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CORRELATION OF ENGINE-COOLING DATA

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MEMORANDUM REPORT

CORRELATION OF ENGINE-COOLING DATA

By D. E. Brimley and Maurice J. Brevoort

SUMMARY

A method of correlating engine-cooling data and its application to a representative engine-cooling test is presented. Consideration is made of the effects of altitude on the engine-cooling performance. The correlation equations are developed so that application to specific engine-cooling problems is simple and direct.

The essentials of the correlation method are:

1. The rate of heat flow from the combustion gases to the engine cylinder is equated to a function of the indicated horsepower corrected for fuel-air ratio, several temperatures, and the exhaust back pressure. This treatment simplifies the application of the correlation method to the calculation of engine-cooling performance under any conditions.

2. Temperature differences are employed which closely approach the effective values.

3. The weight flow of cooling air is related to the loss of total pressure and to the air density at the rear of the engine.

A section is included on experimental procedure. An example of determining the cooling-pressure loss for given engine-operating conditions at altitude is given.

INTRODUCTION

The NACA currently uses a method of correlation of engine-cooling data based on references 1 and 2. Good results have been obtained by use of this method in predicting low-altitude cooling performance on the basis of wind-tunnel tests. For some time it has been generally

recognized that modifications to the method are needed for high-altitude engine-cooling correlation and much work has been done on the problem. References 3 and 4 are representative examples of the recent work.

References 3, 4, 5, and 6 indicate that, for cooling correlation over a wide range of altitudes, the temperature rise of the cooling air must be known in addition to the variables considered in references 1 and 2. The present report introduces the temperature-rise variable in a simple and direct manner by use of the relation in which the heat absorbed by the cooling air is equated to the product of the weight flow, specific heat, and temperature rise of the cooling air. The report gives additional analytical justification for the general belief that the weight flow of cooling air is determined uniquely by the pressure drop across the cylinder and the air density at the rear of the engine.

The variable of principal interest to the engine manufacturers and operators on the hot-gas side of the cylinder is the engine power. To a first approximation, the heat flow is a function of engine power. The correlation method presented equates heat flow on the hot-gas side of the cylinder to a function of engine power modified for the effect of fuel-air ratio, several temperatures, and the exhaust back pressure. If additional factors are discovered in the future which affect the rate of heat flow on the hot-gas side of the cylinder, they may be conveniently included as modifying factors to the engine power.

The treatment of the heat flow on the hot-gas side of the cylinder eliminates the need for the concept of the mean effective hot-gas temperature which was introduced in references 1 and 2. This concept has a useful physical significance and has been employed in the report to obtain correction factors, but, because it is an integrated quantity over the four engine cycles involving temperature, flow, and area, it cannot be measured directly. The method proposed in this paper for the correlation of engine-cooling data employs factors which may all be directly measured.

The report makes no recommendation on the method of measurement of the various temperatures and pressures needed for complete correlation. It is pointed out,

however, that introduction of the cooling-air temperature-rise variable eliminates the necessity of separate constant pressure loss and constant engine power runs in the correlation tests.

SYMBOLS

c_p	specific heat at constant pressure, Btu per pound per $^{\circ}\text{F}$
C_1, C_2, C_3, C_4, C_5	empirical constants
$C_{F/A}$	fuel-air correction factor
F/A	fuel-air ratio
h	heat-transfer coefficient, Btu per second per square foot per $^{\circ}\text{F}$
H	rate of heat flow, Btu per second
I	indicated horsepower
I_e	effective indicated horsepower
K_1, K_2, K_3	empirical constants
m, n	empirical exponents
P_0	standard pressure, 29.9 inches of mercury
P	total pressure of cooling air, inches of mercury
ΔP	total baffle pressure loss, inches of water
ΔP_e	exhaust back pressure minus 30, inches of mercury
ΔP_{ex}	total baffle exit pressure loss, inches of water
ΔP_f	total baffle friction loss, inches of water
ΔP_m	total baffle momentum pressure loss, inches of water

q_{av}	mean dynamic pressure in fin passages, inches of water
q_2	mean dynamic pressure in baffle entrance, inches of water
q_3	mean dynamic pressure in baffle exit, inches of water
S	engine surface area, square feet
T_0	standard temperature, 59° F
T	temperature of cooling air, °F
T_e	average engine temperature, °F
T_h	representative measured engine temperature, °F
T_m	inlet manifold charge temperature, °F
ΔT	$T_h - T_4$, °F
ΔT_1	$T_h - T_1$, °F
ΔT_a	$T_4 - T_1$, °F
ΔT_h	$T_h - 400$, °F
ΔT_m	$T_m - 250$, °F
W_c	weight flow of cooling air, pounds per second
x, y	empirical exponents
σ	ratio of air density to standard air density

Subscripts:

av average

1, 2, 3, 4 refer to station numbers shown in figure 1

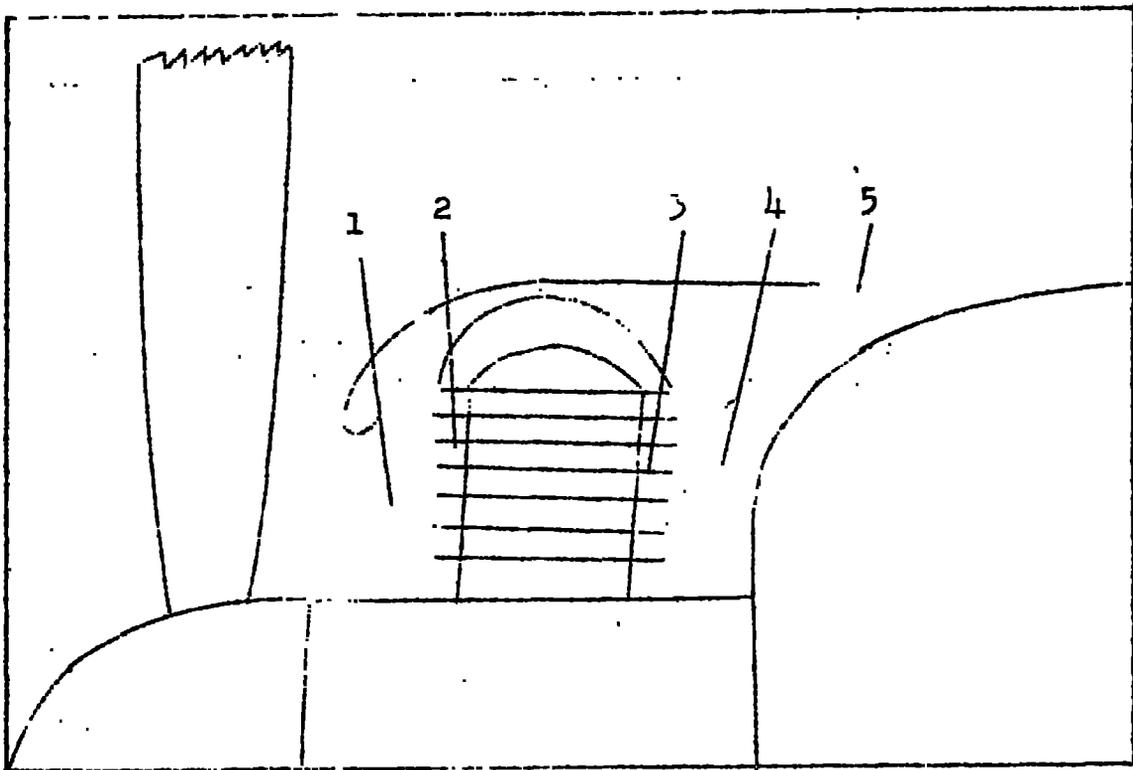


Figure 1.- Diagram of engine station numbers.

ANALYSIS

Heat Flow from the Cooling-Air Side of the Cylinder

The heat flow referred to in this paper is that which is transferred to the cooling air which passes through the fin passages and baffles and exits at the rear of the engine. The heat flow measured by the temperature change of the cooling air is

$$H = W_c c_p (T_4 - T_1) \quad (1)$$

The heat flow may also be written in terms of the heat-transfer coefficient, total cooling-surface area, and temperature difference between the surface and the

cooling air as follows:

$$H = hS (T_e - T_{av}) \quad (2)$$

For a given engine

$$S = K_1 \quad (3)$$

Analytically the determination of h involves an averaging of the individual values of h around the cylinder with widely different flow conditions. Empirically to a sufficient degree of accuracy for this paper

$$h = K_2 W_c^y \quad (4)$$

The temperature difference to be used in equation (2) should be the mean temperature difference existing between the hot metal cylinder and fins and the cold air flowing through the cooling-air passages. This mean value is not easily determined. For low-altitude engine-cooling correlation, good correlation was obtained with the temperature difference $T_h - T_l$. It is generally understood that for correlation over a range of altitudes a temperature difference must be used which approximates the effective average temperature difference.

Figure 2 is drawn for an idealized case showing the engine and cooling-air temperatures along the fin passages for a high-altitude and low-altitude condition. It is apparent from the figure that for a given engine temperature measured at the rear of the cylinder the average engine temperature is lower at high altitudes.

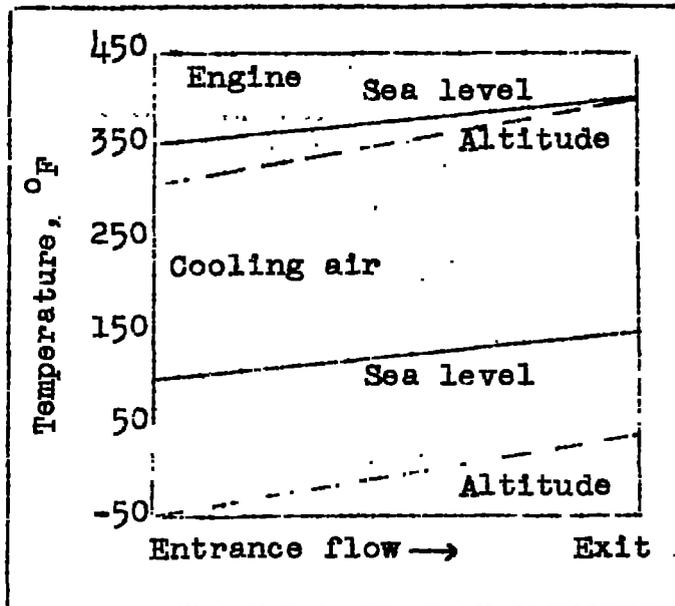


Figure 2.- Engine and cooling-air temperatures along the fin passages.

It may also be noted from figure 2 that an error will be introduced in the correlation if the temperature difference between the rear engine temperature and inlet cooling air is used instead of the mean temperature difference between the engine and the cooling air.

For purposes of this correlation the average cylinder and fin temperature is defined as

$$T_e = T_h - \frac{\Delta T_a}{2} \quad (5)$$

where T_h is a representative engine head temperature measured near the rear of the cylinder and ΔT_a is the cooling-air temperature rise. The representative engine temperature may be the average rear spark-plug temperature or the average temperature of a number of thermocouples imbedded in the cylinders at specified locations. For the idealized case shown in figure 2, T_e is the exact arithmetic mean temperature. For an actual engine, T_e can only be regarded as an approximation which approaches the effective average temperature.

The average cooling-air temperature is approximately

$$T_{av} = T_1 + \frac{\Delta T_a}{2} \quad (6)$$

Combining equations (5) and (6) and substituting $T_4 - T_1$ in place of ΔT_a ,

$$\Delta T = T_e - T_{av} = T_h - T_4 \quad (7)$$

Substituting equations (3), (4), and (7) in equation (2) and K_3 for $K_1 \times K_2$, equation (2) becomes

$$H = K_3 W_c^y (T_h - T_4) \quad (8)$$

Cooling-Air Pressure Loss

The cooling-air pressure loss is usually measured as the difference between the total pressure ahead of the engine at station 1 and the static pressure behind the engine at station 4. Since the directed dynamic pressure at these two stations is small, the total-pressure loss is almost the same as the static-pressure loss. The following pressure-loss equations are for total-pressure losses.

Between stations 1 and 2 the total-pressure loss is usually negligible. The pressure losses between stations 2 and 3 are due to friction-pressure loss and acceleration-pressure loss. Useful approximate equations for these pressure losses are:

$$\Delta P_f \propto q_{av} \propto \left(\frac{1}{\sigma_{av}} \right) W_c^2 \quad (9)$$

$$\Delta P_m \propto q_3 - q_2 \propto \left(\frac{1}{\sigma_3} - \frac{1}{\sigma_2} \right) W_c^2 \quad (10)$$

Between stations 3 and 4 an expansion and mixing pressure loss occurs. This is the largest pressure loss

between stations 1 and 4. (See reference 5.) It is given approximately by the following equation:

$$\Delta P_{ex} \propto q_3 \propto \left(\frac{1}{\sigma_3}\right) W_c^2 \quad (11)$$

In each of equations (9), (10), and (11), the controlling σ is σ_3 . An analytical summation of equations (9), (10), and (11) written in terms of the engine-operating conditions is usually quite complicated. Several papers have been written on the subject. Since equations (9), (10), and (11) are similar in form and σ_3 is the controlling density in each equation, recent attention has been directed to the establishment of an empirical relation between σ_3 , W_c , and the overall pressure loss.

It is difficult to measure the value of σ_3 . Reference 6 shows that, for an abrupt expansion in which the ratio of upstream area to downstream area is 0.1613, the density change for all Mach numbers is zero. For expansion area ratios near this value, the density change is small. For the usual aircraft engine the ratio of the free area in the fin passages at the baffle exit to the total area behind the engine is in this region. The density ratio σ_4 may therefore be used in place of σ_3 with little error.

The following approximation may be accurate for correlation purposes over a considerable range of fluid flows and amounts of heat flow:

$$(\sigma_4 \Delta P)^x = K_4 W_c \quad (12)$$

This approximation is suggested in reference 3 and indicated in reference 4, page 17, paragraph 4. Experimental confirmation of the relation for the case of a single cylinder operating under altitude-simulated conditions on a test stand is given in reference 7.

Combining equations (8) and (12),

$$H = C_1 (\sigma_4 \Delta P)^m (T_h - T_4) \quad (13)$$

Combining equations (1) and (12),

$$H = C_2 (\sigma_4 \Delta P)^x (T_4 - T_1) \quad (14)$$

Heat Flow on the Hot-Gas Side of the Cylinder

On an actual engine there are many factors influencing the heat flow from the hot combustion gases to the cylinder walls. The difficulty in correlation is in recognizing and isolating the important factors and in measuring their individual effects with accuracy.

Past work has shown that for a given engine installation, to a rough approximation, the heat flow is a function of the engine power. Another important factor is the fuel-air ratio. Other factors influence the heat flow to a lesser extent. At this time some of the other contributing factors which are recognized are the manifold pressure and temperature, engine speed, engine-operating temperature, cylinder temperature distribution, and manifold back pressure. Factors such as valve and spark timing, fuel type, cylinder geometry, and compression ratio are important in the heat flow from the hot gases to the cylinder; but, for a given engine installation with standardized fuel, these latter factors are constant and do not require consideration or measurement in the correlation procedure.

References 1 and 2 and much subsequent work done by the NACA have treated the heat flow on the hot-gas side of the cylinder in a manner similar to the treatment of the heat flow on the cooling-air side of the cylinder introducing the concept of the mean effective hot-gas temperature which is a function of several variables. In the interests of simplification and directness the following relationship is proposed:

$$H = C_3 I_e^n \quad (15)$$

where I_e is the indicated horsepower multiplied by correction factors for F/A , T_h , T_m , ΔT_1 , and ΔP_e . The correction factor for F/A may in extreme cases introduce a change of 40 percent in the value of I_e . The range of variation of the other variables is usually small and consequently the corrections for the other variables are not large. A discussion of the values of the correction factors and their relative importance is included in the section below on experimental procedure.

General Correlation Equations

Equations (13) and (14) may be combined with equation (15) to give the following general correlation equations by eliminating H :

$$(\sigma_4 \Delta P)^m (T_h - T_l) = C_4 I_e^n \quad (16)$$

$$(\sigma_4 \Delta P)^x (T_l - T_1) = C_5 I_e^n \quad (17)$$

EXPERIMENTAL PROCEDURE

Evaluation of the Constants and Exponents of the Correlation Equations

The exponents m , n , and x and the constants C_4 and C_5 of the correlation equations, (16) and (17), must be experimentally evaluated for each engine installation.

Since the measurement of σ_4 and the cooling-air temperature rise was not considered essential for successful correlation of engine-cooling data for low-altitude operation, no published data are available to check completely the method of correlation presented above. Recently published papers on engine-cooling correlation have shown the necessity for measurement of σ_4 and ΔT_a and it is to be hoped that complete

data will soon be available. The representative example given in this section does not apply to any given engine. The range of variation for the exponents has been calculated from a number of recently published data reports with an estimated allowance for the effects of σ_4 and ΔT_a included.

The following correlation procedure is suggested:

The exponent x may be evaluated by conducting a flow test upon a cold engine. The pressure drop across the engine may be varied and the weight flow of cooling air measured. The exponent x is the slope of the line obtained by plotting W_c against $\sigma_4 \Delta P$ on log log coordinates. In the representative example of this type of test shown in figure 3, the value of x is 0.56.

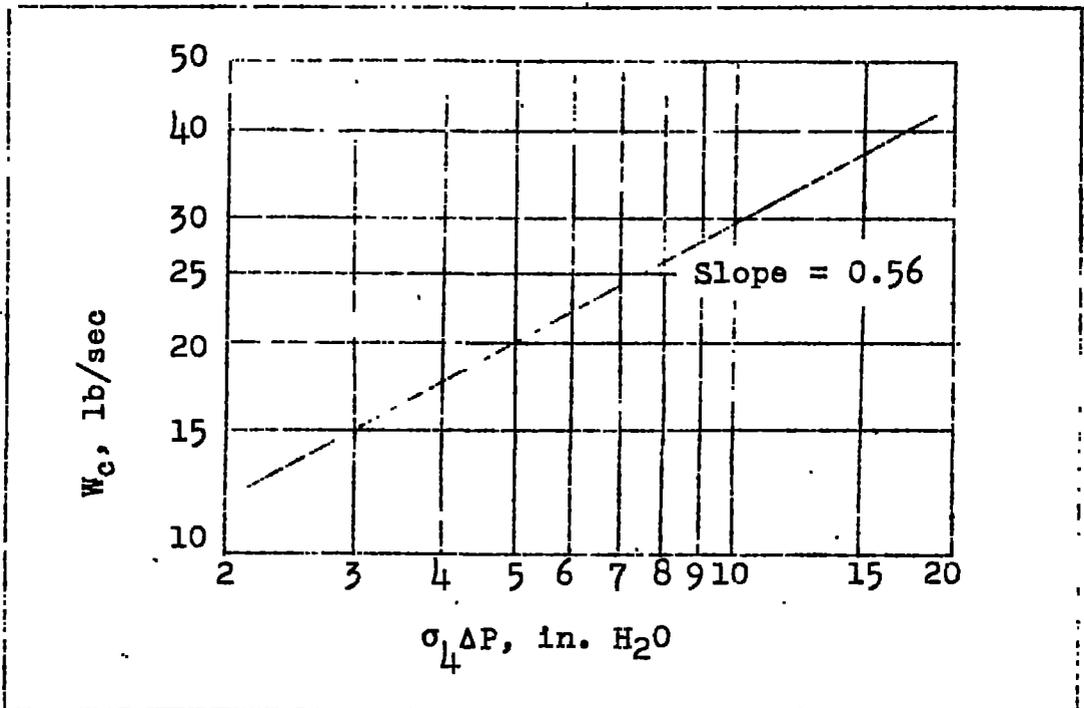


Figure 3.- Cooling-air flow versus pressure drop.

This value is obtained in references 3 and 6. In the present state of the art of building aircraft engines, the range of variation of this exponent is from about 0.55 to 0.59. Considerable changes in the finning and baffling and length-diameter ratio of the fin passages would not appreciably change the value of x .

The next step in the experimental procedure is to conduct a wind-tunnel or test-stand test in which the indicated horsepower is varied over a considerable range with the fuel-air ratio held at a convenient constant reference value. When equilibrium conditions exist, i_{hp} , P_1 , ΔP , T_1 , T_4 , T_m , T_h , and ΔP_e are measured. The correction factor for fuel-air ratio may be taken equal to 1.0 when F/A is held at the reference value. The other correction factors may be estimated as shown below.

Using the data obtained, $(\sigma_4 \Delta P)^x (T_4 - T_1)$ may be plotted against I_e on log log coordinates and the exponent n and the constant C_5 may be determined. An example of this type of plot is shown in figure 4 in

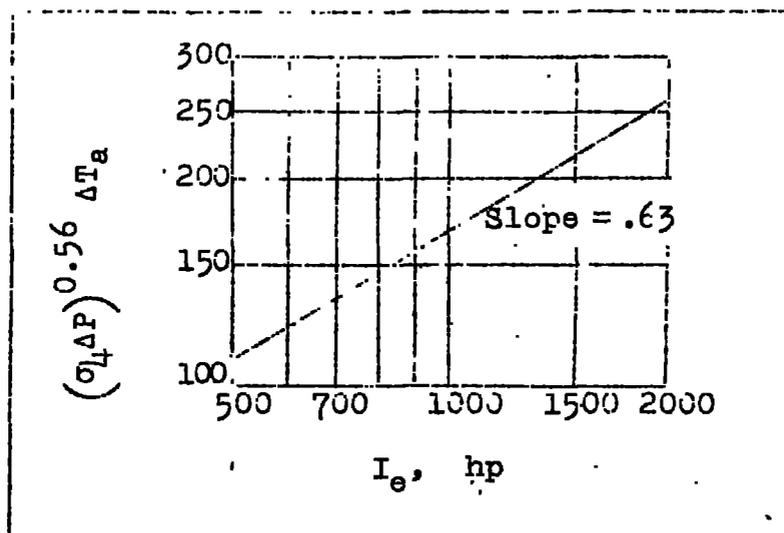


Figure 4.- $\Delta T_a (\sigma_4 \Delta P)^{0.56}$ versus I_e .

which n is equal to 0.63. The range of variation of n is from about 0.59 to 0.67. Such things as compression ratio, spark, and valve timing will affect the value of n . The constant C_5 is shown equal to 2.18. The value of C_5 varies considerably between different engine installations.

The exponent m and the constant C_4 may next be determined by plotting $I_e^m / (T_h - T_4)$ against $\sigma_4 \Delta P$ on log log coordinates. The exponent m is shown in figure 5 to be equal to 0.33. If engine fins are made wider and the fin spacing is narrower, m will be smaller, but progress that can be made in this direction is limited. The value of m changes very slowly with respect to fin width and spacing.

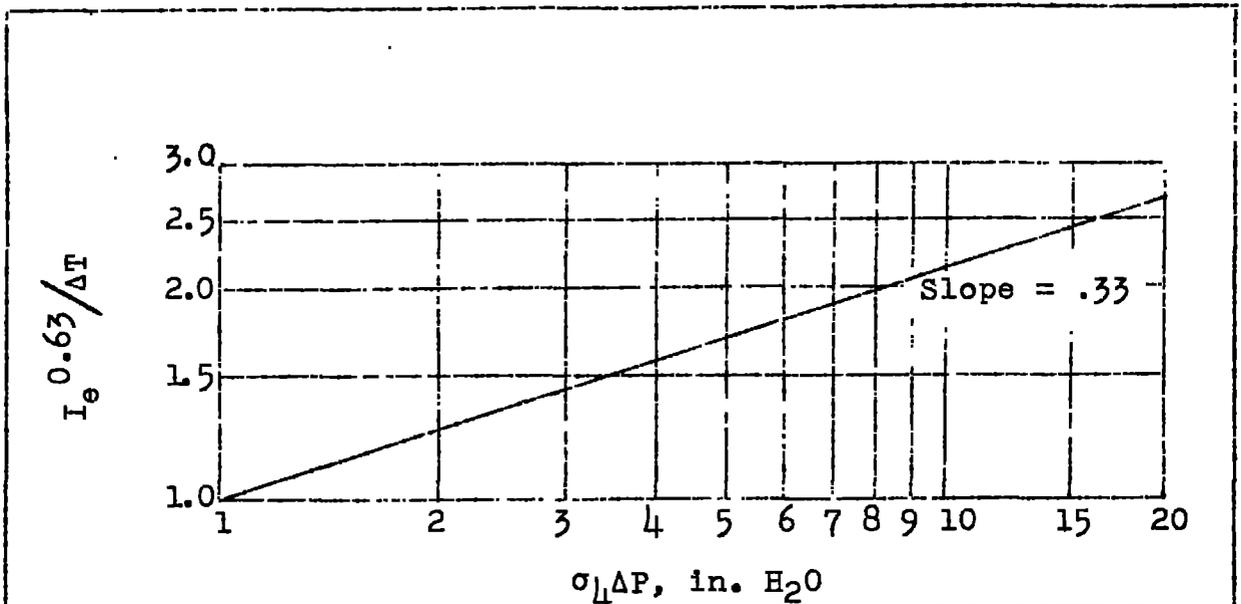


Figure 5.- $\sigma_4 \Delta P$ as a function of $I_e^{0.63} / \Delta T$.

The value of C_4 , shown to be equal to 6.00, varies considerably between engine installations.

The next test is to determine the effect of fuel-air ratio upon the heat flow. Several test points may be obtained with variable fuel-air ratio measuring ihp, $\sigma_4 \Delta P$, ΔT , etc. By equation (16),

$$I_e = \left[\frac{(\sigma_4 \Delta P)^m \Delta T}{C_4} \right]^{1/n} \quad (18)$$

By definition I_e is the measured indicated horsepower times the correction factors for F/A , T_h , T_m , ΔT_1 , and ΔP_e . Accordingly the correction factor for F/A may be written:

$$C_{F/A} = \frac{\left[\frac{(\sigma_4 \Delta P)^m \Delta T}{C_4} \right]^{1/n}}{\text{ihp times corrections for } T_h, T_m, \Delta T_1, \text{ and } \Delta P_e} \quad (19)$$

A typical test curve of $C_{F/A}$ versus F/A is shown in figure 6.

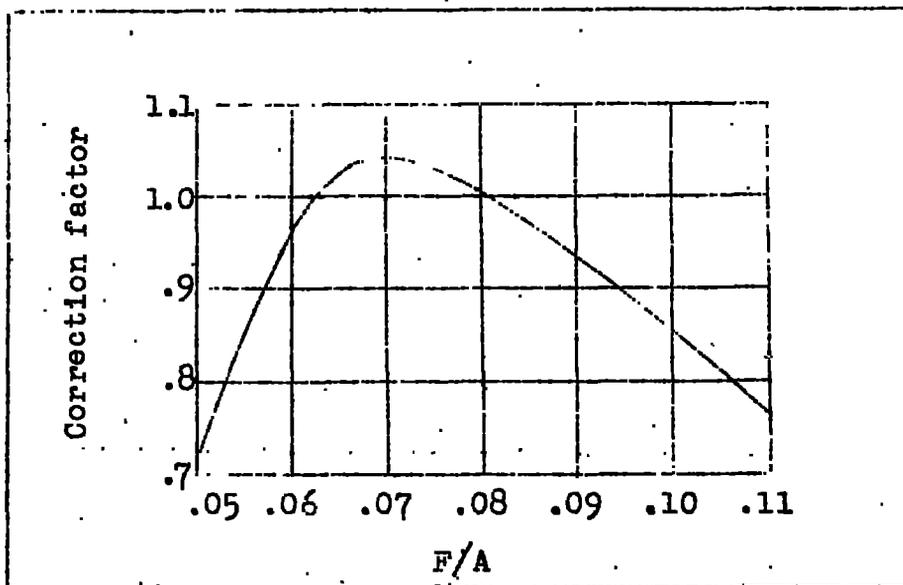


Figure 6.- Correction factor for fuel-air ratio.

Correction Factors for T_m , T_h , ΔT_1 , and ΔP_e

Obviously it is not possible in the preceding tests to hold the values of T_h , T_m , ΔT_1 , and ΔP_e constant while the tests are being run to determine the exponents and constants of the correlation equations. Feasible corrections can be applied by the results of past experience since the range of variation of these is not large during a test run and because the correction factors themselves are nearly equal to 1.0.

The effective average temperature of the charge air for heat-transfer purposes is about 1600° F absolute. (See references 1 and 2.) Most modern engines operate with average rear-cylinder temperatures about equal to 900° F absolute. A 50° difference in either of these temperatures thus causes roughly a 7-percent change in the average effective temperature difference between the cylinder head and the hot combustion gases. A 1° change in the manifold temperature causes a change of about 0.8° in the effective average hot-gas temperature. Accordingly a correction factor for T_m may be evaluated as is shown in figure 7. Any convenient value of T_m may be chosen as the reference value at which the correction is 1.0. The reference value shown in figure 7 is 250° F. This is a value near that at which the usual engine operates. It will be noticed that for a 50° change in the manifold temperature, an error of 20 percent in the correction factor for T_m will cause an error of less than 1 percent in the calculated heat dissipation. For most purposes the correction factor for T_m shown in figure 7 will serve for all engine-cooling tests. If it is believed that T_m for a given engine has an unusual effect on the heat dissipation, the correction factor of figure 7 may be used in the correlation tests to establish the constants and exponents of the equations and then the engine may be tested specifically for the effect of T_m by varying it over a wide range and determining the resulting correction in a manner similar to the way in which the correction for F/A was established.

The same procedure may be used with the remaining corrections given in the following discussion as is done in determining the correction factor for T_m .

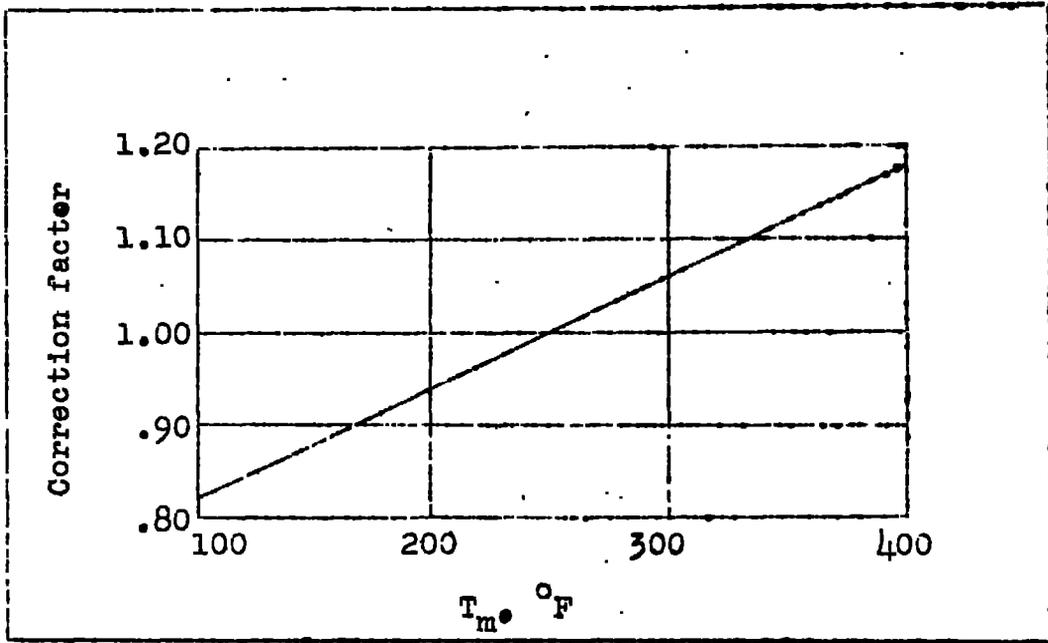


Figure 7.- Correction factor for T_m .

The correction factor for T_h is shown in figure 8.

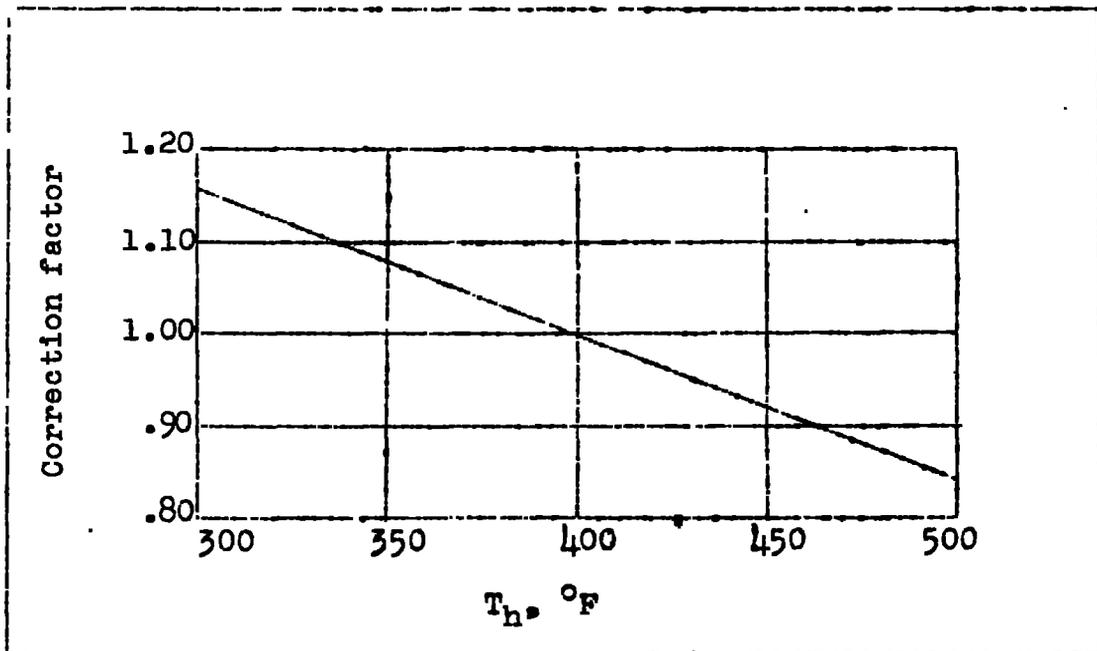


Figure 8.- Correction factor for T_h .

This correction was determined in the same manner as that for T_m , on the basis of the usual existing temperature difference between the hot-gas temperature and the cylinder.

Usually T_h is not the average of front and rear engine-cylinder temperatures but is a temperature measured near the rear of the cylinder. Like many other factors which enter into the cooling picture an integrated average cylinder temperature is physically significant but cannot be successfully measured. The fin temperatures near the front of the cylinders may approach the entrance cooling-air temperature while the rear spark-plug-gasket temperature may be as hot as 500° F. As the temperature of the cooling air decreases, the relative weight flow of cooling air required for adequate engine cooling also decreases. The temperature change of the cooling air will increase. It is evident that these changes which occur as the flight altitude increases will cause a change in the temperature distribution around the cylinder which results in a larger difference between the average cylinder temperature and the temperature T_h measured at the rear of the cylinder. (See fig. 2.) Therefore, for a given value of T_h , as T_1 decreases, a greater over-all temperature difference exists between the hot combustion gases and the engine cylinder. The correction factor for ΔT_1 shown in figure 9 accounts for this effect which is small for

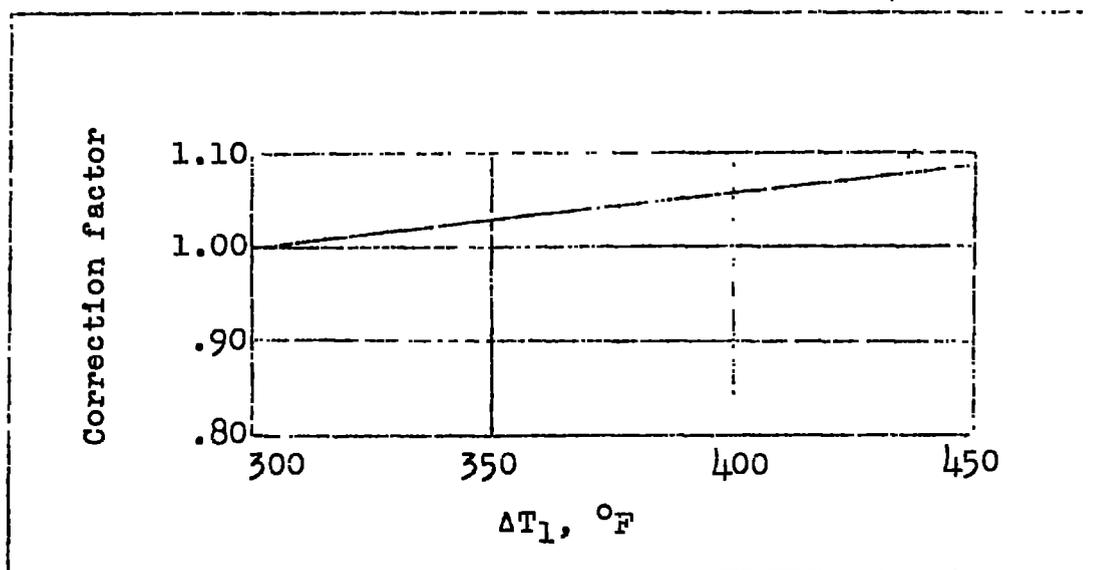


Figure 9.- Correction factor for ΔT_1 .

sea-level tests but important at high altitudes. The magnitude of this correction was estimated on the basis of the idealized case shown in figure 2.

The correction factor for ΔP_e is shown in figure 10. A variation of 15 inches of mercury in the back pressure causes a change in the heat dissipation of $6\frac{1}{2}$ percent. This correction is determined from recent unpublished test data.

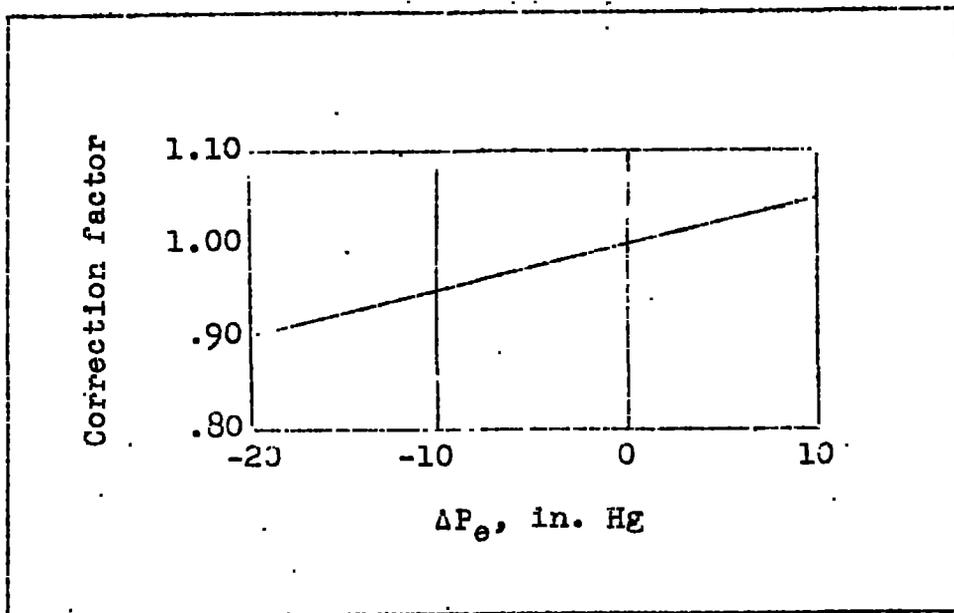


Figure 10.- Correction factor for ΔP_e .

ILLUSTRATIVE EXAMPLE

With the engine-cooling-correlation curves of equations (16) and (17) established by methods developed in the section on experimental procedure, it is desirable to present the cooling-performance information in a form that will be most useful to the engine designers and operators. The example given in this section shows the

cooling-air pressure loss as a function of engine power and altitude for carburetor settings of maximum economy and automatic rich for an engine temperature T_h of 400° F.

The following procedure is used to solve equation (17) for P:

From the gas law,

$$\sigma_4 = \frac{T_0 + 460}{T_4 + 460} \frac{13.6P_1 - \Delta P}{13.6P_0} \quad (20)$$

The value of T_0 is 59° F and the value of P_0 is 29.9 inches of mercury.

Substituting for σ_4 in equation (17) and solving for ΔP by the binomial theorem:

$$\Delta P = \frac{13.6P_1 - \sqrt{(13.6P_1)^2 - \frac{12.64 (T_4 + 460)}{(T_4 - T_1)^{1.79}} I_e^{1.12}}}{2} \quad (21)$$

Equation (21) contains the variable T_4 which is not given by the initial conditions. To determine T_4 eliminate $\sigma_4 \Delta P$ from equations (16) and (17) to obtain

$$\frac{(T_h - T_4)^{3.03}}{(T_4 - T_1)^{1.79}} = 56.7 I_e^{0.781} \quad (22)$$

The value of T_4 may be obtained from equation (22) for any values of T_h , T_1 , and I_e . Using 400° F for T_h , a figure may be constructed showing T_4 as a function of I_e with T_1 as a parameter. Figure 11 is constructed by assigning values to T_4 and T_1 and solving for the resulting value of I_e .

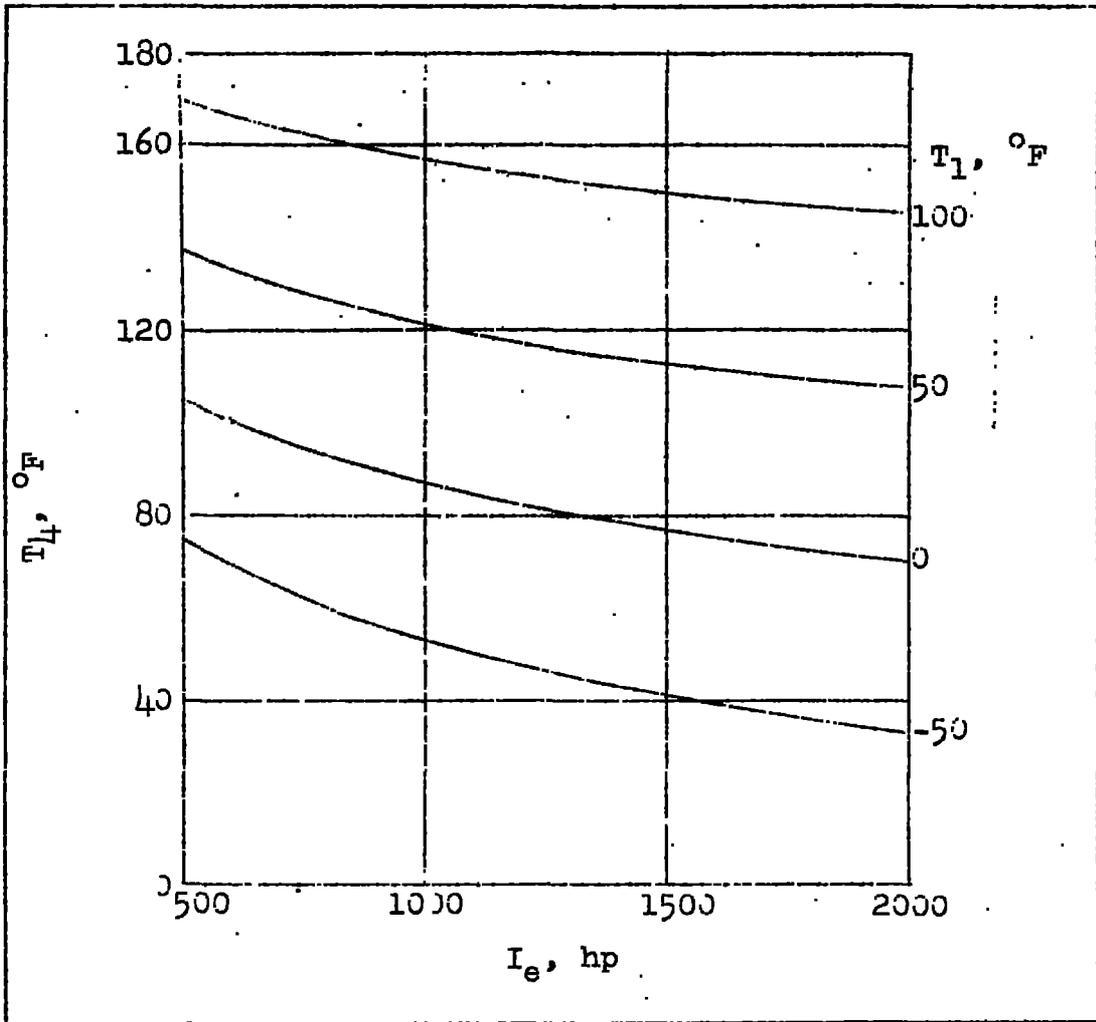


Figure 11.- T_4 as a function of I_e and T_1 .

We may now use figure 11 to determine T_4 and calculate the value of ΔP for any altitude or engine-operating condition with T_h equal to 400°F . A value of T_4 for any other value of T_h may be determined from figure 11 by adding $T_h - 400$ to the values of T_4 and T_1 of figure 11.

Figure 12 shows ΔP as a function of I and altitude for three engine-mixture conditions - automatic rich, maximum economy, and, as a comparison, I uncorrected. A typical calculation necessary to determine a point on figure 12 follows for the condition of automatic rich carburetor setting at 2000 indicated horsepower at 20,000 feet altitude.

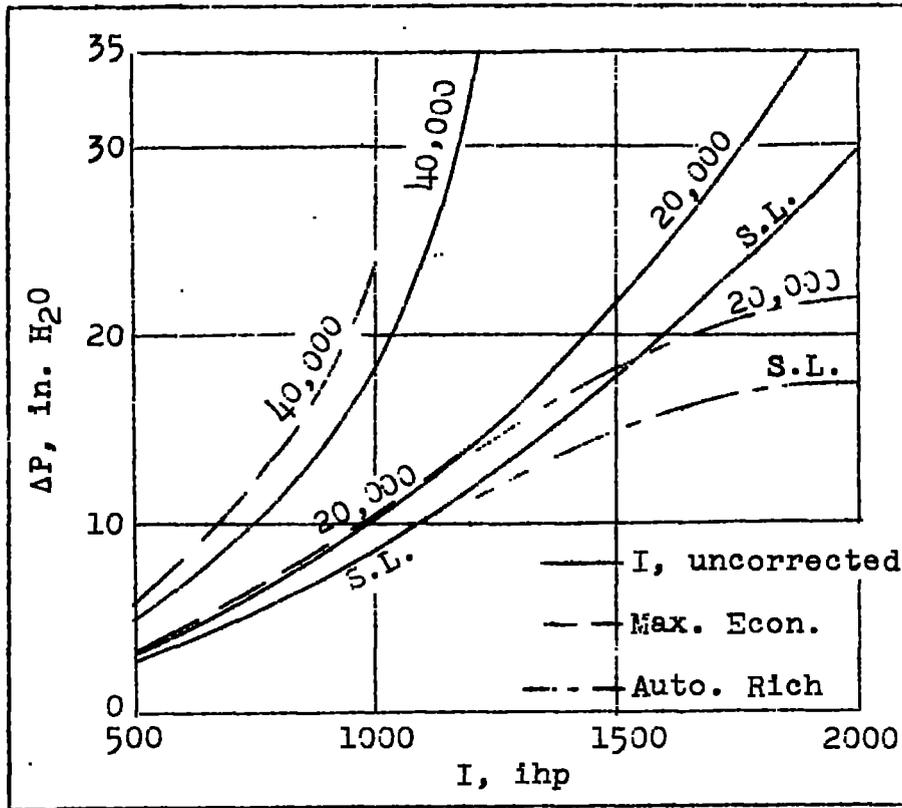


Figure 12.- Pressure drop as a function of horsepower and altitude.

The fuel-air ratio as a function of engine power for automatic rich carburetor setting is shown in figure 13.

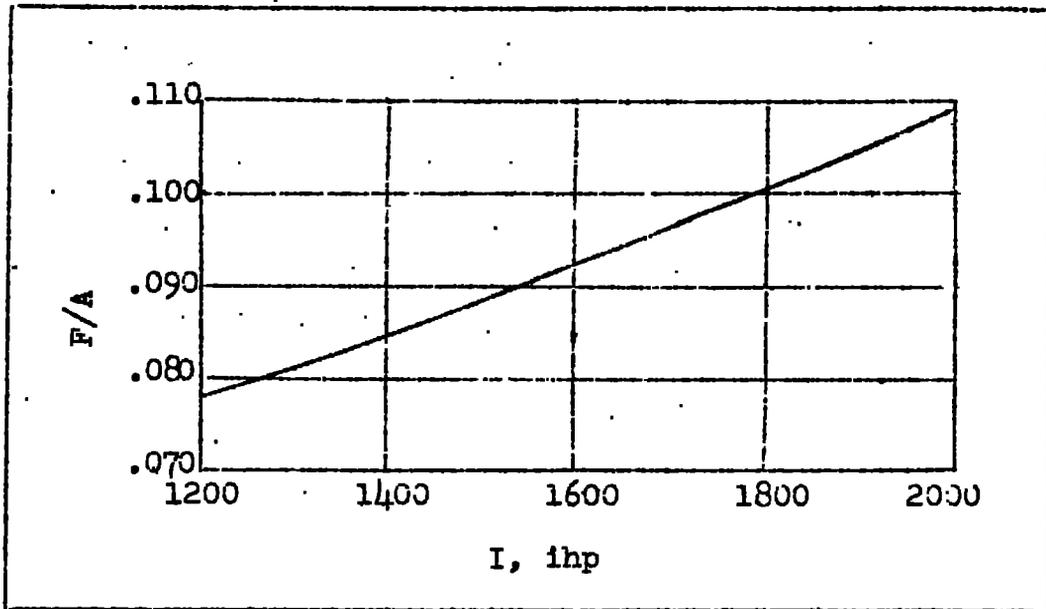


Figure 13.- Fuel-air ratio versus I for automatic rich carburetor setting.

Altitude, feet 20,000

From tables of Army summer air:

$P_{\text{free air}}$, inches of mercury	13.8
$T_{\text{free air}}$, $^{\circ}\text{F}$	28
Assumed ram pressure rise	0
Assumed ram temperature rise	0
P_1 , inches of mercury	13.8
T_1 , $^{\circ}\text{F}$	28
Assigned value of I, indicated horsepower	2000
F/A from figure 13	0.109
$C_{\text{F/A}}$ from figure 6	0.77
Calculated value of T_m , $^{\circ}\text{F}$	250
Correction for T_m from figure 7	1.00
Assigned value of T_h , $^{\circ}\text{F}$	400
Correction for T_h from figure 8	1.00

$T_1 = T_h - T_1$, °F	372
Correction for T_1 from figure 9	1.04
P_e (turbocharger installation), inches of mercury	30.0
Correction for ΔP_e from figure 10	1.00
I_e (I times correction factors)	1610
T_4 from figure 11, °F	98

Substitute the above values in equation (21)

$$\Delta P = \frac{13.6 \times 13.8 - \sqrt{(13.6 \times 13.8)^2 - \frac{12.6 (98 + 460)}{(98 - 28)^{1.79}} \times 1610^{1.12}}}{2}$$

$$\Delta P = 21.8 \text{ in. H}_2\text{O}$$

CONCLUDING REMARKS

A method of correlating engine-cooling test data taken under various conditions based on present usage and incorporating recent improvements has been developed. The advantages of the method are:

1. Temperature differences are used which approach the effective average values. The weight flow of cooling air which determines the rate of heat flow for given temperature differences is related to the cooling-air pressure loss and the density of the air behind the engine cylinders. In consequence of these improvements, good correlation is assured over a larger range of altitudes.

2. Application of the method to the solution of specific problems is simple and direct. This has been accomplished by relating the heat flow on the hot-gas side of the cylinder to the indicated horsepower corrected for fuel-air ratio, several temperatures, and the exhaust back pressure.

3. Comparatively few tests are required to obtain the necessary constants of the correlation equations. It is not necessary to make separate test runs with constant values of the cooling-air pressure loss and the indicated horsepower. The tests may be made on a test stand or in a wind tunnel at sea level or in flight at any altitude.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., January 17, 1945

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