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CHARGE-AIR DISTRIBUTION AMONG THE CYLINDERS OF A DOUBLE-ROW RADIAL AIRCRAFT ENGINE

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NACA AIRCRAFT ENGINE RESEARCH LABORATORY

MEMORANDUM REPORT

for the

Air Materiel Command, Army Air Forces

CHARGE-AIR DISTRIBUTION AMONG THE CYLINDERS OF A DOUBLE-ROW RADIAL AIRCRAFT ENGINE

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SUMMARY

A motoring investigation was made on a full-scale double-row radial aircraft engine to determine the magnitude of charge-air weight variations among the cylinders and the factors contributing to these variations. Charge-air distribution patterns were obtained from measurements of the maximum compression pressures in the individual cylinders at various operating conditions with the cylinder intake ports open to the atmosphere and with the complete engine.

Engine operating variables including engine speed, carburetor-throttle angle, and volume flow had little effect on the charge-air distribution pattern of either row of cylinders of the complete engine. The spread in these patterns was found to be only slightly greater than the spread encountered in the individual cylinder rows with the intake ports open to the atmosphere. Although engine speed had little effect on the distribution pattern of an individual row of cylinders, it had a pronounced effect on the relative amount of charge air taken into the front and the rear rows of cylinders of the complete engine. Possibly because of resonance effects in the front-row and rear-row intake pipes, which had different lengths, the front-row cylinders received an average charge approximately $7\frac{1}{2}$ percent greater than the average of the rear-row cylinders at an engine speed of 2000 rpm. With an increase in speed, this difference decreased until the front-row cylinders received an average charge 1 percent less than that of the rear-row cylinders at 2600 rpm.

Calculations indicated that the maximum spread in the over-all charge-air distribution observed in these tests would account for a spread of about 23° F in the rear-spark-plug-gasket temperatures in an engine operating under normal conditions at an engine speed of 2000 rpm as compared with a spread of about 60° F obtained at the same speed in tests of a similar double-row radial engine equipped with an injection impeller. Temperature spreads due to variations in charge air among the cylinders of the front and the rear rows taken separately were calculated to be only 10° and 5° F, respectively.

INTRODUCTION

An investigation requested by the Air Materiel Command, Army Air Forces, to improve the cooling characteristics of a double-row radial engine has shown that a large variation exists among the cylinder-head temperatures of the standard engine (reference 1). Because the temperature of the hottest cylinder determines the cooling-air pressure drop and the fuel enrichment required for operation within cylinder-head temperature limitations, a large variation in individual cylinder-head temperatures seriously limits engine performance and fuel economy. Factors contributing to variations in cylinder-head temperature are nonuniform distribution of fuel and charge air to the cylinders, unequal cooling-air distribution, and inherent differences in the construction of the cylinders that affect the heat transfer through the cylinder walls. The results of the investigation reported in reference 1 show that a considerable improvement in mixture distribution and in cylinder-head temperature variation can be obtained by the use of an NACA injection impeller. A reduction in the difference of cylinder-head temperatures between the front and rear rows was obtained by the use of ducted head baffles, which directed cooling air to the critical-temperature regions of the cylinders (reference 2). Even with these improvements, a variation in the cylinder-head temperature still existed.

Accordingly, additional tests were made at the NACA Cleveland laboratory to determine the magnitude of charge-air weight variations among the cylinders and the factors contributing to these variations. A full-scale double-row radial aircraft engine was motored by a variable-frequency electric motor and the charge-air distribution was determined by measurements of the maximum compression pressures in the individual cylinders.

Variations in charge-air distribution among the cylinders due to such factors as inherent differences in cylinder construction, piston blow-by, and differences in the piston-displacement curves caused by the angular positions assumed by the master rods were first determined by motoring the engine at various speeds with the cylinder intake ports open to the atmosphere. The charge-air distribution among the cylinders of the complete engine was then investigated throughout a range of carburetor-throttle settings and volume flows and for speeds ranging from 1600 to 2600 rpm to evaluate the effect of the nonuniform charge-air distribution around the engine-stage supercharger collector noted in reference 3. These tests also permitted a determination of the effect of the difference in length of the intake pipes on the distribution of charge air to the cylinders. The charge-air distribution patterns are presented as nondimensional curves of the ratio of the charge-air weight in a particular cylinder to the average charge-air weight in all the cylinders plotted against cylinder number.

Calculations were made to determine the approximate spreads in the cylinder rear-spark-plug-gasket temperatures that could be expected from the variation in charge-air distribution observed in the motoring tests.

APPARATUS

Test equipment. - The charge-air distribution was investigated on an R-3350-21A engine driven by a variable-frequency electric motor rated at 1500 horsepower at a speed of 3600 rpm. A photograph of the setup is shown in figure 1. The propeller reduction gears were removed from the nose of the engine and replaced with a direct-drive connection between the propeller shaft and the crankshaft to obtain the necessary power from the drive motor. The air-intake system included an orifice tank, a throttle valve, and a straight section of rectangular ducting 7 feet long immediately upstream of the carburetor to insure a uniform flow into the carburetor. A standard aircraft exhaust-collector assembly was used with an exhaust system maintained at approximately 2 inches of mercury below atmospheric pressure.

In the first series of tests, the supercharger section had to be disconnected from the power section of the engine; the engine was therefore modified by removing the intake pipes and installing a separate collector to deliver the supercharger exhaust to the exhaust system. For the second series of tests, the intake pipes were reinstalled and tests were made on the complete engine.

Instrumentation. - The weight flow of air through the engine was determined by measuring the static-pressure drop across a thin-plate orifice with a micromanometer. The inlet-air static pressure, total pressure, and temperature were measured upstream of the carburetor upper deck at a distance twice the narrow dimension of the inlet duct. Static-pressure and temperature measurements were taken in each of the cylinder intake pipes to determine the volume flow at the supercharger outlets. Although the actual static pressures were probably inaccurate owing to the fluctuating flow in the intake pipes, consistent values of an average pressure were obtainable at the various operating points because of the damping action of the long pressure tubes.

Direct measurement of the charge-air weight in each cylinder is difficult. Because the charge-air weight is proportional to the maximum pressure in the cylinder, an indication of the charge-air weight was obtained by measuring the maximum pressure during the compression cycle. Inasmuch as 18 maximum-pressure units were required, units of simple construction similar to the diaphragm-indicator unit described in reference 4 were used. The method used to connect the units to a common balancing-pressure system and to an electronic indicator circuit is shown in figure 2. The vacuum connection to the pressure manifold was used only as a means of increasing the life of the diaphragm in the maximum-pressure units by preventing movement during periods when no readings were being taken.

TESTS

Intake ports open to atmosphere. - For the tests with intake ports open to the atmosphere, the intake pipes were removed in order that the cylinders could take in air directly from the atmosphere. Because the air flow could not be measured under these conditions, the maximum pressures in the cylinders were the only air measurements made. Runs were made at engine speeds of 1600, 1850, 2000, 2200, 2400, and 2600 rpm. An unstable condition of the drive motor prevented operation at exactly 1800 rpm.

Complete engine. - For the tests on the complete engine, the intake pipes were connected. The effect of engine speed on the charge-air distribution was determined by motoring the engine at speeds of 1600, 1850, 2000, 2200, 2400, and 2600 rpm with the carburetor throttle set in the wide-open position. Air-flow, pressure, and temperature measurements upstream of the carburetor and in the intake pipes, as well as the maximum cylinder pressures, were taken at each speed. At two engine speeds, 2000 and 2400 rpm, runs were also made at carburetor-throttle settings of 50° and 40° from the closed position to determine the effect of the carburetor-throttle position on the charge-air distribution.

Two runs were made at 2000 and 2400 rpm with two volume flows at each speed to determine if the change in velocity accompanying a change in volume flow at the supercharger inlet would cause a displacement of any distortion in the charge-air distribution pattern. Because the position of the carburetor made installation of adequate instrumentation difficult, the volume flow at the supercharger inlet could not be determined. The volume flow at the supercharger outlets expressed in terms of Q_2/n (where Q_2 is the volume flow at the supercharger outlets in cu ft/sec and n is the supercharger speed in rps) was therefore used as a parameter. The values of Q_2 were calculated from the total charge-air weight flow and the average density of the charge air in the 18 intake pipes. The value of Q_2/n could be varied only from approximately 0.14 to slightly more than 0.16 by throttling at the inlet; this limited range, however, is representative of the range in actual engine operation.

Calibration of maximum-pressure units. - As a check on the operation of the maximum-pressure units, periodic calibration runs during the tests were made at an engine speed of 2000 rpm, at wide-open carburetor throttle position (in the case of tests on the complete engine), and at a constant carburetor upper-deck pressure. A basic charge-air distribution pattern for operation under these conditions was established by seven runs made with different maximum-pressure units in a given cylinder during each run. From these data, an average charge-air distribution pattern was obtained. A maximum spread in the pressure recorded by the seven units in any particular cylinder of about 1.9 percent of the average pressure indicates the reliability of the maximum-pressure readings. The average spread was only 1.4 percent of the average pressure. Differences in running conditions may have caused some of the spread in pressures as the seven calibrations were made on different days. In order to compensate for differences between units, a correction was obtained each day for every unit by comparing the calibration run of that day with the average charge-air distribution pattern.

RESULTS AND DISCUSSION

Inasmuch as the charge-air weight in a cylinder when the piston is at top dead center is directly proportional to the maximum pressure in the cylinder, the results of all the charge-air distribution tests are presented as nondimensional plots of W/W_a (where W/W_a is the ratio of the charge-air weight in a particular cylinder W to the average weight in all the cylinders W_a) against cylinder number. The spread of a distribution pattern is defined as the difference between the maximum and the minimum values of W/W_a for the cylinders in that pattern.

Distribution Patterns with Intake Ports Open to Atmosphere

The charge-air distribution patterns at engine speeds from 1600 to 2600 rpm with the intake ports open to the atmosphere are shown in figure 3. In general, the front-row cylinders received a smaller charge of air than the rear-row cylinders, probably because the rear-row cylinders partly restrict the flow of air into the front-row cylinders when the intake pipes are not installed. Little change in the distribution pattern was apparent with change in speed. For the six speeds, the average spreads in the separate patterns of the front-row and the rear-row cylinders were approximately $2\frac{1}{2}$ and $4\frac{1}{2}$ percent, respectively. This variation in charge air among cylinders in the same row was probably due to differences in cylinder construction, in piston blow-by, and in the piston-displacement curve caused by the angular positions assumed by the master rods.

Distribution Patterns of Complete Engine

Effect of engine speed. - The effect of engine speed on the charge-air distribution in the complete engine is shown in figure 4. A carburetor-throttle angle of 68° (wide open) and a Q_2/n of approximately 0.16 were maintained during these tests. A pronounced effect of speed on the difference between the charge-air in the front-row and the rear-row cylinders is shown by the distribution patterns presented. At an engine speed of 1600 rpm, the average charge-air weight of the front-row cylinders was about $2\frac{1}{2}$ percent greater than that of the average rear-row cylinder. This difference increased with increasing speed to a maximum of $7\frac{1}{2}$ percent at 2000 rpm and then decreased until at 2600 rpm, which was the highest speed investigated, the front-row cylinders were receiving an average charge-air weight about 1 percent less than the average rear-row cylinder. This phenomenon was probably due to ram effects produced by resonance in the intake pipes. Because the front-row intake pipes are a different length ($24\frac{1}{2}$ in.) from the rear-row intake pipes ($15\frac{1}{2}$ in.), resonance does not occur at the same speed for the two rows of cylinders. A redesign of the intake pipes to make the front-row and rear-row pipes the same length might therefore help equalize the charge-air distribution between the two rows of cylinders.

Although engine speed had a pronounced effect on the charge-air distribution between the two rows of cylinders, it had little effect on the distribution pattern among cylinders of the same row. The distribution to the rear-row cylinders was quite uniform, having an average spread of about $2\frac{1}{2}$ percent for the six speeds investigated. The distribution to the front-row cylinders, however, was less uniform than to the rear-row cylinders, having an average spread of about 5 percent for the six speeds. A large part of this spread can be attributed to cylinder 14, which was low at all speeds. This characteristic of cylinder 14 was also found in the distribution at the supercharger-collector outlets (reference 3).

The spread in the distribution pattern of each row of cylinders with the intake ports open to the atmosphere was only slightly less than that of the complete engine. For the six speeds, the average spreads in the front and the rear rows of the engine with the open intake ports were $2\frac{1}{2}$ and $4\frac{1}{2}$ percent, respectively; whereas the spreads with the complete engine were 5 percent and $2\frac{1}{2}$ percent, respectively. Mechanical differences among cylinders apparently had as great an effect upon the charge-air distribution as any flow distortion in the supercharger section.

Effect of carburetor-throttle angle. - The effect of carburetor-throttle angle on the charge-air distribution among the cylinders of the complete engine is shown in figure 5. Distribution patterns at carburetor-throttle angles of 68° (wide open), 50°, and 40° from the closed position and at a constant value of Q_2/n of approximately 0.16 are shown for engine speeds of 2000 and 2400 rpm. The coincidence of the patterns shows that the carburetor-throttle angle had no effect on the charge-air distribution of this particular installation.

Effect of volume flow. - The effect of volume flow on the charge-air distribution among the cylinders is shown in figure 6. The distribution patterns were obtained at engine speeds of 2000 and 2400 rpm with the carburetor throttle in the wide-open position, 68°. The distribution patterns at both speeds showed no definite change with the limited change in Q_2/n that was possible in the range of engine operating conditions.

Calculated cylinder-head temperature spread. - In order to determine the approximate spread in the cylinder rear-spark-plug-gasket temperatures that would result from the charge-air distribution spread indicated by the tests, calculations were made based on NACA cooling-correlation curves for an earlier model of the double-row radial engine (reference 5). These calculations were made with values of fuel weight, cooling-air temperature, and cooling-air pressure drop that were assumed equal for all the cylinders and with charge-air weights determined by the charge-air distribution patterns in figure 4. At 2000 rpm, where the charge-air spread was greatest, the calculated over-all rear-spark-plug-gasket temperature spread was found to be 23° F; whereas the spreads in each cylinder row were only 10° and 5° F in the front and the rear rows, respectively. These spreads in cylinder rear-spark-plug-gasket temperatures are considerably less than the over-all spread of approximately 60° F and front-row and rear-row spreads of approximately 50° and 35° F, respectively, obtained in actual operation at 1200 brake horsepower and 2000 rpm (reference 1). Inasmuch as a reasonably uniform distribution of fuel can be expected from the injection impeller used in the tests reported in reference 1, most of the temperature spread found in those tests was apparently due to differences in cooling characteristics among the cylinders such as cooling-air pressure drop, cylinder-fin heat-transfer coefficient, and cylinder internal cooling. A similar condition was found in cooling tests on a double-row radial engine of 2800-cubic-inch displacement (reference 6), which presented calculations showing that the temperature variations remaining after solution of all distribution problems, including cooling-air pressure drop, would amount to approximately ±20° F.

SUMMARY OF RESULTS

From tests in which a full-scale double-row radial aircraft engine was motored in an investigation to determine the charge-air distribution among the cylinders, the following results were obtained:

1. Engine operating variables including speed, carburetor-throttle angle, and volume flow had little effect on the charge-air distribution of either the front-row or rear-row cylinders of the complete engine.

2. The spread in the charge-air distribution of either row of cylinders with the intake ports open to the atmosphere was of the same magnitude as the spread encountered in the complete engine. The average spreads found in the front and the rear rows were $2\frac{1}{2}$ and $4\frac{1}{2}$ percent, respectively, with the intake ports open to the atmosphere and 5 and $2\frac{1}{2}$ percent, respectively, in the complete engine.

3. Change in engine speed had a pronounced effect on the difference in the charge-air weight received by the front and the rear rows of the complete engine. At an engine speed of 1600 rpm, the front-row cylinders received an average charge-air weight about $2\frac{1}{2}$ percent greater than the average of the rear-row cylinders. This difference increased

to a maximum of $7\frac{1}{2}$ percent at 2000 rpm and then decreased with increasing speed until at 2600 rpm, which was the highest speed investigated, the front-row cylinders were receiving an average charge-air weight about 1 percent less than the average of the rear-row cylinders. Resonance effects in the front-row and the rear-row intake pipes, which were of different lengths, may be an explanation of this phenomenon.

4. Calculations based on cooling-correlation data indicated that the maximum charge-air distribution spread encountered in the motoring tests (at an engine speed of 2000 rpm) would account for an over-all spread in rear-spark-plug-gasket temperatures of about 23° F and spreads among the front-row and the rear-row cylinders taken separately of 10° and 5° F, respectively. Rear-spark-plug-gasket temperatures obtained under actual operating conditions at the same engine speed from a similar engine equipped with an injection impeller showed an over-all spread of about 60° F and spreads of about 50° and 35° F among the front-row and the rear-row cylinders taken separately. Because a reasonably uniform fuel distribution can be expected from an injection impeller, comparison of these data indicates that much of the temperature spread can be attributed to differences in cooling characteristics among the cylinders.

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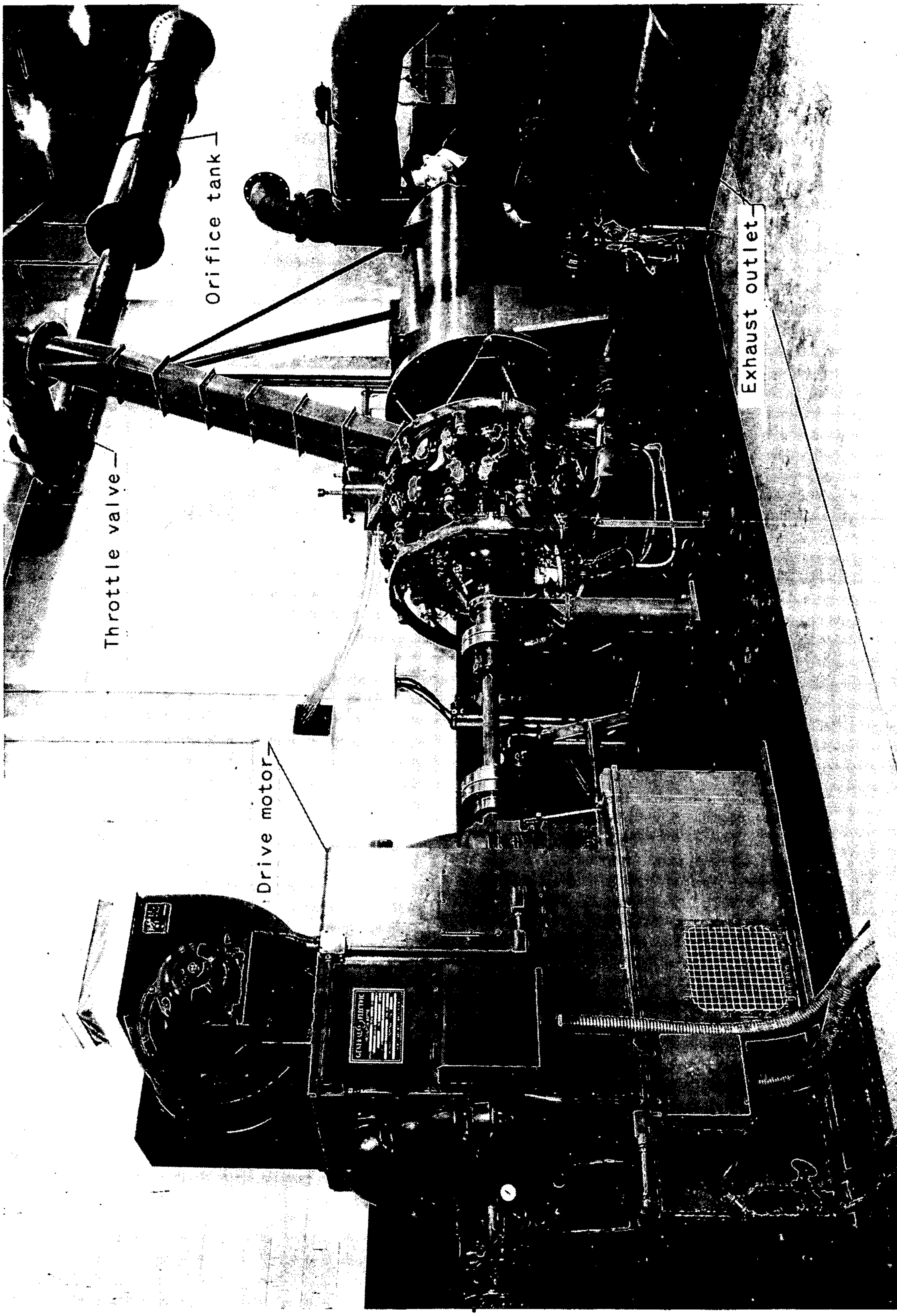

Figure 1. – Double-row radial aircraft engine motoring rig.

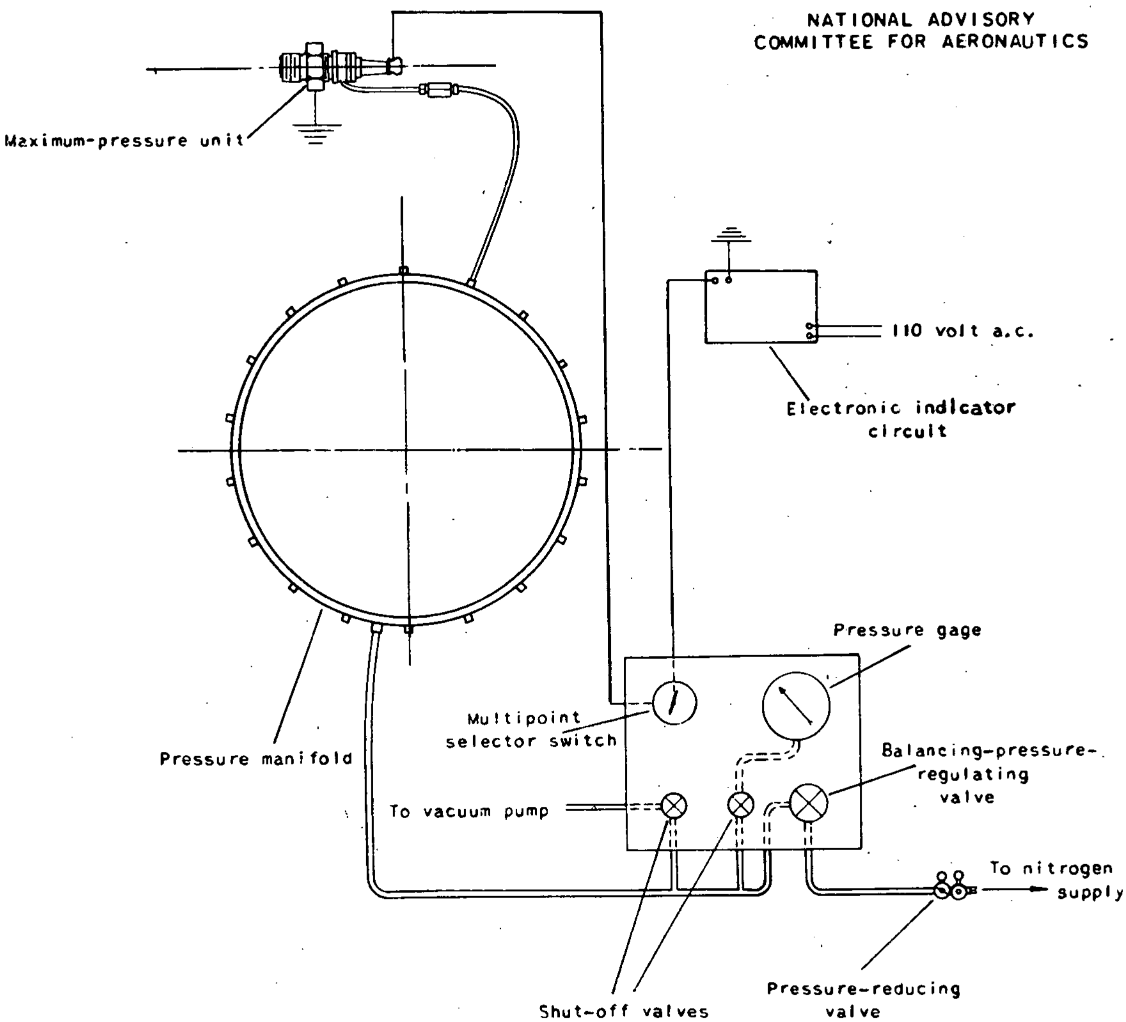

Figure 2. - Schematic diagram of maximum-pressure-measuring system for motoring tests of a double-row radial aircraft engine.

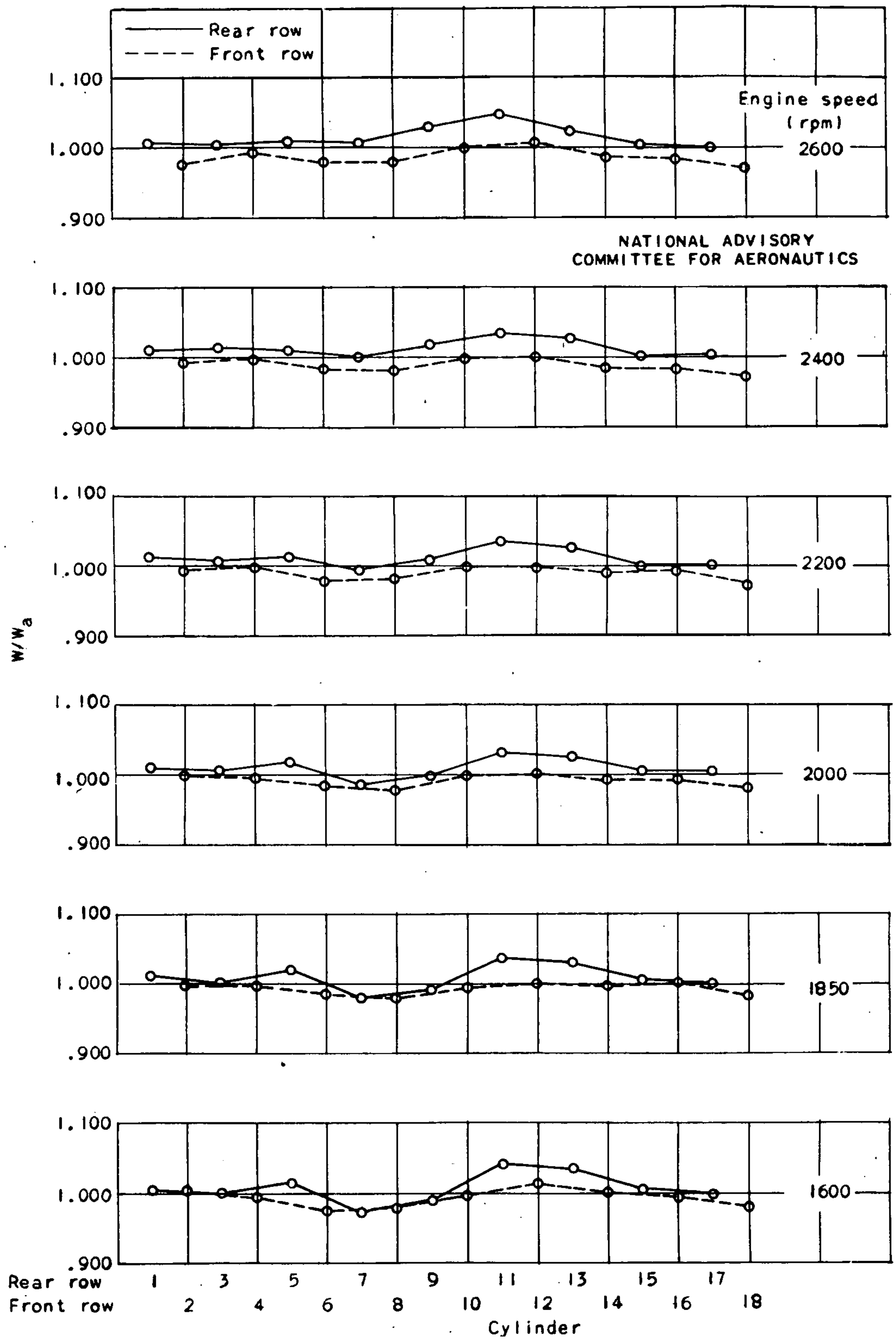

Figure 3. - Effect of speed on charge-air distribution of double-row radial aircraft engine with cylinder intake ports open to the atmosphere.

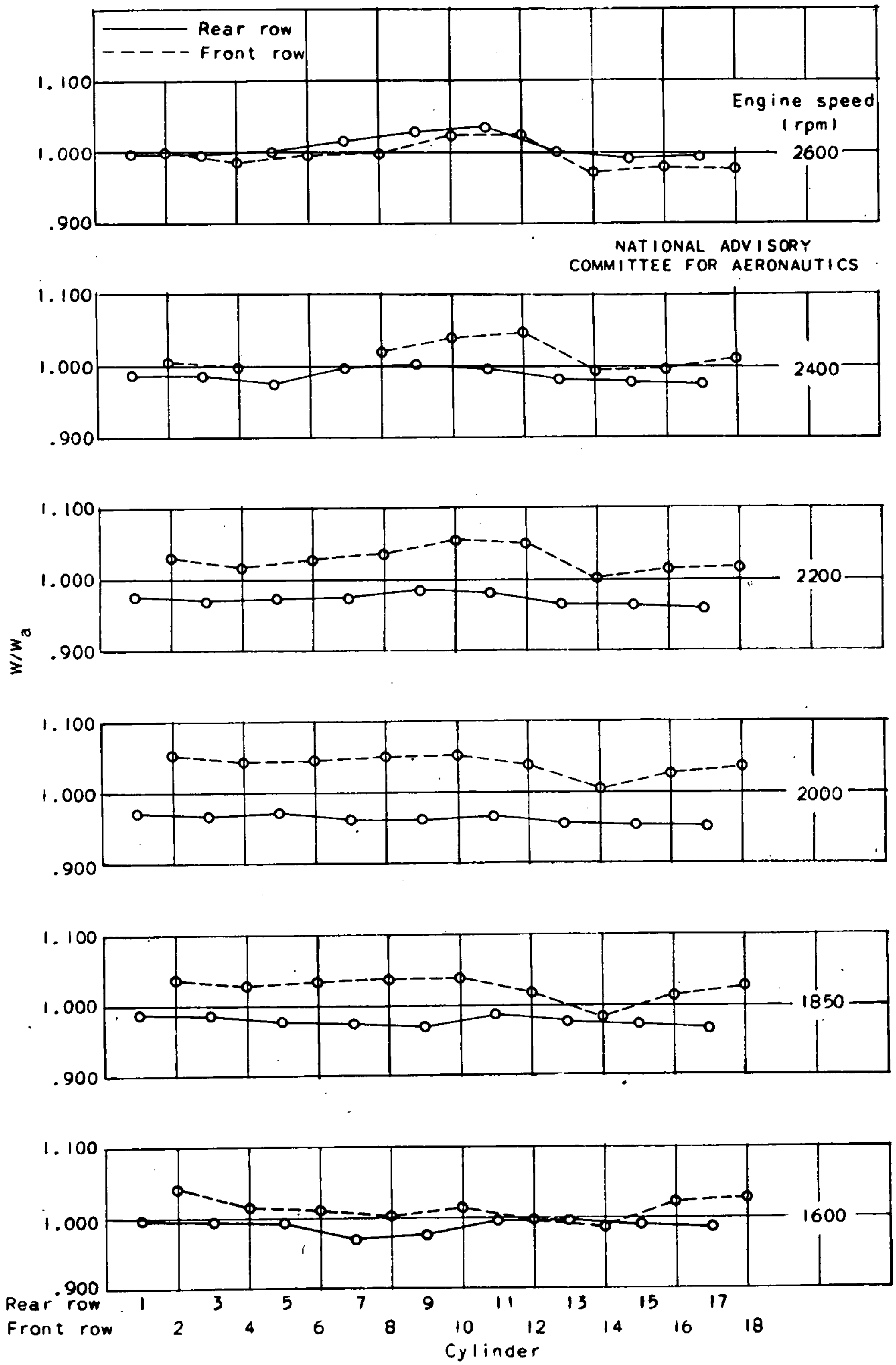

Figure 4. - Effect of speed on charge-air distribution of double-row radial aircraft engine with full-open carburetor-throttle angle, 68°, and Q_2/n of ap ximately 0.16.

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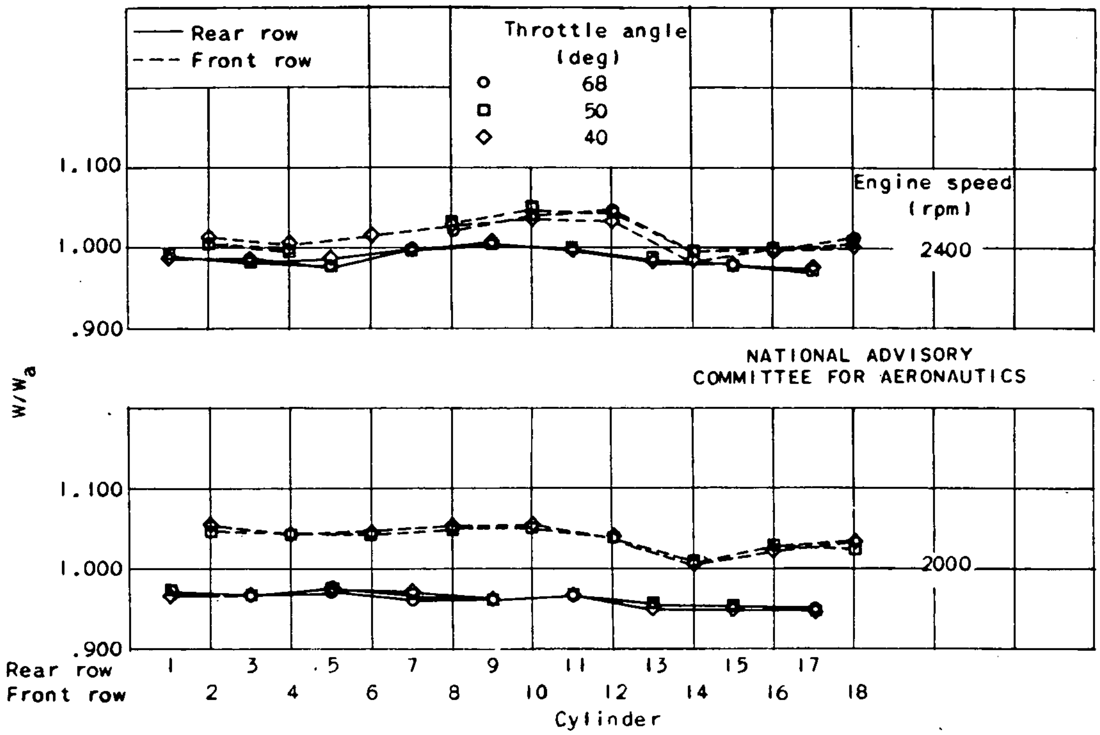

Figure 5. - Effect of carburetor-throttle angle on charge-air distribution of double-row radial aircraft engine at a Q_2/n of approximately 0.16.

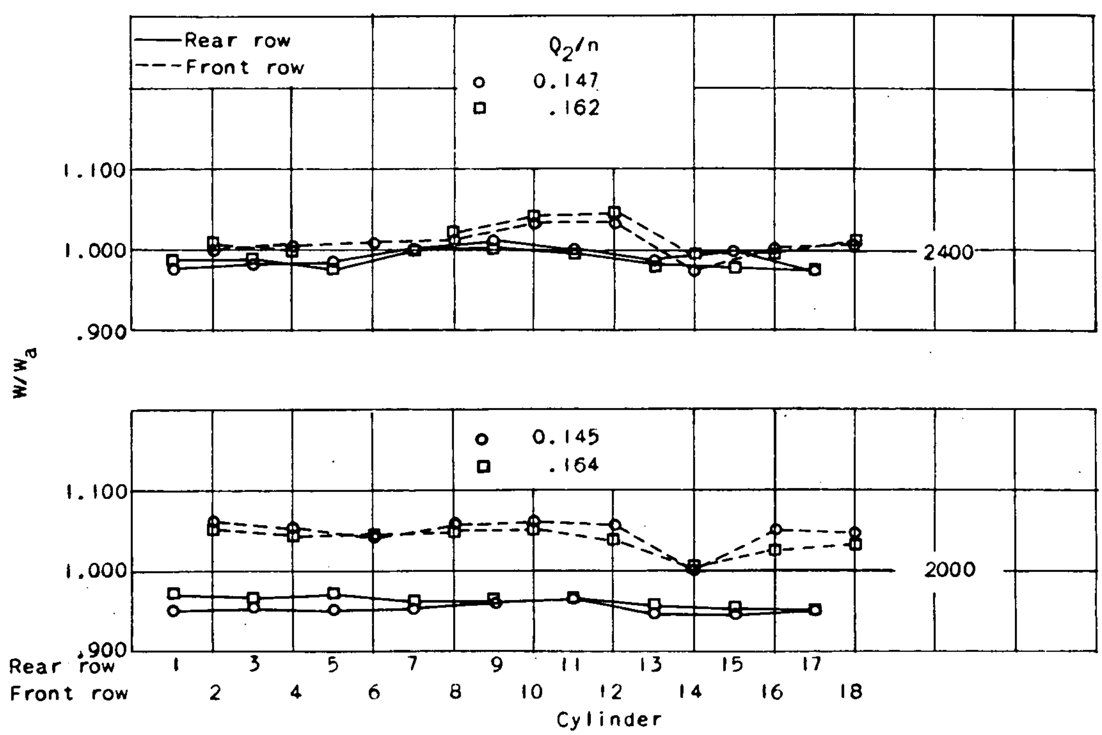

Figure 6. - Effect of volume flow on charge-air distribution of double-row radial aircraft engine with full-open carburetor throttle, 68°.