REPORT NO. 804

AIR-CONSUMPTION PARAMETERS FOR AUTOMATIC MIXTURE CONTROL OF AIRCRAFT ENGINES

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SUMMARY

Data obtained from Navy calibration tests of an 18-cylinder, two-row, radial engine of 3350-cubic-inch displacement and a 14-cylinder, two-row, radial engine of 2600-cubic-inch displacement (carburetor types) were analyzed to show the correlation between the air consumption of these engines and the parameters that evaluate the air consumption from intake-manifold temperature and pressure, exhaust back pressure, and engine speed.

The analyses showed that, for the speed range reported, the air consumption of these engines could be represented as a continuous single-valued function of intake-manifold temperature and pressure, exhaust back pressure, and engine speed. This function was shown to be adaptable for automatic mixture control on an engine with a continuous injection system. The analyses indicated that even better adaptability existed for a timed injection system. Design information required for the construction of controls for a fuel-injection system using the foregoing type of automatic mixture control was presented for the two engines. The analyses also showed that the parameters varied for different engine designs and that calibration tests would therefore be required for each design.

INTRODUCTION

The successful design of a mixture-control system for an aircraft power plant requires a fuel-metering system that is specifically related to the air consumption of the engine for which it is designed. (See reference 1.) Both past and recent American developments have involved the use of a venturi for measuring air flow to an engine and, as such, are limited to the conditions under which venturis operate.

The purpose of this analysis was to investigate the use of a function of intake-manifold pressure, exhaust back pressure, intake-manifold temperature, and engine speed in place of a venturi as a means of measuring engine air consumption and to determine if this function is suitable for automatic mixture control. This type of control will be considered for use with either a continuous or a timed fuel-injection system. Practical considerations show that, when used with timed fuel injection, this type of control offers greater simplicity (reference 2) than mass air-flow control.

Although successful designs utilizing a manifold-pressure type of automatic mixture control with timed fuel injection are on the Junkers Jumo JU–211D, the Daimler-Benz 601–A, and the BMW–801 engines, the fundamental relations on which these designs are based are still largely unknown. The secondary purpose of this analysis was to provide some information on the possible line of reasoning behind these designs.

The data for this analysis were obtained from calibration tests performed on two carburetor-type engines having 18 and 14 cylinders at the Naval Material Center, Naval Air Experimental Station, Philadelphia. These calibration tests were the only ones available that contained sufficient information on which a complete analysis could be based.

The analysis presented herein was made at the NACA Cleveland laboratory during the latter part of 1943.

METHOD OF ANALYSIS

The amount of charge taken in by an engine is influenced by intake-manifold pressure, exhaust back pressure, intake-manifold temperature, exhaust-gas temperature, intake-valve and exhaust-valve areas, valve timing, cylinder-head and cylinder-barrel temperatures, fuel-air ratio, engine speed, and heat transfer before intake-valve closure. Although it would be desirable to account for all these factors in a control system, only those factors that have a predominating influence on the air consumption of a particular engine are considered in this analysis. These factors are: (1) intake-manifold pressure, (2) exhaust back pressure, (3) intake-manifold temperature, and (4) engine speed. The change in air flow produced by a change in cylinder temperature or fuel-air ratio is accounted for only by its effect on intake-manifold temperature.

The function of the analysis is as follows: (1) to determine if the air consumption of an engine can be represented as a continuous single-valued function of the absolute intake-manifold pressure and exhaust back pressure at a given intake-manifold temperature and engine speed; (2) to determine the relation between engine air consumption and intake-manifold temperature; and (3) to determine the relation between engine air consumption and engine speed.

In order to use these relations for control mediums, they must be both continuous and single valued. On this basis a control system would probably consist of one unit responsive to a change in intake-manifold pressure and exhaust back pressure and another unit responsive to a change in intake-manifold temperature. In a continuous injection system, the effect of engine speed could be accounted for by a governor or by a variable-displacement fuel pump with the proper speed-delivery characteristics. The speed effect in a timed injection system could be accounted for in the speed-delivery characteristics of the fuel-injection pump.

The method of analysis consists in obtaining engine air-consumption data such that the following series of curves can be plotted and analyzed for trends:

(a) Air flow against intake-manifold pressure at various constant speeds but at a constant exhaust back pressure and intake-manifold temperature

(b) Curves similar to (a) but at various exhaust back pressures

(c) Air flow against intake-manifold pressure at various exhaust back pressures but at constant speed and intake-manifold temperature

(d) Air flow against intake-manifold temperature at constant intake-manifold pressure, exhaust back pressure, and speed

(e) Several curves similar to (d) but at various intake-manifold pressures, exhaust back pressures, and speeds

The first two series of curves ((a) and (b)) give the complete air flow-speed characteristics of the engine. Cross plots of these curves indicate the speed response that must be incorporated in the control system.

The (c) series of curves provides the information from which the parameter representing the change in air flow for different intake-manifold pressures and exhaust back pressures can be obtained. This information is necessary for the design of the pressure-responsive unit.

The (d) and (e) series of curves provide the information from which the temperature-responsive unit can be designed.

The following symbols are used in the analysis:

k_1 engine constant, 18-cylinder engine (5.43 for engine used in this investigation)

k_2 engine constant, 14-cylinder engine (5.5 for engine used in this investigation)

n engine speed, rpm

p_e exhaust back pressure, inches mercury absolute

p_m intake-manifold pressure measured at supercharger-case rim, inches mercury absolute

t_m intake-manifold temperature, °F

W air flow, pounds per cycle

Pressure at the supercharger-case rim was used in preference to the intake-manifold pressure because the pressure from only one intake manifold was available. It was thought that the pressure at the supercharger-case rim would probably give a better indication of the total air flow than the pressure at the one known cylinder.

Altitude pressure is considered as the exhaust back pressure for mechanically driven supercharged engines, such as the 18- and 14-cylinder engines used in this analysis; whereas the pressure in the exhaust manifold must be considered as the exhaust back pressure for exhaust turbine-driven supercharged engines.

The intake-manifold temperature for engines that have a carburetor-type fuel-metering system is commonly referred to as the "mixture temperature." For the test data analyzed, this temperature was measured by an unshielded thermocouple in the intake manifold approximately 6 inches from the intake port.

The air flow is the total weight of air in pounds that passes through the engine in one cycle. In the engines tested, this quantity is 18 and 14 times the quantity of air consumed by a single cylinder during the completion of one cycle of its operation.

ANALYSIS AND RESULTS

PARAMETERS FOR 18-CYLINDER ENGINE

The results of the analysis on the 18-cylinder engine are presented in figures 1 to 5. This engine has a 6.125-inch bore, a 6.3125-inch stroke, and a 48° valve-overlap period. The test work from which these data were obtained was conducted according to standard Navy calibration methods; that is, the carburetor-air supply (temperature and pressure) and exhaust back pressure were controlled. This method results in a considerable variation in intake-manifold temperature for different operating conditions owing to the geared supercharger and the introduction of fuel ahead of the supercharger. In order to plot these data according to the previously outlined methods, correction of the data to a standard intake-manifold temperature was necessary. The data available for determining a temperature correction factor are reproduced in figure 1. These data show the relation between air flow and intake-manifold temperature

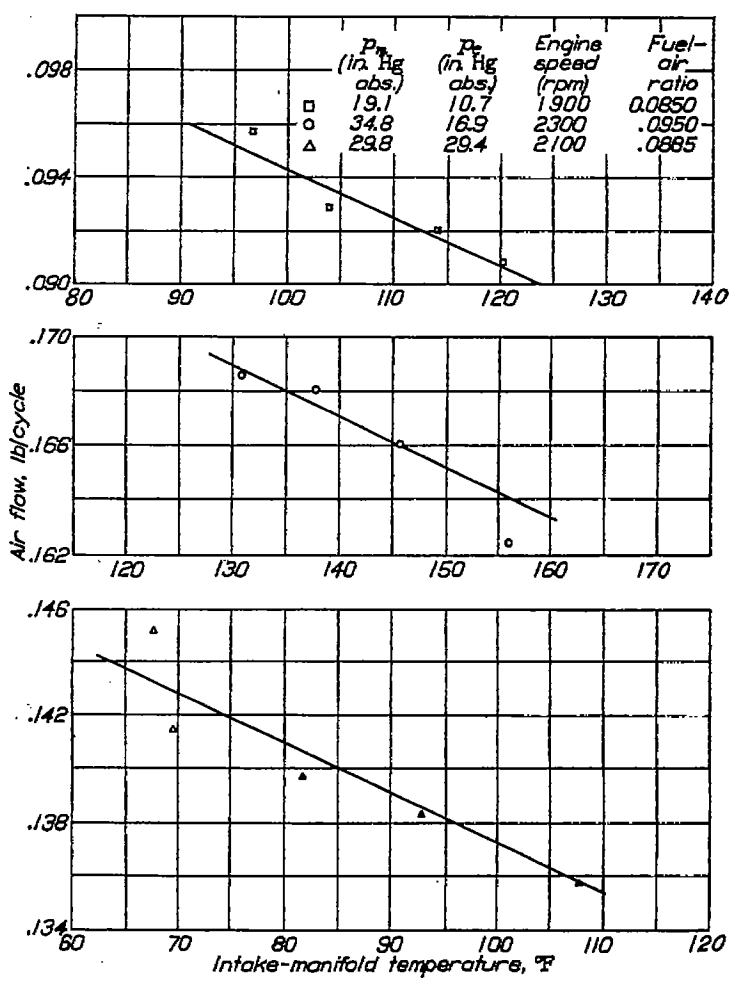

FIGURE 1.—Variation of air flow with intake-manifold temperature for 18-cylinder engine of 3350-cubic-inch displacement.

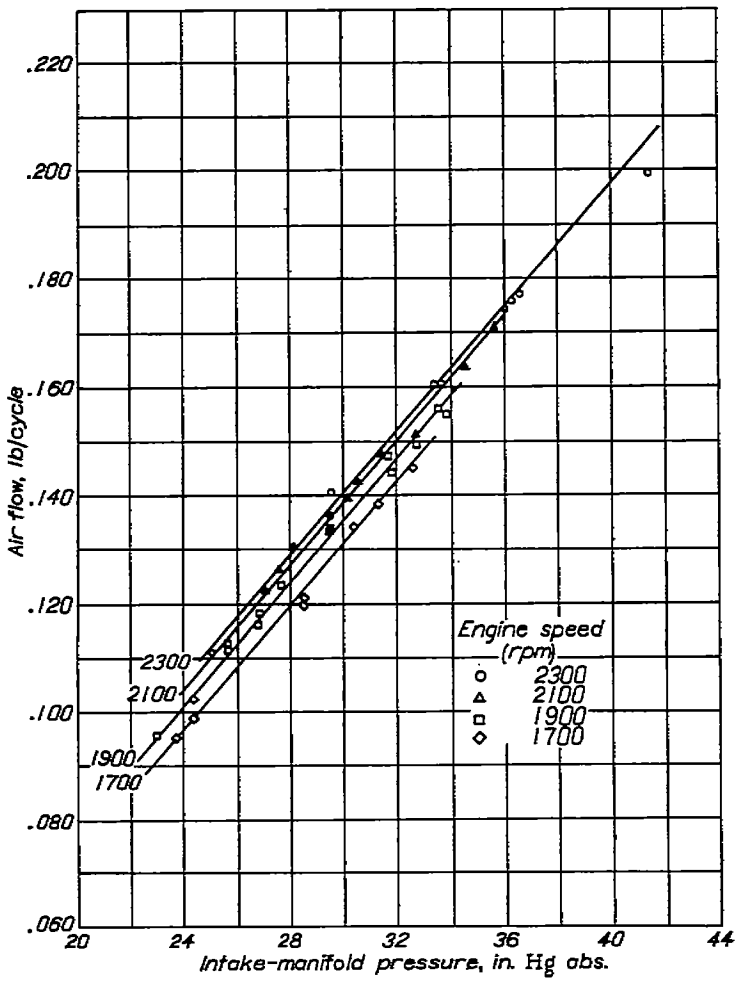

FIGURE 2.—Variation of air flow with intake-manifold pressure at various engine speeds for 18-cylinder engine of 3350-cubic-inch displacement. Exhaust back pressure, 30.00±0.6 inches mercury absolute; air flow corrected to intake-manifold temperature of 100° F.

at three different conditions of intake-manifold pressure p_m, exhaust back pressure p_e, and engine speed. Linear curves of identical slope were drawn through the data points of all three conditions with a maximum deviation of less than 2 percent. Thus, despite the fact that the limited data available for any particular condition might indicate a slightly different slope, the close approximation of the single slope over the entire range made its use justifiable and workable. The value determined for this slope was 0.00019 pound per cycle per °F and is the temperature response that must be incorporated in the control system. The data were then corrected to a constant intake-manifold temperature of 100° F by the use of the foregoing temperature correction factor.

A plot of air flow in pounds per cycle against intake-manifold pressure at various speeds but at a constant exhaust back pressure is shown in figure 2. The faired curves through the points for the four engine speeds are four parallel straight lines indicating a linear relation between air flow and absolute intake-manifold pressure. With the exception of one point (intake-manifold pressure of 41.5 in. Hg absolute at 2300 rpm), the variation of the plotted data from the curves is less than 2 percent. Sufficient data at other back pressures for curves similar to those in figure 2 were not avail-

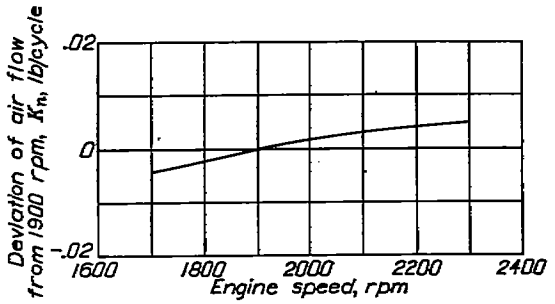

FIGURE 3.—Deviation of air flow with engine speed for 18-cylinder engine of 3350-cubic-inch displacement. (Cross plot of data from fig. 2.)

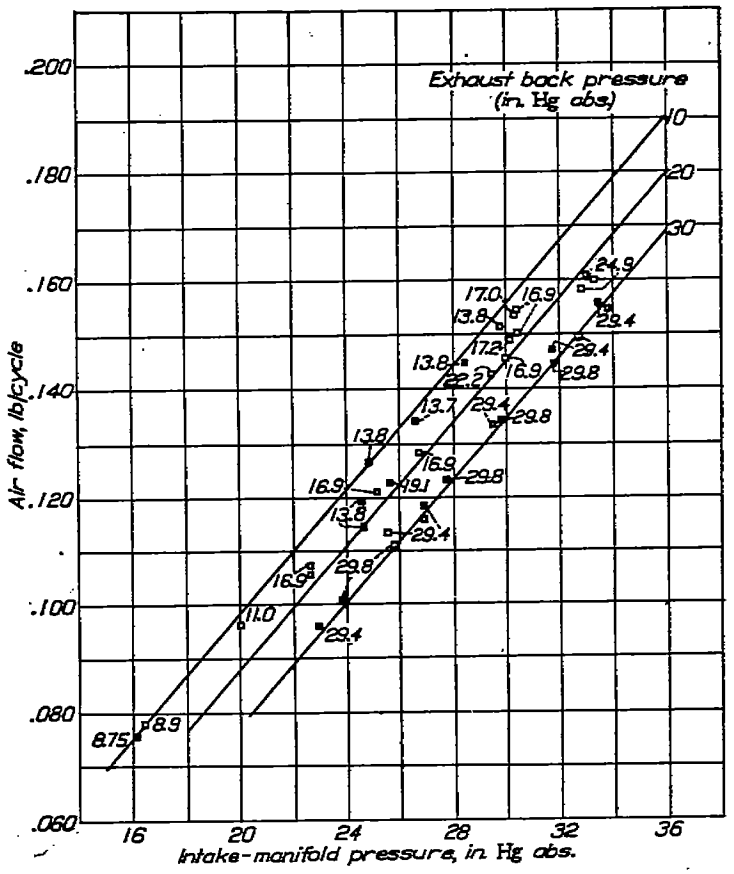

FIGURE 4.—Variation of air flow with intake-manifold pressure and exhaust back pressure at constant engine speed for 18-cylinder engine of 3350-cubic-inch displacement. Engine speed, 1900 rpm; air flow corrected to intake-manifold temperature of 100° F. (Numerical values are exhaust back pressures, in. Hg absolute.)

able. Figure 3 is a cross plot of figure 2 and shows the effect of engine speed on engine air consumption. Because the effect of engine speed is independent of manifold pressure, the deviations in air flow from 1900 rpm rather than actual air-flow values at one condition of manifold pressure were selected for the ordinate scale in figure 3. The symbol K_n has been assigned to this ordinate for use in later computations. The curve in figure 3 provides the design data for the speed response that must be incorporated in the control system.

Air-flow data at various intake-manifold and exhaust back pressures but at a constant engine speed of 1900 rpm are presented in figure 4. Three lines have been interpolated and represent the air consumption at exhaust back pressures of 10, 20, and 30 inches of mercury absolute. A linear rela-

tion of air flow with respect to both intake-manifold pressure and exhaust back pressure is indicated by these lines. The following equation of these lines represents the air consumption at 1900 rpm and an intake-manifold temperature of 100° F:

$$W\begin{pmatrix}1900\text{ rpm}\\100°\text{F}\end{pmatrix}=0.00105\,k_1(p_m-p_e)-0.0045 \qquad (1)$$

With the term $k_1(p_m-p_e)$ in equation (1) as the abscissa, figure 5 was plotted from the data in figure 4. This figure shows the scatter of the data with respect to equation (1), which is represented by the line drawn on this figure. The abscissa in figure 5 represents the relation in accordance with which the pressure-responsive unit must be designed.

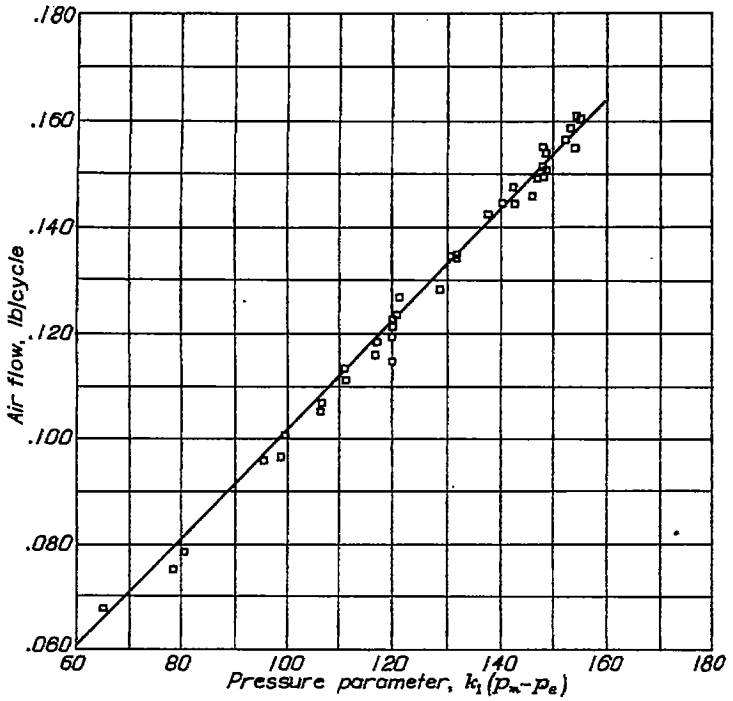

FIGURE 5.—Variation of air flow with pressure parameter for 18-cylinder engine of 3350-cubic-inch displacement. Engine speed, 1900 rpm; air flow corrected to intake-manifold temperature of 100° F. (Replotted from fig. 4.)

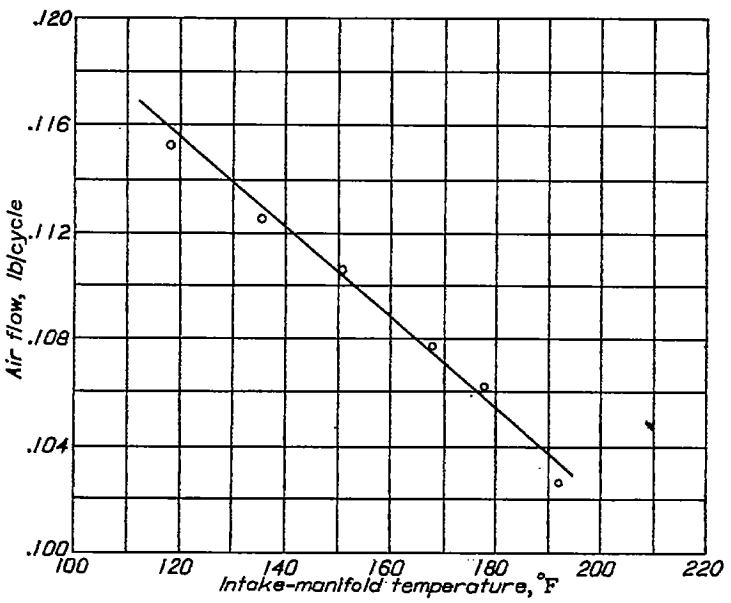

FIGURE 6.—Variation of air flow with intake-manifold temperature for 14-cylinder engine of 2000-cubic-inch displacement. Intake-manifold pressure, 29.9 inches mercury absolute; exhaust back pressure, 18.3 inches mercury absolute; engine speed, 2200 rpm; fuel-air ratio, 0.088.

An equation representing the air consumption of the 18-cylinder engine at any intake-manifold pressure, exhaust back pressure, intake-manifold temperature, and engine speed is

$$W=\underbrace{0.00105\,k_1(p_m-p_e)}_{\text{Pressure parameter}}+\underbrace{0.00019\,(100-t_m)}_{\text{Temperature parameter}}+K_n-0.0045 \qquad (2)$$

The speed factor K_n in equation (2) is the ordinate in figure 3 for the particular speed at which the air consumption is desired. An algebraic relation has not been incorporated in equation (2) because of its complexity.

The use of a linear speed response in place of the response indicated in figure 3 would result in the introduction of an error of approximately 1 percent. A linear response might be more feasible in some control systems, but the more desirable speed response would be that indicated in figure 3. Reference 3 describes methods of obtaining various speed-delivery characteristics in a fuel-injection pump without the use of any special speed-responsive mechanism. Variations of several of these methods could probably be used in a timed fuel-injection system to obtain the speed response indicated in figure 3.

Equation (2) and figure 3 provide the design basis for construction of an automatic mixture-control system for the 18-cylinder engine that uses as the control mediums: intake-manifold pressure, exhaust back pressure, intake-manifold temperature, and engine speed.

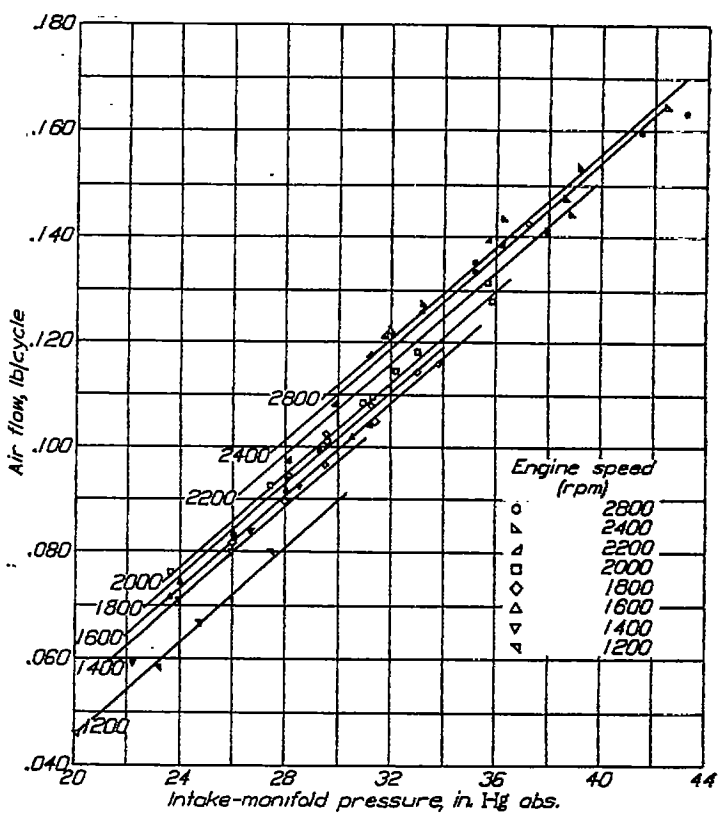

FIGURE 7.—Variation of air flow with intake-manifold pressure at various engine speeds for 14-cylinder engine of 2000-cubic-inch displacement. Exhaust back pressure, 30.00±0.5 inches of mercury absolute; air flow corrected to intake-manifold temperature of 100° F

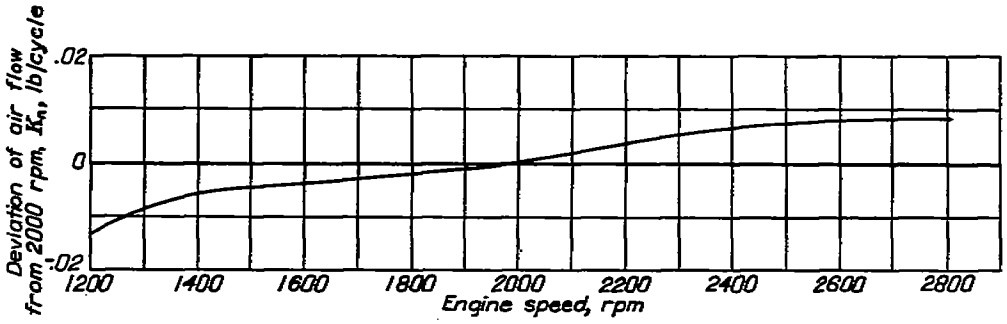

FIGURE 8.—Deviation of air flow with engine speed for 14-cylinder engine of 2600-cubic-inch displacement. (Cross plot of data from fig. 7.)

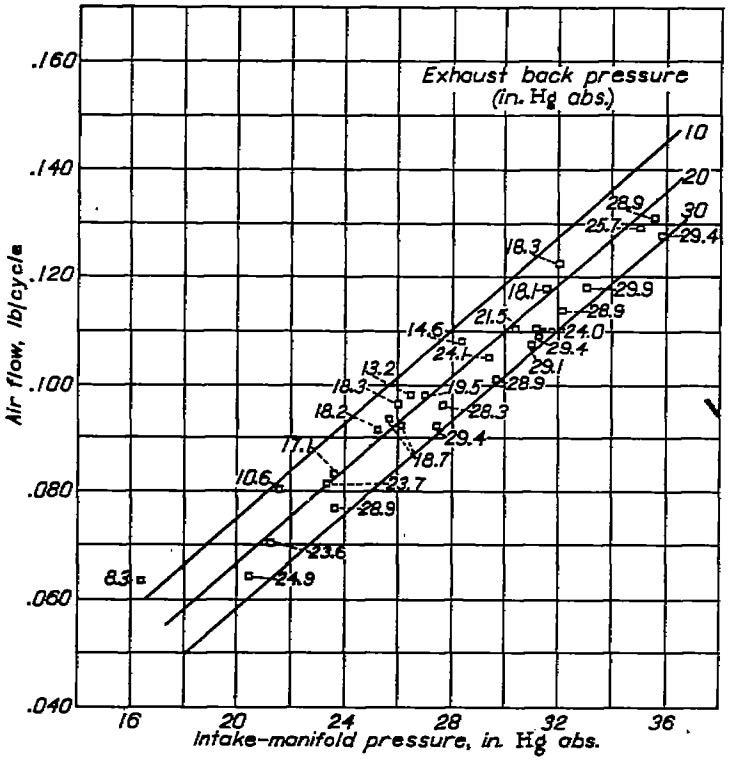

FIGURE 9.—Variation of air flow with intake-manifold pressure and exhaust back pressure at constant engine speed for 14-cylinder engine of 2600-cubic-inch displacement. Engine speed, 2000 rpm; air flow corrected to intake-manifold temperature of 100° F. (Numerical values are exhaust back pressures, in. Hg absolute.)

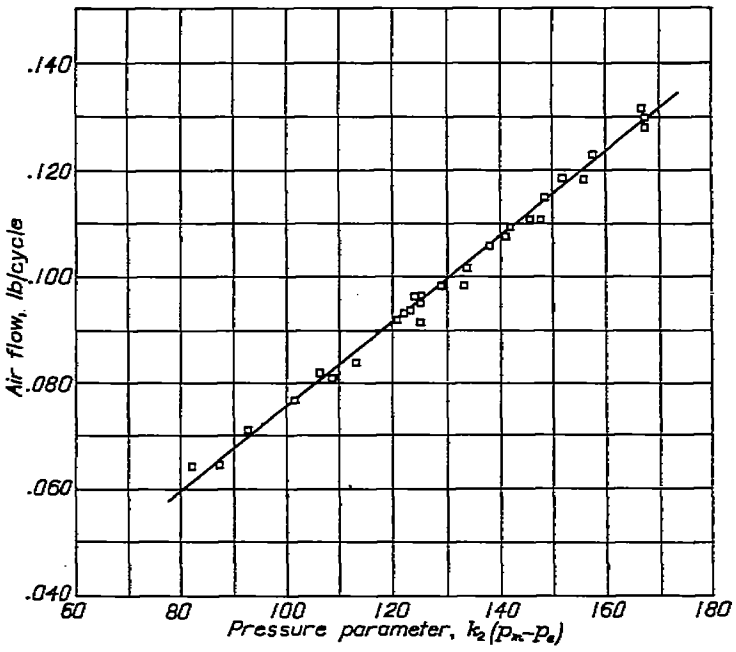

FIGURE 10.—Variation of air flow with pressure parameter for 14-cylinder engine of 2600-cubic-inch displacement. Engine speed, 2000 rpm; air flow corrected to intake-manifold temperature of 100° F.

PARAMETERS FOR 14-CYLINDER ENGINE

A similar procedure was carried out with data from the 14-cylinder engine. The results are presented in figures 6 to 10, which, in general, are similar to figures 1 to 5 for the 18-cylinder engine. The exceptions are a slight difference in the numerical values of the temperature and pressure parameters and the speed characteristics. The faired curves in figure 7 are parallel straight lines and thus indicate a relation between air flow and engine speed that is again independent of manifold pressure. The maximum deviation of most of the data is within 2 percent.

The equation representing the air consumption of the 14-cylinder engine at any engine operating condition is

$$W=0.0008\ k_2(p_m-p_e)+0.00017\ (100-t_m)+K_n-0.006 \qquad (3)$$

Pressure parameter Temperature parameter

The speed factor K_n is plotted on figure 8 and is used in the same manner as described for the 18-cylinder engine. Figure 8 shows the variation in air flow to a minimum speed of 1200 rpm. An engine is, however, seldom operated for any prolonged periods at speeds below 1500 rpm; this fact permits an increase in the mixture tolerances in the speed range below 1500 rpm and thus reduces the requirements for an acceptable mixture-control system for this engine. The data for speeds below 1500 rpm are presented in order to show that the correlations between engine air consumption and the parameters are valid for all speeds for which data are now available. The substitution of a linear speed response above 1500 rpm for the response shown in figure 8 would introduce a maximum error of less than 2 percent. Data at conditions other than those shown in any of the figures were either missing or insufficient for a reliable analysis.

DISCUSSION AND APPLICATION OF RESULTS

The close agreement between the pressure parameters of the 18-cylinder and the 14-cylinder engines is probably due to the similarity in intake and exhaust systems and the fact that the dimensions and construction of the two cylinders correspond very closely. The slight difference in the pressure parameters may be attributed to the difference in valve timing and in the valve-overlap period. The 14-cylinder engine has a valve-overlap period of 60°; whereas the 18-cylinder engine has a valve-overlap period of 48°. The difference in the constants in equations (2) and (3) is believed

to be due to the different number of cylinders in these engines. Data from more engines are necessary before any definite statements can be made as to which factors have the greatest effect on air consumption.

The scatter of some of the data is believed to be due to the difficulties encountered in obtaining reliable intake-manifold temperatures with carburetor-type engines. Better correlations would probably be obtained if there were no fuel in the intake manifold. Such data could be obtained from an engine with direct-head fuel injection.

Because changes in manifold temperature exert only a small influence upon engine air flow as compared with changes in either intake-manifold pressure or exhaust back pressure, the data used for the temperature parameters are considered sufficiently accurate despite the relatively few data available.

The effects of engine speed on air flow, and hence on fuel requirements, may necessitate some difference in the application of air-consumption parameters to either a continuous or a timed fuel-injection system. These effects are twofold: First, for a given set of manifold conditions, a change in speed will vary the air charge per cycle, as is shown in figures 3 and 8; second, a change in speed will vary the number of cycles completed in a given time interval and thus the amount of air consumed during this interval. In a timed fuel-injection system these two effects are both accounted for at the fuel-injection pump: the first by incorporating the desired speed-delivery characteristic, and the second by directly gearing the pump to the crankshaft so that it completes an equal number of cycles per second. The foregoing methods of accounting for the effects of engine speeds also apply to a continuous injection system using a variable-displacement fuel pump. In a continuous injection system using a standard fuel pump, however, a constant fuel pressure is delivered to the metering device independent of engine speed. Hence, a special speed-responsive mechanism must be incorporated in the system.

A discrepancy might result from the application of the parameters computed from tests with carburetor-type engines to direct-head fuel-injection engines because fuel-injection engines will have no fuel in their intake manifolds. The change in engine air flow due to the absence of the fuel in the induction system is not well established; it is believed, however, that the parameters will not change but that engine operation with direct-head fuel injection will only cause operation at a higher intake-manifold temperature and a slightly different intake-manifold pressure for the same air flow. In any case, indications are that parameters can be obtained for an engine with a direct-head fuel-injection system that differ inappreciably, if at all, from those obtained for an engine with a carburetor-type fuel system.

The use of the suggested parameters will give a measure of the air delivered to the engine and not the air remaining after intake-valve closure. When these parameters are used in conjunction with a direct-head fuel-injection system, with injection after exhaust-valve closure, an error is introduced owing to the bypassing of some of the air during the valve-overlap period. This loss of air is not accounted for in the control system and therefore a slight discrepancy in fuel-air ratio results. This same error occurs, however, in the case of a mass air-flow type of mixture-control system when it is used with direct-head fuel injection with the beginning of injection after exhaust-valve closure. For very accurate mixture control of direct-head fuel-injection systems, the quantity of fuel delivered should be metered according to the air trapped in the cylinder. If necessary, the amount of air bypassed and the required metering correction can be investigated by introducing a tracer gas in the intake manifold. (See reference 4.)

CONCLUSIONS

Analyses of air-consumption data from Navy calibration tests of an 18-cylinder, two-row, radial engine of 3350-cubic-inch displacement and a 14-cylinder, two-row, radial engine of 2600-cubic-inch displacement indicate the following results:

1. The air-consumption data of these engines can be represented as a continuous single-valued function of intake-manifold temperature and pressure, exhaust back pressure, and engine speed.
2. This function can be used as a basis for the design of an automatic mixture control for an engine with either a continuous or a timed fuel-injection system.
3. The relations between air consumption and other engine conditions vary for different designs of engine, and individual calibration tests are therefore required for each design.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
CLEVELAND, OHIO, *September 1, 1944.*

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