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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 610

EFFECT OF AIR-ENTRY ANGLE ON PERFORMANCE OF A 2-STROKE-CYCLE COMPRESSION-IGNITION ENGINE

By Sherod L. Earle and Francis J. Dutee
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SUMMARY

An investigation was made to determine the effect of variations in the horizontal and vertical air-entry angles on the performance characteristics of a single-cylinder 2-stroke-cycle compression-ignition test engine. Performance data were obtained over a wide range of engine speed, scavenging pressure, fuel quantity, and injection advance angle with the optimum guide vanes. Friction and blower-power curves are included for calculating the indicated and net performances.

The optimum horizontal air-entry angle was found to be 60° from the radial and the optimum vertical angle to be zero, under which conditions a maximum power output of 77 gross brake horsepower for a specific fuel consumption of 0.52 pound per brake horsepower-hour was obtained at 1,800 r.p.m. and 16-1/2 inches of Hg scavenging pressure. The corresponding specific output was 0.65 gross brake horsepower per cubic inch of piston displacement. Tests revealed that the optimum scavenging pressure increased linearly with engine speed. The brake mean effective pressure increased uniformly with air quantity per cycle for any given vane angle and was independent of engine speed and scavenging pressure.

INTRODUCTION

Air swirl, as an aid to fuel distribution, has been obtained in 4-stroke-cycle compression-ignition engines by a number of methods. At this laboratory the displacer-type piston (reference 1) and the prechamber cylinder head (reference 2) have been thoroughly investigated. Shrouded intake valves have been less successfully used to produce an air swirl in the engine cylinder. Ricardo obtained good results with an air swirl set up through sleeve-valve ports and augmented by the cylinder head design (reference 3). Directing the entering air in a 2-stroke-cycle engine serves the dual purpose of assisting in scavenging the cylinder and of mixing the fuel with the combustion air.

Owing to the extremely large number of interdependent variables affecting the performance of the 2-stroke-cycle compression-ignition engine, a program was planned whereby a group of influencing factors would be held constant and the effects of the major variables separately investigated. One of the items in the general program is the manner in which the scavenging and combustion air enters the cylinder. This note covers the tests with variation of the horizontal angle for constant and variable flow areas and with variation of the vertical entry angle. Fundamental trends and limiting values of power and economy were established over a range of engine speeds and scavenging pressures.

APPARATUS AND METHODS

The single-cylinder, water-cooled, 2-stroke-cycle, compression-ignition engine described in reference 4 was used for these performance tests. The 4-5/8 by 7-inch cylinder admits air through eight inlet ports in the lower end of the cylinder liner and exhausts through four poppet valves recessed 1/16 inch in the cylinder head. The combustion chamber is a flat disk formed between the piston crown and the cylinder head. A diagrammatic arrangement of the test equipment is shown in figure 1. Scavenging and combustion air are supplied by an independently driven 4-inch Roots blower with a large surge tank interposed between it and the engine manifold. Removable guide vanes directed the air into the cylinder at the desired angle. A negative pressure of approximately 3/4 inch of water was maintained in the exhaust trench by a large-capacity fan. The pressure of the scavenging air was indicated by a mercury manometer connected to the surge tank.

Tests had shown that the lengths of the inlet and the exhaust pipe strongly influenced the charging efficiency and therefore the power output of this engine cylinder. The pipe lengths can be adjusted to give optimum performance at any one engine speed at the expense of decreased output at other speeds. In order to eliminate the factor of pipe length from these tests, the surge tank was closely coupled to the engine manifold by a large-diameter pipe and the exhaust stacks were just long enough (6 inches) to accommodate a cooling-water connection and a flanged fitting.

Unless otherwise noted in the text, the following auxiliary equipment and engine conditions were those selected and maintained constant throughout the investigation:

Cylinder head: N.A.C.A. C-1; compression ratio based on swept volume, 13.5; based on volume above ports, 11.8; four 1-3/4 inch exhaust valves; exhaust-port diameter, 1-19/32 inches; total exhaust-port area at minimum section, 7.3 square inches.

Valve and port timing (degrees A.T.C.):

Exhaust opens, 95.
Exhaust closes, 228.
Inlet opens, 130.
Inlet closes, 230.
Exhaust-cam dwell, 12°.

Inlet-port dimensions:

Height, 1 inch; width, 1.45 inches; number of ports, 8.

Operating temperatures:

Oil (out), 155° F.
Water (out), 110° F.
Inlet air to blower (average room temperature), 80° F.

Maximum cylinder pressure:

1,000 pounds per square inch.

Fuel-injection pump: Bosch, cam-operated, constant-stroke type, 9 mm diameter plunger, injection period 40° to 45°.

Fuel-injection valve: N.A.C.A. automatic, spring-loaded to 3,000 pounds per square inch. Nozzle used had three orifices in same plane 60° apart; central orifice 0.020 inch, side orifices each 0.010 inch.

Fuel: Diesel oil, 0.83 specific gravity at 68° F., 41 seconds Saybolt Universal viscosity at 80° F., 68 cetane number.

Maximum cylinder-pressure indicators: Farnboro and balanced-pressure types.

The effect of admitting the combustion and scavenging air at various degrees of swirl was investigated by using three series of guide vanes. The different series were composed of a number of guide-vane sets, each set having a different entry angle. In the first series the horizontal entry angle was varied from 0° (radial) to 70° from radial by using seven sets of guide vanes. The gas-flow area was also varied owing to the angularity of the vanes. In order to determine independently the effect of entry angle, tests were repeated with the second series of guide vanes by which the entry angle was varied from 0° to 60° but with the gas-flow area maintained constant and equal to that giving best performance with the first series. The third series of vanes, designed to give the air an upward entry into the cylinder, was then used in conjunction with the optimum horizontal vanes. Tests covered a vertical entry angle from 0° to 40° from the horizontal. Power and economy data were obtained for each set of vanes for a range of engine speeds from 1,200 to 1,800 r.p.m. and of scavenging-air pressures of 5, 10, and 15 inches of Hg.

The effect of fuel quantity, injection advance angle, and exhaust-valve timing on engine performance was determined with the optimum guide vanes at an engine speed of 1,800 r.p.m. and a scavenging-air pressure of 15 inches of Hg. Tests covered a range of fuel quantities from 0.00015 to 0.00045 pound per cycle, injection advance angles from 8° A.T.C. to 7° B.T.C., and exhaust-valve timing from 85° to 100° A.T.C. Tests were also made with three different combinations of inlet and exhaust pipe lengths. Indicator cards were taken in the inlet manifold, exhaust stack, and cylinder for reference in selecting pipe dimensions. The pipe length tests were made for a speed range of 1,200 to 1,800 r.p.m. and a scavenging pressure of 5 inches of Hg. Motoring characteristics were also determined for all test conditions.

The method used to obtain the test points for the various arrangements of guide vanes was as follows: After the water and lubricating-oil temperatures, engine speed, and scavenging-air pressure had been brought to the desired test conditions, the fuel quantity was varied until the maximum power was obtained. The maximum cylinder pressure was maintained constant at 1,000 pounds per square inch by varying the injection advance angle along with the fuel quantity. The fuel quantity was then reduced until the power was 98 percent of the maximum, maintaining the maximum cylinder pressure at 1,000 pounds per square inch, and the test data were recorded. This value of the power was selected as the test point because the fuel quantity at the maximum power varied over a wide range and a fair comparisom of the specific fuel consumptions could not be made. In many instances the fuel consumption was reduced 15 to 20 percent for the 2 percent reduction in power. This method of testing gave consistent and comparable results and was therefore used for all tests of variable air-entry angles.

RESULTS AND DISCUSSION

Horizontal Entry Angle

Variable flow area.- The performance data were plotted for each of the sets of guide vanes over a range of air-entry angles from 0° to 70° and from these curves the cross plot shown in figure 2 was prepared. These curves, for a scavenging pressure of 15 inches of Hg, show that, as the air-entry angle was increased, the brake mean effective pressure for each engine speed increased to a maximum and then fell off at a very rapid rate with further increase in angle. Although not included in this paper, similar data for the scavenging pressures of 5 and 10 inches of Hg were obtained and showed that the entry angle at which the maximum output was developed changed little with engine speed and scavenging pressure. Alcock (reference 5) obtained similar results in his investigation of air swirl in oil engines. Except for a small increase between 0° and 20°, the air consumption decreased with flow area. Between 20° and 60° the decrease was nearly linear; beyond 60°, however, there was a sharp drop. The specific fuel consumption decreased steadily as the entry angle was increased from 0°. For 98 percent load the minimum specific fuel consumption obtained was 0.52 pound per brake horsepower-hour at a speed of 1,800 r.p.m. and at 60° entry angle. The injection advance angle required to maintain a constant maximum cylinder pressure of 1,000 pounds per square inch decreased linearly with increase in air-entry angle.

The increase in performance with air-entry angle was due to a combination of better scavenging and improved combustion. Scavenging efficiency could not be independently determined; hence the relative improvement from scavenging and mixing could not be evaluated. It should be noted that the maximum mean effective pressure was not obtained at the air-entry angle giving maximum air consumption, but at an angle of 60°, at which setting the consumption was approximately 82 percent of the maximum for any engine speed. The rapid decrease in brake mean effective pressure and air consumption with air-entry angles between 60° and 70° is due to the restricted air-flow area caused by the angularity of the guide vanes. An abscissa scale has been added to figure 2 to show the relation between horizontal entry angle and effective flow area.

Constant flow area.- The results of an investigation in which the air-entry angle was varied and the flow area maintained constant at that area corresponding to 60° air-entry angle are shown on figure 3. The brake mean effective pressure for the different engine speeds increased uniformly with air-entry angle. The increase in air consumption with air-entry angle for any engine speed was small and varied linearly between 20° and 60°. In general, the specific fuel consumption decreased steadily with increase in air-entry angle and was nearly the same for all engine speeds investigated.

By a superimposition of figures 2 and 3, it is seen that the power output was greater for constant than for variable flow area vanes at small air-entry angles. The air-entry angle at which the brake mean effective pressure curves cross one another was affected by the engine speed, becoming less as the speed was increased. Owing to the reduced flow area, less air was passed through the engine cylinder for the constant flow area than for the variable flow area vanes. From considerations of fuel economy the constant flow area vanes gave the best performance of any investigated.

Vertical Air-Entry Angle

The curves presented in figure 4 show the effect on performance of varying the vertical entry angle from 0° to 40° from the horizontal for all test speeds with a scavenging pressure of 15 inches of Hg. It is seen that the greatest brake mean effective pressure and air consumption were obtained by the use of 0° vanes for all engine speeds. This condition also held true for the scavenging pressures of 5 and 10 inches of Hg. The specific fuel consumption was not affected by change of entry angle at the higher speeds and was only slightly affected at the lower speeds. The injection timing was consistently latest with the 10° vanes and became earlier with a further increase of air-entry angle. This result pointed to slower burning at the larger angles owing to reduced scavenging and mixing efficiency. The falling of the air-consumption curve with increase of air-entry angle was due to the decrease in effective inlet port area, which may be seen by referring to the scale at the bottom of figure 4.

Engine Speed

The performance obtained for scavenging-air pressures of 5, 10, and 15 inches of Hg with the optimum entry angle for the inlet air is shown in figure 5. It is noted that the brake mean effective pressure decreased with increase of engine speed. The brake horsepower, however, increased with speed and the maximum test speed was not high enough to peak the curve when using a scavenging-air pressure of 15 inches of Hg. Maximum power and minimum fuel consumption together with moderately clean exhaust were obtained at an engine speed of 1,800 r.p.m. The slope of the power curves indicates the desirability of increased scavenging-air pressure as speeds increase. The curves of specific fuel consumption for scavenging-air pressures of 5 and 10 inches of Hg show an upward trend with increase in engine speed, whereas for 15 inches of Hg the trend is downward.

Scavenging-Air Pressure

The effect of scavenging-air pressure on engine performance at 98 percent maximum power settings with the optimum air-entry vanes is shown in the curves of figure 6. The power output increased with scavenging-air pressure and engine speed as was to be expected. Also, the air consumption increased linearly with scavenging-air pressure and varied approximately inversely with the engine speed. The specific fuel consumption for the different engine speeds decreased steadily and passed through a minimum when the scavenging-air pressure was increased. The scavenging-air pressure at which the minimum fuel consumption occurred increased linearly with engine speed. A possible explanation for this condition lies in the probability of an optimum air velocity for scavenging and for fuel and air mixing at each engine speed and, as the speed is increased, the scavenging-air pressure must be increased accordingly. These data indicate, therefore, that there is an optimum scavenging-air pressure for each engine speed, above and below which it is less economical to operate.

Figure 7 was prepared from figure 6 by cross-plotting the performance data corresponding to the optimum scavenging-air pressure for each engine speed. This figure shows clearly the improvement in power output to be obtained by increasing the engine speed and the scavenging-air pressure together.

Air Quantity

Examination of the test data shows a definite relationship between brake mean effective pressure and air consumed in cylinder volumes per cycle for any air-entry angle of a given series regardless of engine speed and scavenging pressure. These data are shown in figure 8 for horizontal air-entry angles of 20°, 40°, and 60°; the data cover a speed range of 1,200 to 1,800 r.p.m. and scavenging-air pressures from 3 to 16-1/2 inches of Hg. Each of the curves was obtained by fairing through approximately 20 test points. The maximum deviation of any experimental point from the curves was 5 percent. The brake mean effective pressure increased with air consumption and air-entry angle. The specific fuel consumption curves decreased to an optimum value when the air quantity was increased. The data again show the very definite improvement in performance due to the use of the 60° air-entry vanes.

Fuel Quantity

Figure 9 shows the effect of variable fuel quantity on engine performance with the 60° horizontal guide vanes, engine speed of 1,800 r.p.m., 15 inches of Hg scavenging-air pressure, and injection advance angle of approximately

4°. It is seen that the brake horsepower and the brake mean effective pressure curves are practically peaked at a fuel quantity of 0.00045 pound per cycle. At a fuel quantity of 0.00022 pound per cycle a minimum specific consumption of 0.44 pound per horsepower-hour is obtained; the corresponding brake horsepower is 55 and the brake mean effective pressure 103 pounds per square inch. When the fuel quantity is increased to 0.00045 pound per cycle, the power curve reaches a maximum of 75.5 brake horsepower and the specific fuel consumption is 0.64 pound per brake horsepower-hour. The air consumption decreases from 1.3 to 1.13 cylinder volumes per cycle when the fuel quantity is increased from 0.00014 to 0.00045 pound per cycle.

Injection Advance Angle

The results of the variable injection advance angle test are shown in figure 10. The maximum cylinder pressure increased linearly from 700 to 1,050 pounds per square inch when the injection advance angle was changed from 8° A.T.C. to 7° B.T.C. Maximum power and minimum fuel consumption were obtained for the earliest injection timing used. It may be noted that, when the injection advance angle was 4° B.T.C., the performance curves had about reached their maximum, whereas the maximum cylinder pressure curve was still rising steeply. Thus it is seen that there is little, if any, advantage to be had by a further advance in injection timing.

Attention is called to the occasional apparent discrepancy in the brake mean effective pressure and brake horsepower between the data shown in figures 2, 5, 6, 9, and 10 when the engine operated under optimum conditions. The variations are accounted for by small differences in fuel quantity and engine speed. Considering that the data were obtained over a period of several months and that numerous throttle settings at 98 percent maximum power had to be made, the reproducibility, which is within 4 percent, is considered satisfactory

Motoring Characteristics

Figure 11(a) shows the variation of friction mean effective pressure with engine speed when the optimum air-entry angle is used. The maximum increase of friction mean effective pressure due to engine speed occurred with a low scavenging-air pressure and amounted to 3 pounds per square inch. The maximum increase due to scavenging-air pressure occurred at 1,400 r.p.m. and was 5 pounds per square inch.

Variation of friction mean effective pressure with horizontal air-entry angle for both the variable and the constant flow area series of vanes is shown in figure 11(b). It is seen that the friction mean effective pressure at low horizontal air-entry angles for the variable flow area vanes is greater than for the constant flow area vanes. Greater air consumption and higher compression pressure, due to the larger flow area, are the factors that apparently caused this difference.

The variation of friction mean effective pressure with vertical air-entry angle shown in figure 11(c) was small and followed no regular trend.

Indicator Cards

The pressure-time indicator card shown in figure 12 was taken while using optimum air-entry angles. The engine was operating under 98 percent of maximum power, at a speed of 1,800 r.p.m., and with a scavenging-air pressure of 15 inches of Hg. Engine operation was smooth. The maximum rate of pressure rise was 50.5 pounds per square inch per crankshaft degree.

Figure 13 comprises plots from the records of three light-spring indicator cards taken at the same time as the one shown in figure 12 and under the same conditions. One record was taken in the cylinder, one in the exhaust stack at a position close to the cylinder head, and one in the inlet manifold. There were slight pressure waves in the inlet manifold due to the inertia of the gases, but their effect on scavenging and charging was of no appreciable consequence because their magnitudes were small. The sharp rise of the inlet-manifold pressure immediately after opening of the inlet ports was caused by the flow of cylinder gases through the ports into the inlet manifold. This back flow was due to the cylinder pressure being higher than the manifold pressure at the time of port opening, the pressure differential being approximately 23 pounds per square inch. Tests made with comparable engine conditions showed that an earlier exhaust valve timing corrected this condition but that the power output was reduced at the same time, probably owing to loss of power on the expansion stroke.

Miscellaneous Tests

The data obtained from variable exhaust-valve timing tests showed that the optimum timing for maximum power was advanced with an increase of engine speed. It was not appreciably affected by change of scavenging-air pressure at the lower speeds, but at higher speeds it was retarded with an increase of scavenging pressure. The range of variation of optimum timing with speed was greater for low than it was for high scavenging pressures. For pressures of 5 and 15 inches of Hg this range was 7.5° and 2°, respectively, when the speed was changed from 1,200 to 1,800 r.p.m. The average optimum exhaust-valve opening was 95° after top center.

Tests with various combinations of inlet and exhaust pipe lengths gave a decrease of performance from that obtained without effective pipe length. It was found that when a 5-inch-diameter inlet pipe was used the velocity in the pipe was so low that the pressure surges in the manifold were negligible. A 3-inch-diameter inlet pipe was substituted and the magnitudes of the pressure surges were greatly increased. However, immediately after the inlet ports opened, the manifold pressure dropped to a very low value, indicating that the pipe was not capable of supplying air fast enough for efficient scavenging and charging. These tests with long pipes did not cover a sufficient range of pipe diameter and scavenging-air pressure to allow conclusions to be drawn regarding the possibility of improving performance by their use.

Correction for Net Power

All presented performance curves are on a gross basis. Performance on a net basis may be obtained by deducting from the gross the power absorbed by the blower, which can be determined from figure 14; this chart shows the power lost to the supercharger in terms of engine brake mean effective pressure for all test conditions. Figure 15 shows the corresponding values of horsepower.

General Remarks

The conditions selected to be held constant throughout these tests are not necessarily optimum. It is believed that better power and economy can be obtained by a more suitable injection system. The closing time of the exhaust valves with respect to their opening time may not have been optimum; this question was not investigated. It is also possible that a more favorable ratio exists between the time areas of the inlet port and the exhaust valve than was used. General trends of the performance obtained in these tests, however, should not be greatly affected.

Repeated trouble was encountered with the sticking of the piston ring in the top groove for which no satisfactory remedy has been found to date. Overheating of the piston crown was not in evidence.

CONCLUSIONS

From the data presented in this paper the following conclusions have been drawn:

1. The air-entry angle for best performance varied between 45° and 60° from radial, decreasing with increasing engine speeds and lower scavenging-air pressures; 60° was chosen as optimum.

2. Engine performance was adversely affected by deflecting upwardly the entering scavenging and combustion air.

3. Maximum engine output was obtained when the horizontal air-entry angle was 60°, and under this condition the engine developed 0.65 gross brake horsepower per cubic inch of piston displacement. The specific fuel consumption decreased with increase in air-entry angle and was a minimum at the optimum angle.

4. The air consumed per cycle decreased with flow area and was approximately inversely proportional to the engine speed. Also, the air consumption increased linearly with scavenging pressure.

5. From considerations of specific fuel consumption the optimum scavenging pressure was found to increase linearly with engine speed.

6. For any given air-entry angle the brake mean effective pressure increased uniformly with air consumption in cylinder volumes per cycle regardless of engine speed and scavenging pressure.

7. The friction mean effective pressure increased with air-entry angle, scavenging pressure, and engine speed. In general, the variation was small over the entire range of variables investigated, the value ranging between 19 pounds per square inch and 26 pounds per square inch.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 26, 1937.

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4. Spanogle, J. A., and Whitney, E. G.: A Description and Test Results of a Spark-Ignition and a Compression-Ignition 2-Stroke-Cycle Engine. T.R. No. 495, N.A.C.A., 1934.

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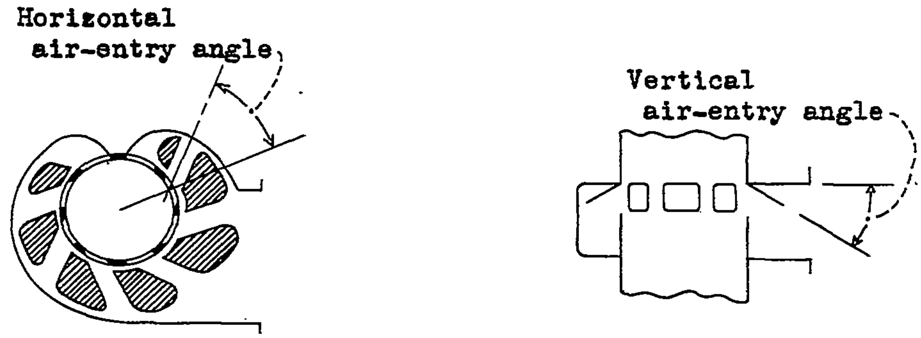


Section through inlet ports

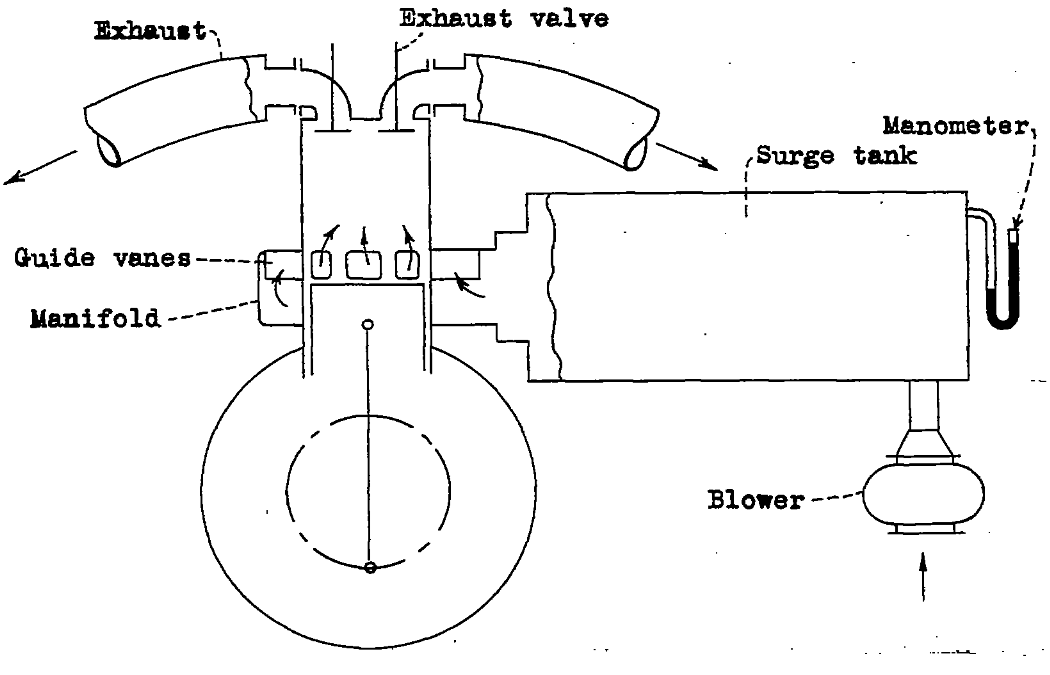


Figure 1.- Diagrammatic arrangement of test equipment.

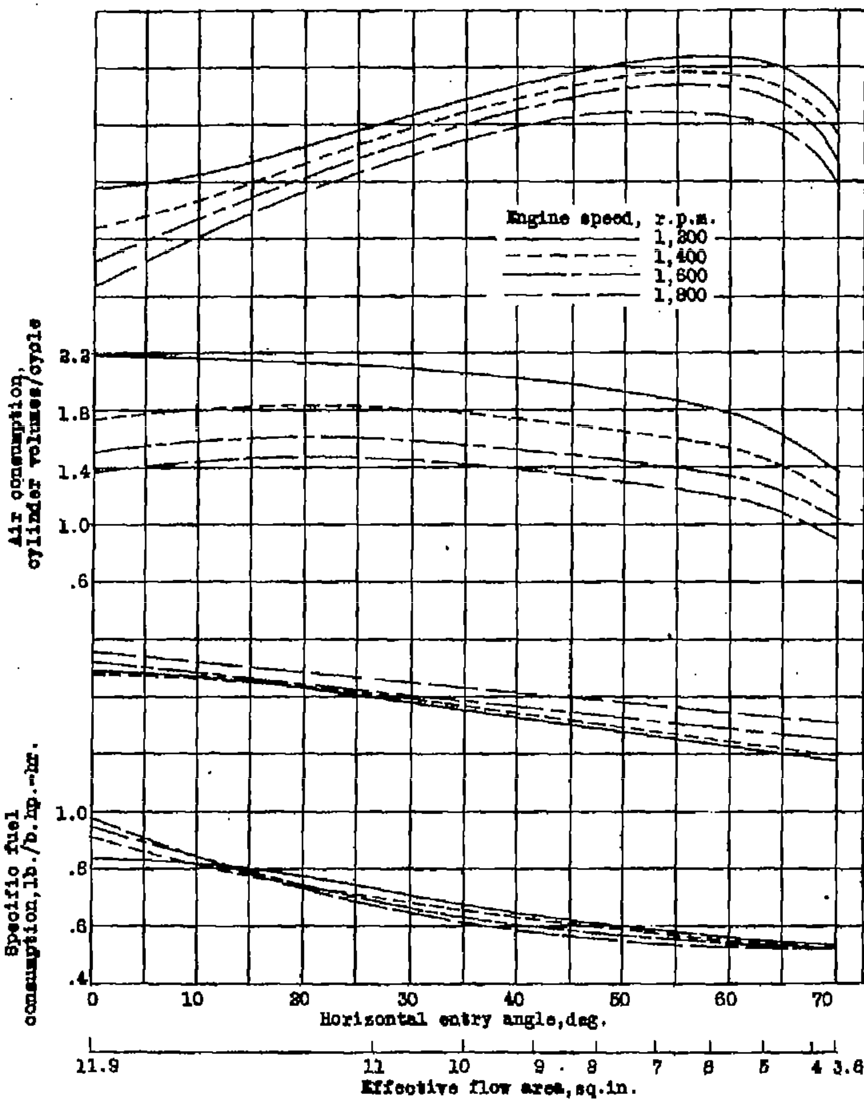


Figure 2.- Effect of horizontal air-entry angle on engine performance. Variable flow area; scavenging-air pressure, 15 inches of Hg.

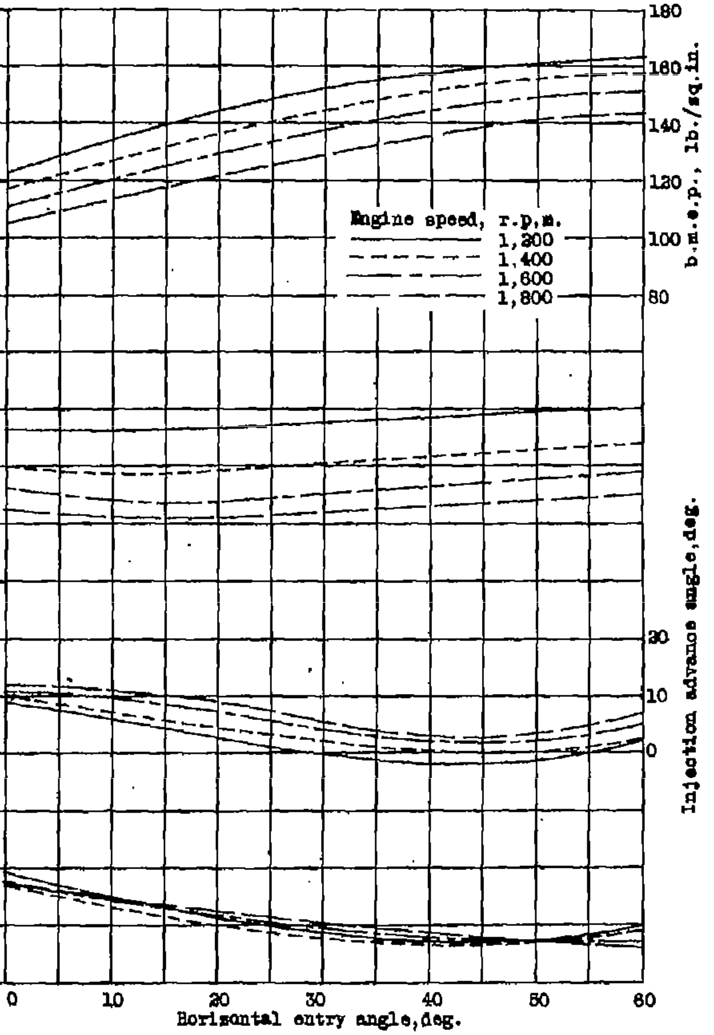


Figure 3.- Effect of horizontal air-entry angle on engine performance. Constant flow area (5.7 sq.in.); scavenging-air pressure, 15 inches of Hg.

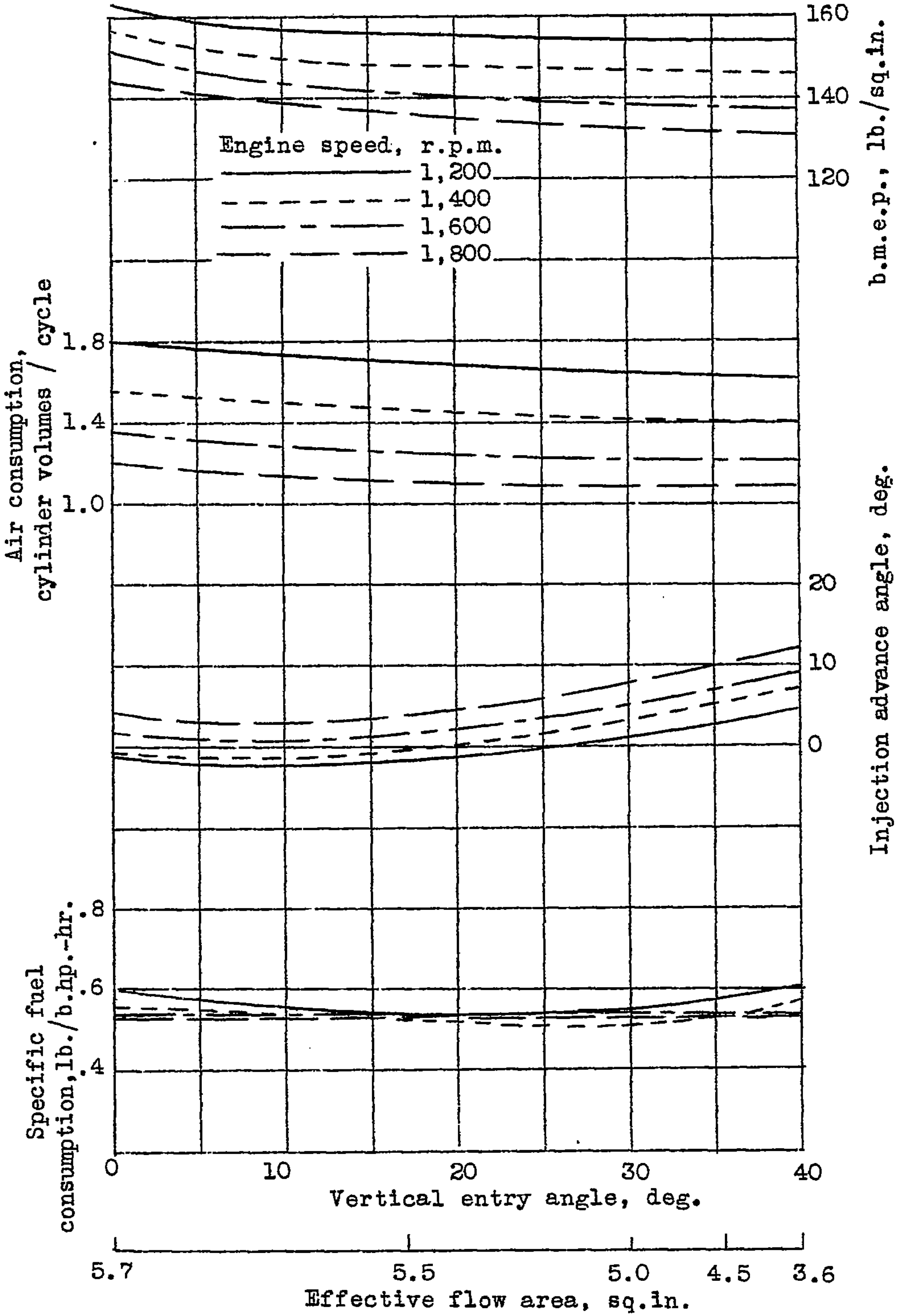


Figure 4.- Effect of vertical air-entry angle on engine performance. Horizontal air-entry angle, 60°; scavenging-air pressure, 15 inches of Hg.

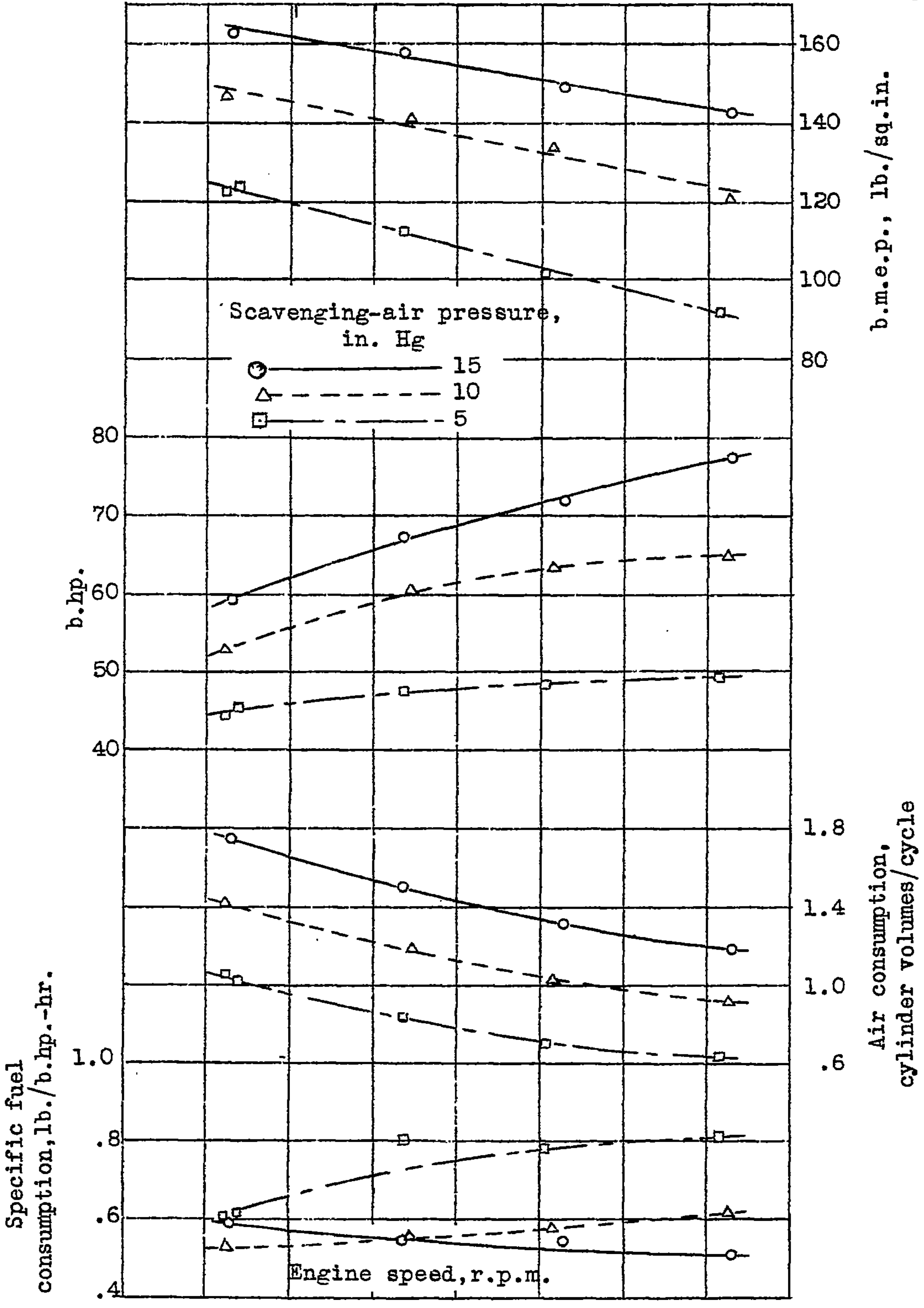


Figure 5.- Effect of engine speed on performance. Horizontal air-entry angle, 60°; vertical air-entry angle, 0°.

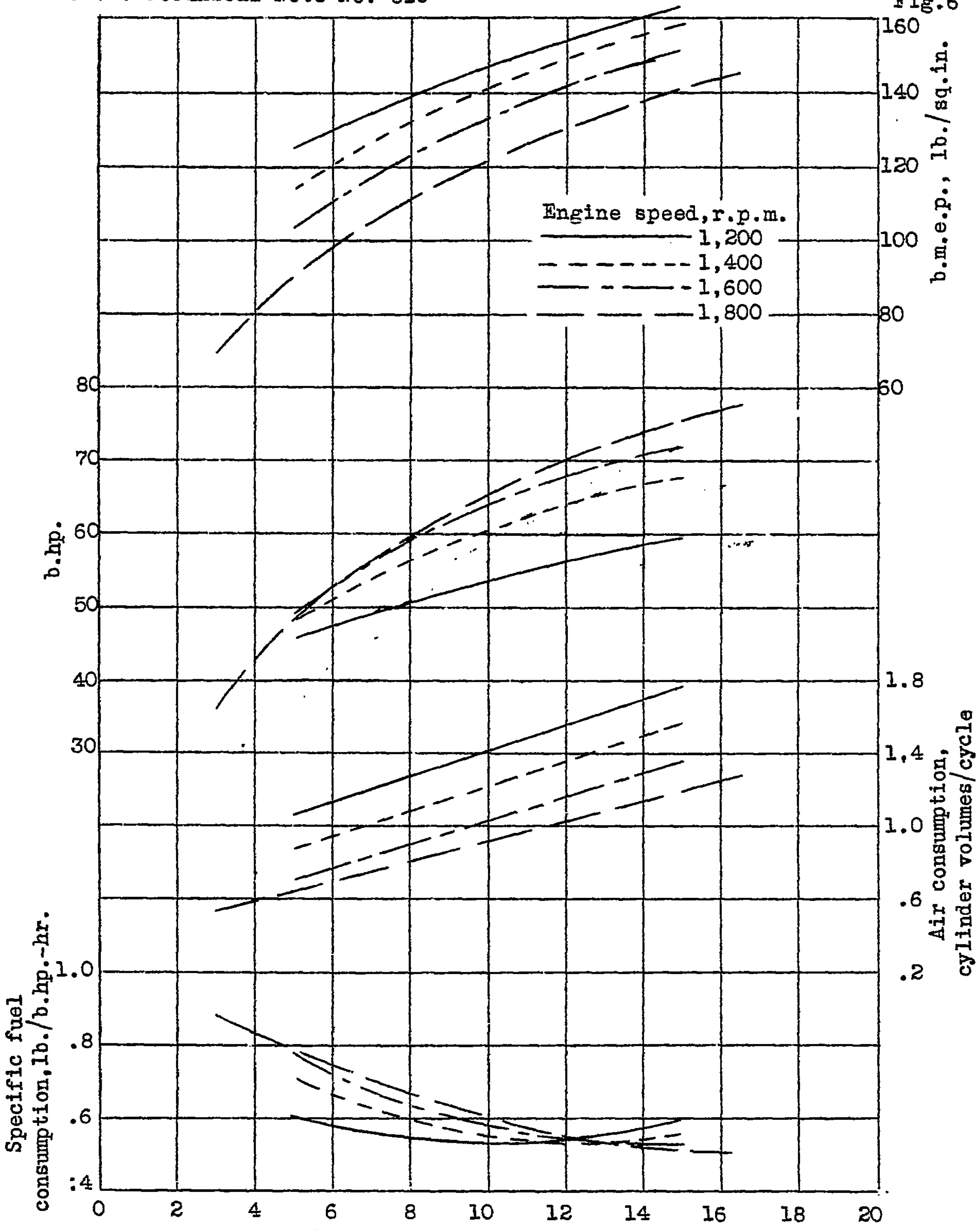


Figure 6.- Effect of scavenging-air pressure on engine performance. Horizontal air-entry angle, 60°; vertical air-entry angle, 0°.

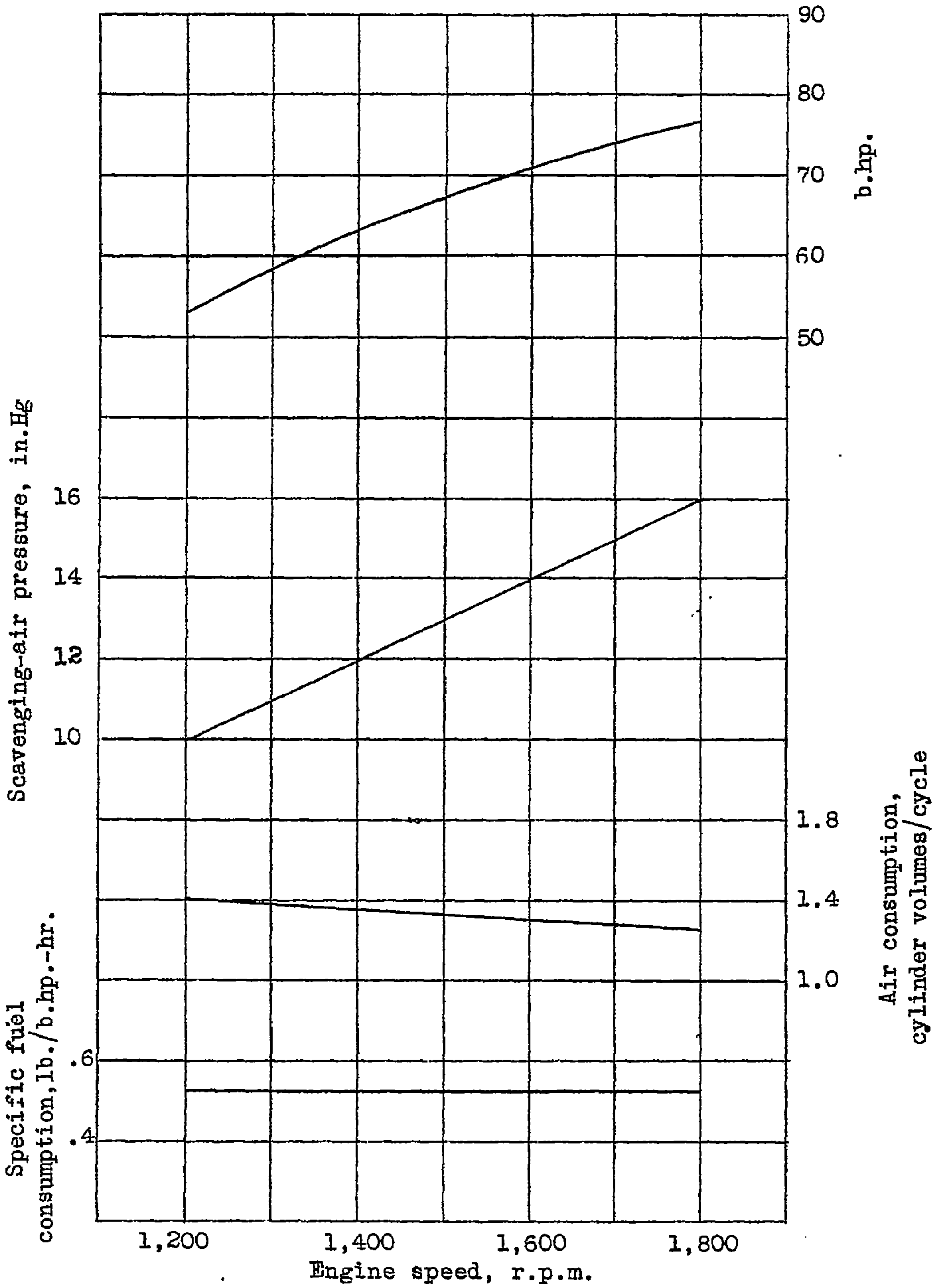


Figure 7.- Effect of engine speed on performance at optimum scavenging-air pressures. Horizontal air-entry angle, 60°; vertical air-entry angle, 0°.

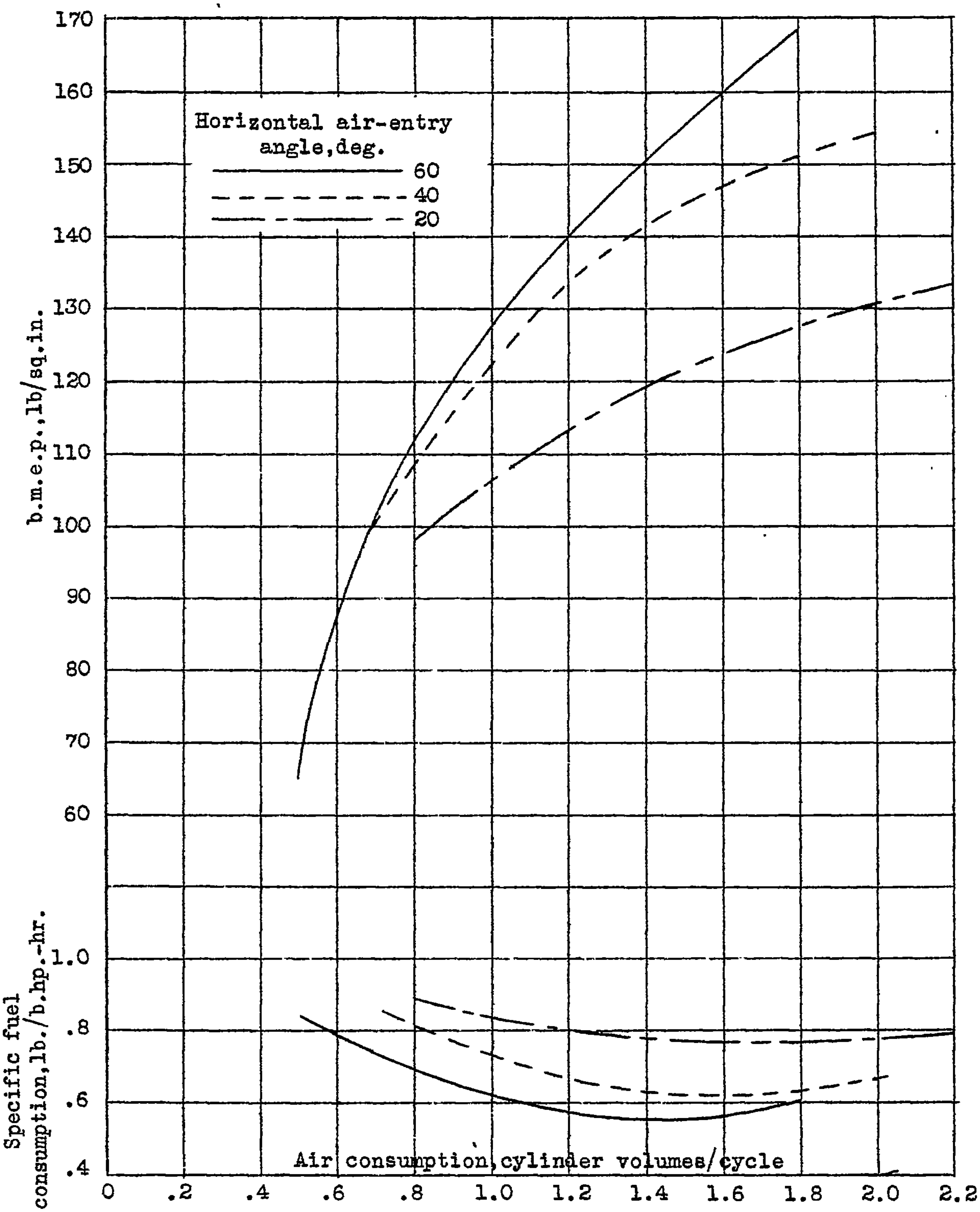


Figure 8.- Effect of air quantity on b.m.e.p. and fuel consumption. Variable flow area; vertical air-entry angle, 0°.

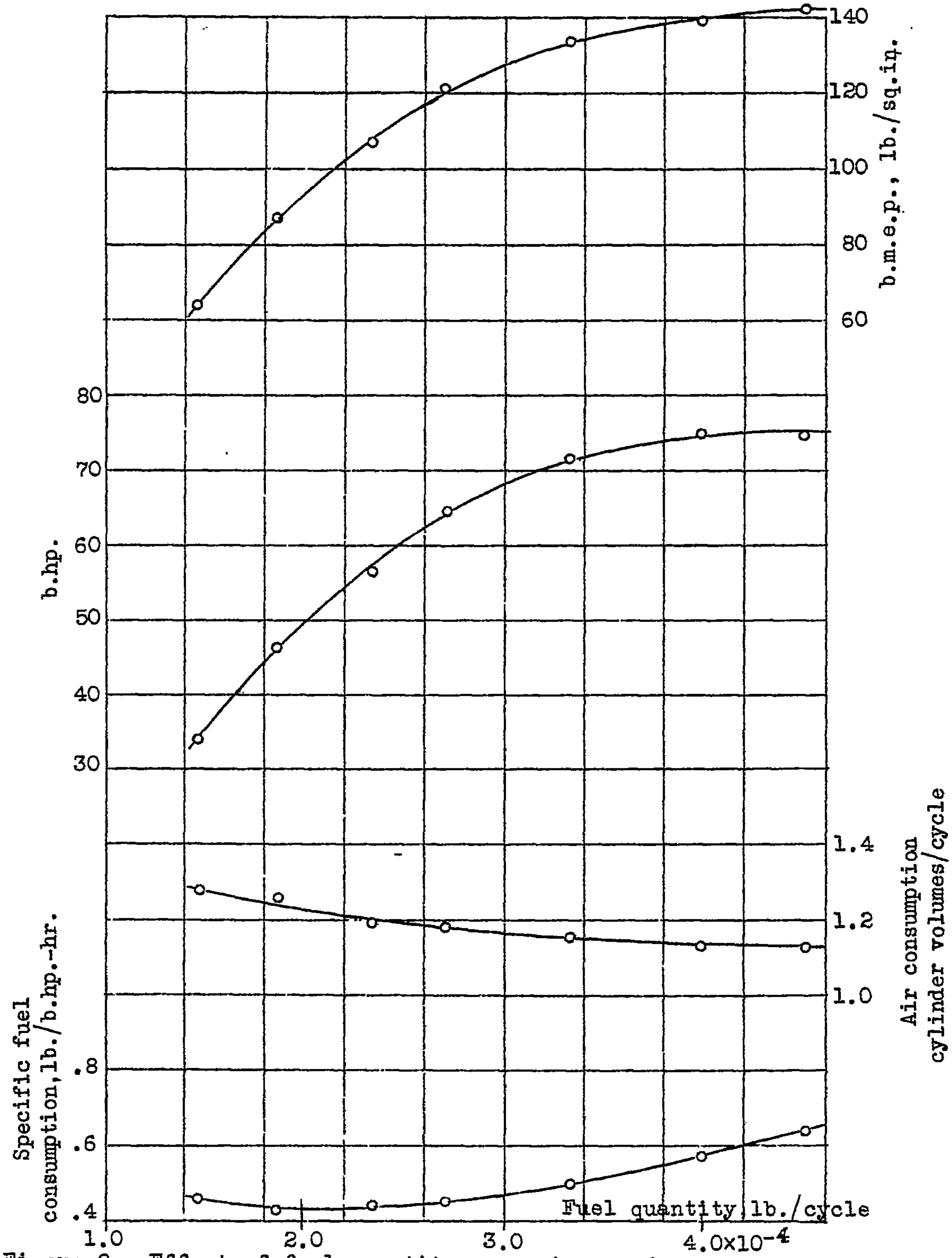


Figure 9.- Effect of fuel quantity on engine performance. Horizontal air-entry angle, 60°; vertical air-entry angle, 0°; engine speed, 1,800 r.p.m.; scavenging-air pressure, 15 inches of Hg.

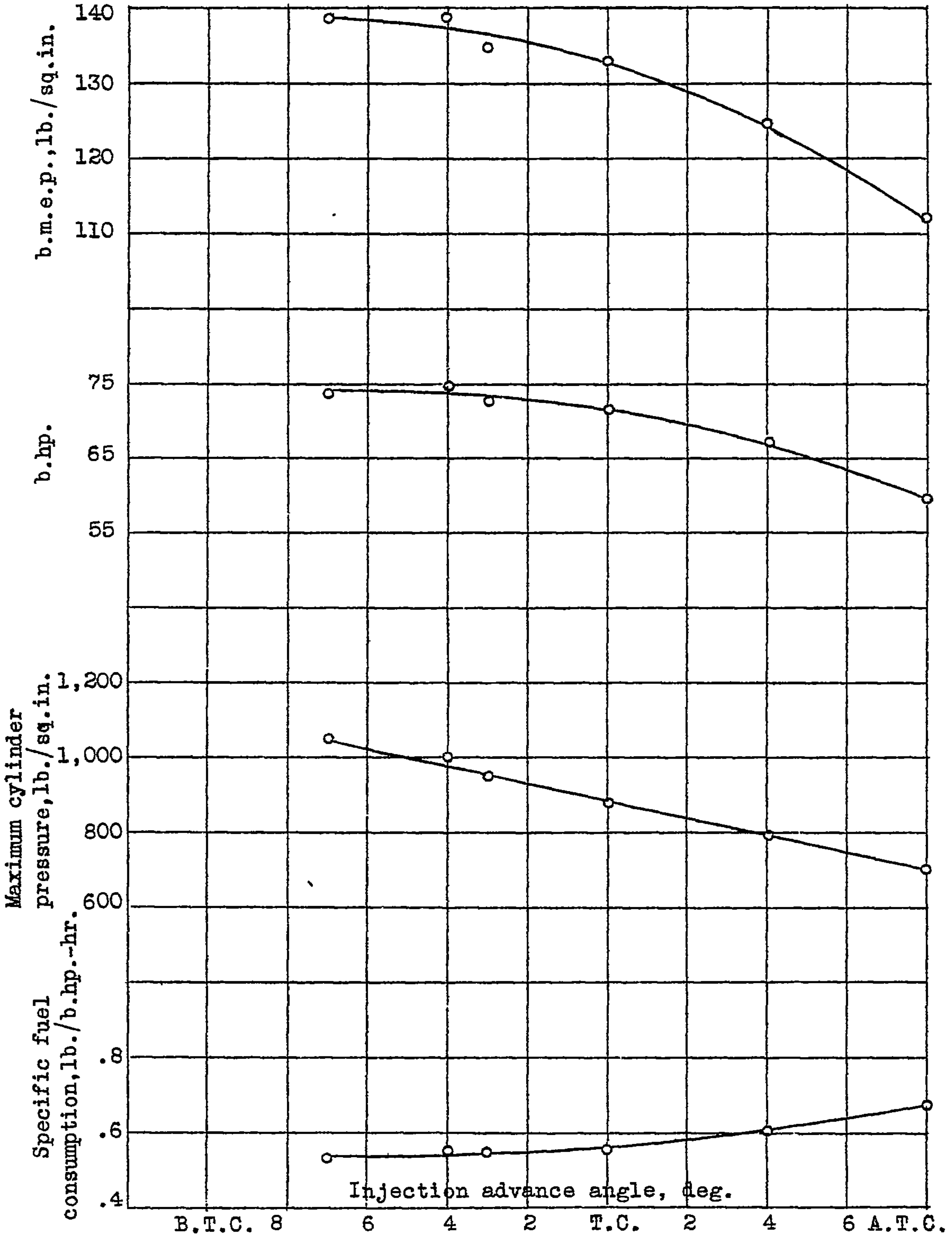
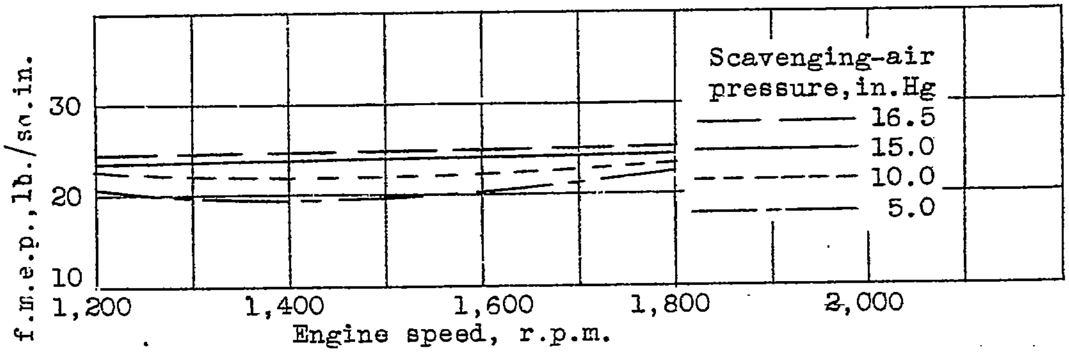
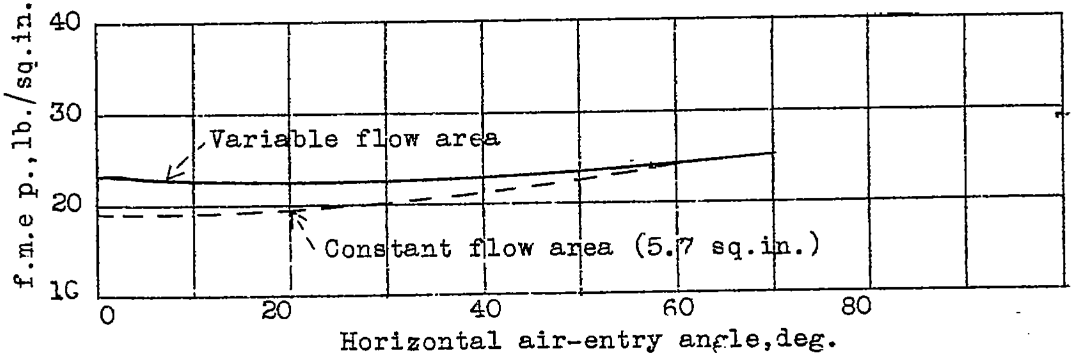


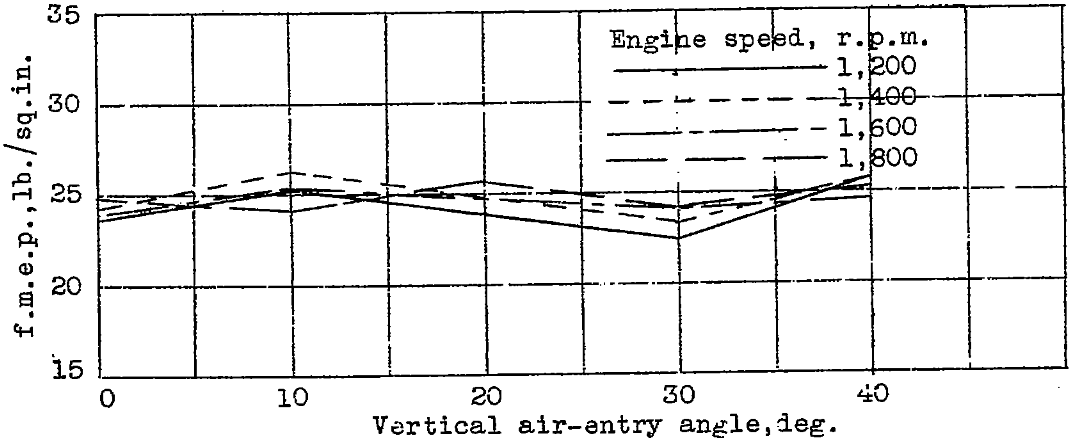
Figure 10.- Effect of injection advance angle on engine performance. Horizontal air-entry angle, 60°; vertical air-entry angle, 0°; engine speed, 1,800 r.p.m.; scavenging-air pressure, 15 inches of Hg.



(a) Horizontal air-entry angle, 60°



(b) Engine speed, 1,800 r.p.m.
Scavenging-air pressure, 15 in.Hg



(c) Horizontal air-entry angle, 60°
Scavenging-air pressure, 15 in.Hg

Figure 11.- Effect of various factors on the friction mean effective pressure.

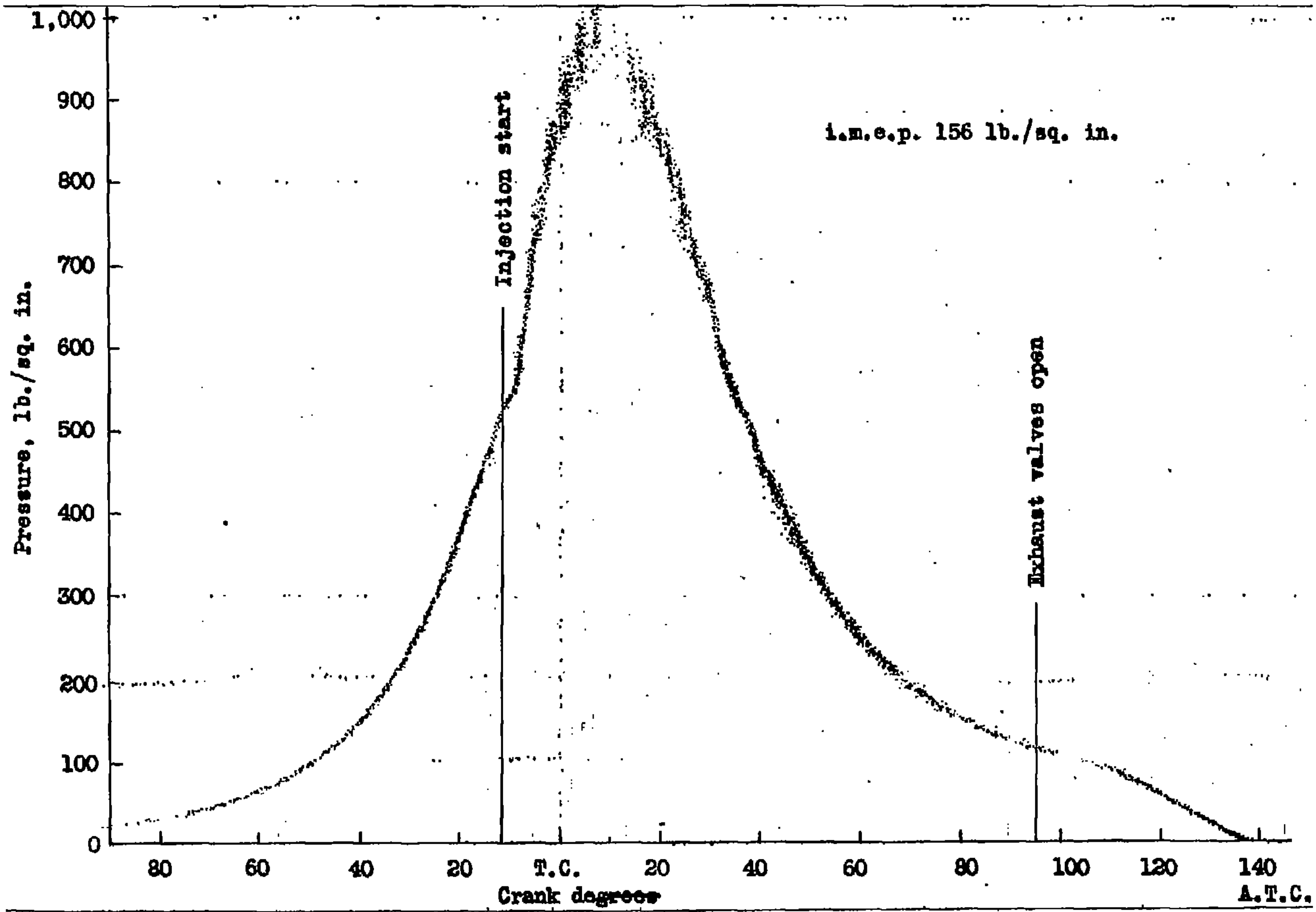


Figure 12.- Pressure-time indicator card. Horizontal air-entry angle, 60°; vertical air-entry angle, 0°; engine speed, 1,800 r.p.m.; scavenging-air pressure, 15 inches of Hg; maximum rate of pressure rise, 50.5 pounds per square inch per degree.

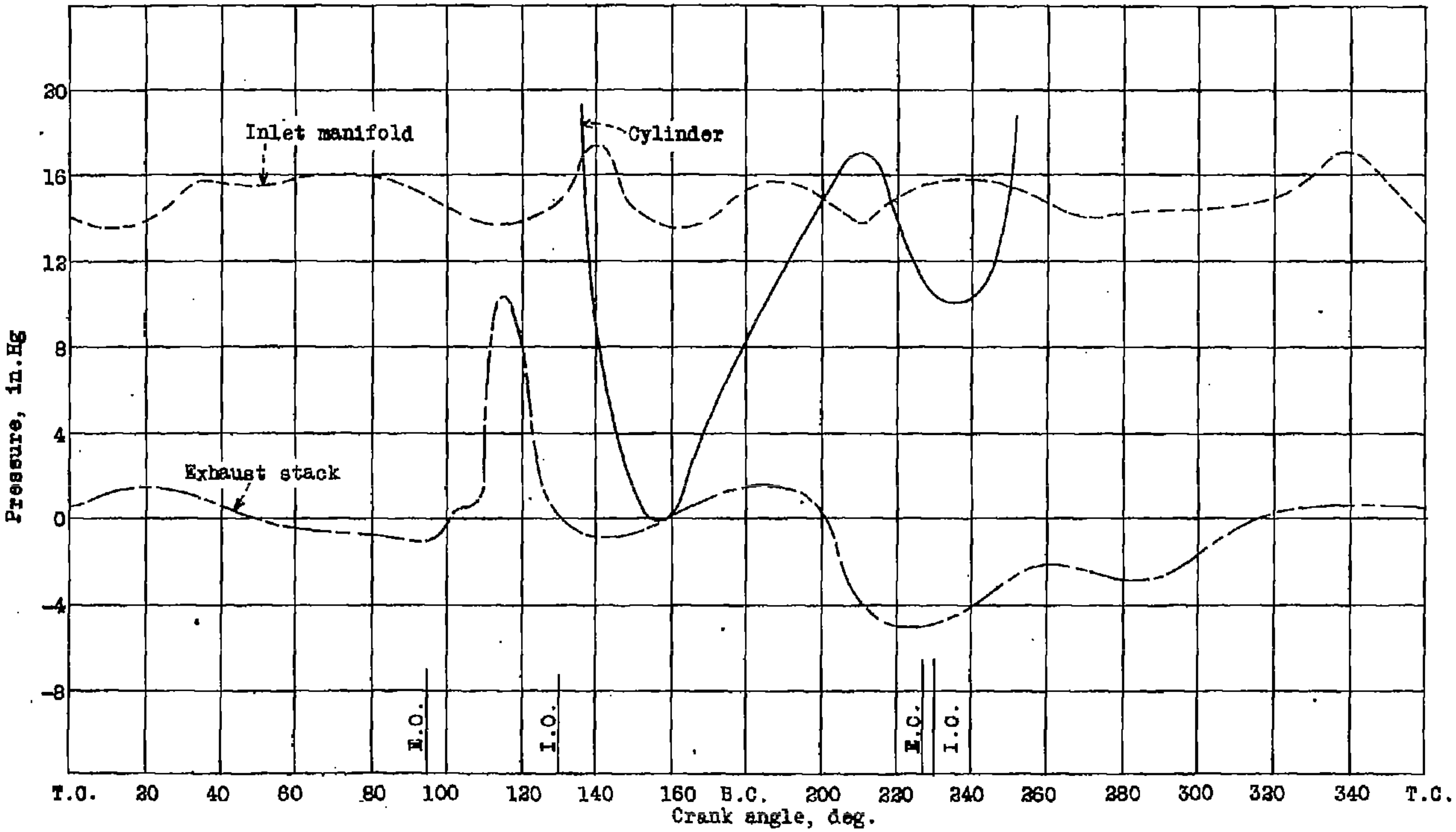


Figure 13.- Composite low-pressure indicator card. Horizontal air-entry angle, 60°; vertical air-entry angle, 0°; engine speed, 1,800 r.p.m.; scavenging-air pressure, 15 inches of Hg; injection advance angle, 11°.

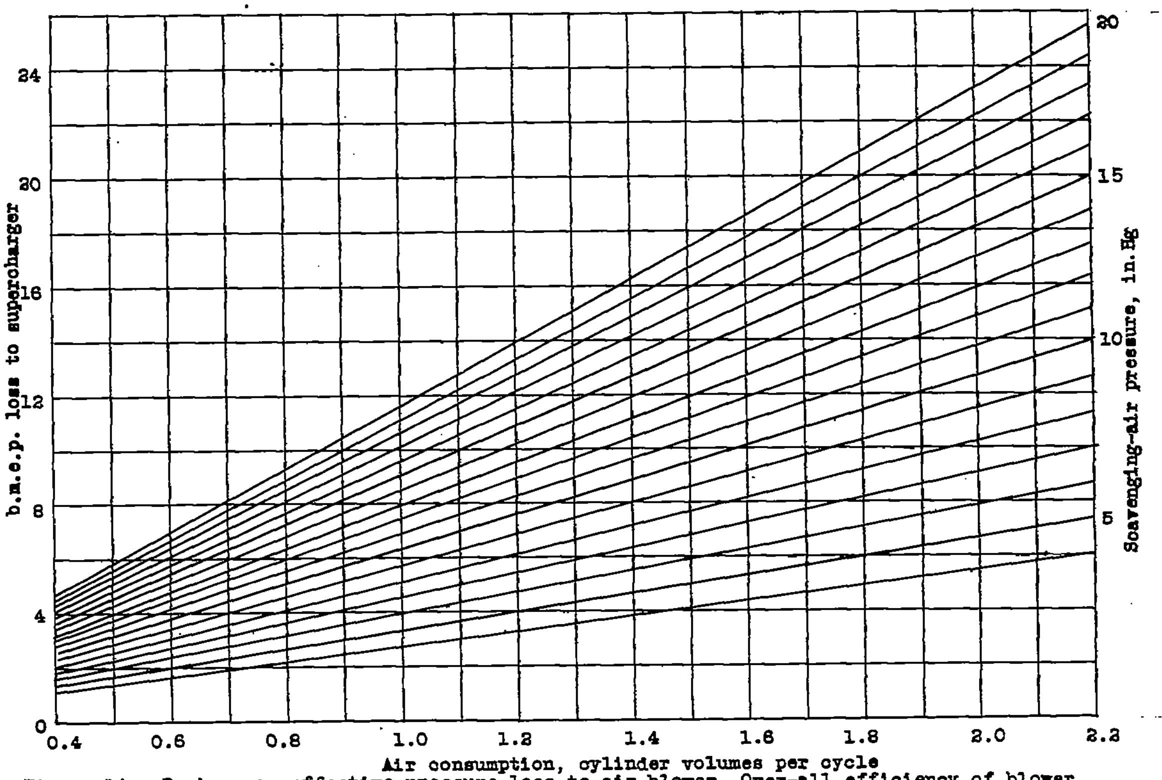


Figure 14.- Brake mean effective pressure loss to air blower. Over-all efficiency of blower, 70 percent.

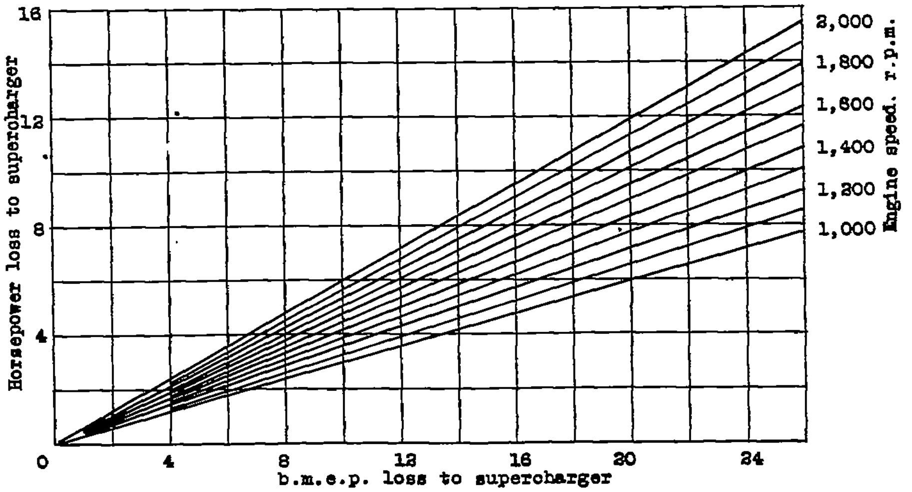


Figure 15.- Brake horsepower loss to air blower.