682	.777	------	------
	4	244	350	431	.702	.793	------	------
	6	205	346	429	.642	.763	------	------
	7	277	350	429	.774	.826	------	------
	8	235	351	436	.682	.780	------	------
	9	249	355	440	.698	.788	------	------
	10	245	334	407	.750	.821	------	------
	11	198	361	434	.595	.752	------	------
	13	227	335	392	.710	.821	------	------
	14	224	393	462	.550	.742	------	------

TABLE IV.—VALUES OF b OBTAINED FROM CYLINDER TESTS

Cylinder	Engine speed (r. p. m.)	Indicated mean effective pressure (lb./sq. in.)	Indicated horsepower	$\Delta p \rho / \rho_0$ (in. of water)	Fuel consumption (lb./i. hp./hr.)	Carburetor-air temperature (°F.)	b	
							Head	Barrel
1340-H	1,501	140.6	41.53	17.18	0.461	45–120.2	0.794	0
	1,502	153.1	45.25	18.50	.470	47.3–126	1.096	.519
	1,537	97.7	29.54	19.35	.448	74–187	.740	0
1535	1,523	119.2	26.7	15.47	.444	45–153	.846	.364
	1,787	135.1	35.5	15.97	.459	34–154	.607	.360
1820-F	1,302	94.25	31.96	13.32	.601	39–148	−.159	0
	1,501	117.12	45.80	13.84	.442	76–128	.324	.21
	1,503	120.23	47.07	13.97	.477	84–160	.366	.279
1830	1,634	117.9	31.79	20.52	.518	58.5–150	.590	.358
	1,650	117.3	31.93	20.63	.467	81–148	.519	.634
1510	1,503	118.0	24.2	16.33	.433	46–157	.254	.209
	1,702	122.6	28.5	16.14	.442	78–153	.233	.117

TABLE V.—EFFECT OF FLIGHT CONDITIONS ON ENGINE TEMPERATURE CORRECTION FACTORS

Flight condition	y	z	x	λ	$T_{h_{max}}$ (°F.)	T_h (°F.)	$T_{b_{max}}$ (°F.)	T_b (°F.)	T_c (°F.)	[a] α_λ	
										Head	Barrel
A. Constant carburetor-air temperature and engine power:											
1. Climb at constant indicated air speed to a given pressure altitude	0	0	1	1	475	350	330	300	0	0.88	0.60
					475	350	330	300	100	.87	.67
					400	275	255	225	0	.91	.72
					400	275	255	225	100	.91	.80
2. Level flight at a given pressure altitude	0	0	1.33	1.33	475	350	330	300	0	.93	.65
					475	350	330	300	100	.91	.69
					400	275	255	225	0	.96	.76
					400	275	255	225	100	.95	.82
3. Stationary on ground at given barometer	0	0	1.50–1.66	1.50–1.66	475	350	330	300	0	.98	.69
					475	350	330	300	100	.94	.71
					400	275	255	225	0	1.00	.78
					400	275	255	225	100	.97	.84
4. Constant airplane velocity	0	0	2	2	475	350	330	300	0	1.05	.78
					475	350	330	300	100	.98	.74
					400	275	255	225	0	1.06	.83
					400	275	255	225	100	1.00	.85
5. Constant mass flow	0	0	0	0	475	350	330	300	0	.70	.50
					475	350	330	300	100	.76	.60
					400	275	255	225	0	.76	.63
					400	275	255	225	100	.83	.75
B. Carburetor-air temperature equal to and varying with atmospheric temperature, engine power varying with carburetor-air temperature, constant manifold pressure, and constant engine speed:											
1. Climb at constant indicated air speed to a given pressure altitude	0	1	1	.032	475	350	330	300	0	.85	.75
					475	350	330	300	100	.88	.80
					400	275	255	225	0	.88	.81
					400	275	255	225	100	.91	.87
2. Level flight at a given pressure altitude	.66	1	1.33	.70	475	350	330	300	0	.97	.83
					475	350	330	300	100	.96	.85
					400	275	255	225	0	.98	.88
					400	275	255	225	100	.97	.90
3. Stationary on ground at a given barometer	.33–.5	1	1.50–1.66	.81–.89	475	350	330	300	0	1.00	.85
					475	350	330	300	100	.97	.86
					400	275	255	225	0	1.00	.90
					400	275	255	225	100	.99	.91

[a] The values of α_λ for the head are calculated for T_g=1,150° F. and for the barrel for T_g=600° F.