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CONSIDERATIONS OF AIR FLOW IN COMBUSTION CHAMBERS OF HIGH-SPEED COMPRESSION-IGNITION ENGINES

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CONSIDERATIONS OF AIR FLOW IN COMBUSTION CHAMBERS OF HIGH-SPEED COMPRESSION-IGNITION ENGINES

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SUMMARY

The air flow in combustion chambers is divided into three fundamental classes - induced, forced, and residual. A generalized résumé is given of the present status of air flow investigations and of the work done at this and other laboratories to determine the direction and velocity of air movement in auxiliary and integral combustion chambers. The effects of air flow on engine performance are mentioned to show that although air flow improves the combustion efficiency, considerable induction, friction, and thermal losses must be guarded against.

INTRODUCTION

The movement of air in the combustion chambers of high-speed internal-combustion engines after the inlet valves, or ports, close has been the subject of considerable speculation but of insufficient experimentation as to the exact nature of this air movement. Authors have expressed opinions ranging from the belief that all movement stops the instant induction ceases, to the conviction that an orderly flow persists during compression, combustion, and expansion until the gases are released. Also, the works of Neumann (reference 1) and of Bird (reference 2) have shown that air movement has important influences on ignition and combustion of fuel and air.

The movement of air in an engine cylinder and combustion chamber is of especial importance in a high-speed compression-ignition engine since the mixing of fuel and air must occur in an extremely short time. The fuel-injection system can be much simpler if air movement is used to assist the mixing of fuel and air in the combustion chamber.

The purpose of this discussion is to give a summary of the present knowledge and importance of air movement in cylinders and combustion chambers. Air movement caused by the use of air injection will be disregarded.

TYPES OF AIR FLOW

The term "air flow" as used in this discussion refers to the orderly movement of air throughout an engine cylinder or combustion chamber. The more commonly used term "turbulence" is regarded as the disorderly movement of air and is not considered here. No distinction is made between flow of pure air and of air mixed with residual gases or with fuel.

Air flow may be considered as induced, forced, and residual. Induced air flow is due to the pressure difference existing between the outside and inside of the engine cylinder during the induction. The forced air flow is due to a difference of pressure in parts of the cylinder or combustion chamber resulting from the movement of the piston on its compression stroke. The residual air flow is due to the momentum of the air maintaining motion after the original cause of the movement has ceased.

Induced air flow is of comparatively low velocity - 200 feet per second or less - because the intake port area must be large enough to give a high volumetric efficiency. The velocity of the induced air flow changes with the engine speed. When this type of air movement is used to scavenge a uniflow two-stroke-cycle cylinder the form of the flow is important. Tangential ports and helical air flow in the cylinder are conducive to better scavenging than radial ports with flow along the cylinder axis. Induced air flow can be used to distribute a well-dispersed fuel spray and can be used as a source of residual air flow. The usual form of combustion chamber utilizing this type of air flow is a simple geometric shape such as a short cylinder.

The forced air movement generally reaches a maximum velocity through a restriction either just before or during the early part of the injection period, i.e., approximately 20° B.T.C. This maximum velocity of flow can be varied over a wide range by the size of the restricting passages in the combustion chamber. The forced air flow may have a velocity high enough to mix the air even with a poorly dispersed spray. The time of the maximum flow with respect to the crank angle may be varied within limits by the design of a displacer on the piston to cause an increasing restriction in the air passages just before the top center position.

Induced air flow can occur only during induction, forced air flow can occur only during compression, while residual air flow persists during the compression and expansion. The induced and forced air flow must be directed along a smooth and unobstructed path so that a strong residual movement will persist. If an excess of minor swirls form, the general effect will be a damping of all flow.

In combustion chambers, air flow usually occurs as combinations of two or three of the fundamental types. The combustion chambers employing them may be divided into two general classifications - the integral and the auxiliary-chamber types.

The integral combustion chamber (reference 3) having air flow is usually a section of a cylinder in which the induced air flow continues as a rotational movement. The form of the induced air flow is governed by a feature of the induction system such as tangential passages leading to intake ports, vanes in induction pipes, shrouded intake valves, or any means of directing the air flowing into the cylinder. Some few integral combustion chambers formed in the piston crown have forced and residual air flows which are dependent for form and velocity upon the piston crown shape and upon the remaining area which displaces the air near the end of the compression stroke.

The auxiliary-chamber type (reference 3) has a chamber containing part of the clearance separate from the cylinder bore and connected to it by one or more passages. With this type of combustion chamber the possible range of air flow velocities is very wide and is controlled by the area of the connecting passages. The auxiliary chamber may be formed either in the cylinder head or in the piston and has a definite forced and residual air movement, the direction and velocity of which must be determined if it is to be used to the best advantage.

METHODS FOR MEASUREMENT OF AIR FLOW

The methods developed for analyzing the direction and the velocity of air flow in combustion chambers have been separate in that the direction is usually estimated from the shape of the chambers and passages and the velocity calculated from measuring some characteristics of the air flow such as the effective impact. Velocity determinations have been made both by calculations from force measurements and by direct measurements by means of anemometers.

Probably the simplest means of determining direction is to observe the direction of the grain of carbon deposits in the combustion chamber. This method gives information as to air or mixture flow before combustion and gas flow during combustion. Figure 1 shows the carbon formation on the cupped crown of a piston used in a two-stroke-cycle test engine with tangential vanes before intake ports in the cylinder wall. The tangential markings on the rim of the crown are caused by the induced air flow as directed by the vanes while the markings in the cup of the crown are caused by the residual air flow in the combustion chamber. That residual air flow was present was further indicated by an excessive carbon deposition in the cylinder head to leeward of the fuel valve.

There are a number of cases where transparent cylinders have been used in approximating engine conditions and in observations of visible particles suspended in the flowing air. Hurley and Cooke (reference 4) have reported observations, by means of sparks, oil, and water drops in combustion chambers, which seem to approach engine operating conditions more nearly than any other application of the visual method. They have reported that induced air flow persists to form a residual free vortex whose form is independent of engine speed. These methods give little if any information as to velocity of air flow.

In an engine combustion chamber, H. Hintz (reference 5) has applied the plate method of recording force and has computed velocities up to 20 meters per second at top center but does not obtain his best engine performance with the highest velocities. An objection to this method is that a plate large enough to give sufficient torque for operating the recording apparatus may seriously disturb the natural air flow.

To determine velocities directly Ricardo (reference 6) has used a vane anemometer in his cylindrical combustion chamber and correlated his engine performance with readings of velocity to find a definite relation. This method is open to objection on the ground of preventing the air from assuming its natural flow, in this particular case maintaining a forced vortex regardless of a tendency to become a free vortex.

At the N.A.C.A. laboratory a simple adaptation of the plate method was used to obtain an approximation of the form and relative velocity of air flow in the N.A.C.A. cylinder head No. 3. (Fig. 2.) This cylinder head has a pear-shaped precombustion chamber formed half in the head proper and half in a cap attached by studs. A thin copper gasket was inserted between the cylinder head proper and the chamber cap. This gasket had small nibs around and protruding inside the chamber. Motoring the engine caused the air flow to bend the nibs and by noting the engine speed at which bending started an indication of relative air velocity was obtained. The direction and axis of air rotation were closely checked by tests with several different gaskets.

Referring to the photograph (fig. 2), the nibs nearest in line with the cylinder-to-chamber orifice, i.e., near the "orifice center line," bent at an engine speed of 840 r.p.m. The other nibs would not bend until the supporting root width was reduced by cutting as shown. With this change all nibs were bent at 1,500 r.p.m. as photographed, the nibs opposite the "orifice center line" being the last and least bent.

As a further test other gaskets were inserted in the auxiliary chamber with two long strips of copper projecting across the chamber. After motoring the engine the strips were bent to conform closely to the spherical or conical shape of the chamber depending on whether the long strips projected from the bottom or top of the chamber.

The results of the tests with the copper strips demonstrated that a movement was established which lost much of its force in making abrupt changes of direction so a new cap was used which made the auxiliary chamber spherical. This change in shape resulted in a conservation of the energy of the air flow as bending of the copper nibs at a lower engine speed indicated and as power tests showed an intensification of the effects of the air flow on combustion as previously reported. (Reference 7.) The form of the air flow was further checked by noting carbon deposited inside the cleaned chamber when motoring the engine. The whirls at the ends of the axis about which the air rotated were distinctly marked. The copper gasket and carbon deposit indications of flow are in close agreement. An analysis of the conditions of air flow existing in the spherical chamber is that the residual flow assumes the form of a sphere of air rotating about a definite axis.

EFFECT OF AIR FLOW ON ENGINE PERFORMANCE

The performance of a high-speed, compression-ignition engine was improved by Kemper (reference 8) who placed vanes in the intake pipe to direct the inducted air toward the injection valve.

The importance of having the correct relation between air flow and fuel spray was shown by the authors in reference 7 in which a series of tests was made with the spherical precombustion chamber and N.A.C.A. cylinder head No. 3. (See fig. 2.) From these tests it is evident that the proper relation of air flow to fuel spray improves engine power and fuel economy.

In previous work (reference 9) with N.A C.A. cylinder head No. 4 (fig. 3) with a straight throat there was no effective air flow, the distribution of fuel to the air being effected by injection from a multiple-orifice nozzle. A tangential throat (see fig. 3) of equal area was fitted to the cylinder head such that the forced air flow, though of low velocity, was directed to one edge of the vertical, disk-shaped combustion chamber. If the forced air flow were strong enough there should have resulted a residual rotation of air in planes parallel to the valve faces.

The performance testing with the tangential throat was done at the same time as the tests reported for the straight throat in reference 9. The test unit and test conditions were the same except for the substitution of the tangential flow throat. The multiple-orifice nozzle No. 17-1, which gave the best results with the straight throat, was used with the tangential throat but the performance was poor. The performance was also poor when using a single-orifice nozzle.

The best performance with the tangential throat was obtained with a lip nozzle which directed a narrow, wedge-shaped, sheet of spray into the throat. With this arrangement (fig. 3) the performance used for comparison and discussion was obtained. The angle of the spray from the lip nozzle was considered the same as the angle of the lip because spray photographs showed that the difference was negligible. The tests started with a lip angle of 35° from the vertical which would allow the spray to pass through one side of the throat and impinge upon the piston if not prevented by the air flow. The lip angle was increased by 5° increments to 60° at which angle the spray would impinge upon the opposite side of the throat unless prevented by the air flow.

The curves in Figure 4 show that the optimum performance was obtained when the spray was directed at 50° which was toward the center of the throat, thereby obtaining the best relation between the spray and the air flow. Performance with the valve turned through an angle of 180° was very poor. For comparison of best performance with and without air flow, curves with variable fuel quantities are shown in Figure 5 for the 50° lip nozzle with the tangential throat and the multiple-orifice nozzle with the straight throat. An examination of the curves in Figure 5 shows that although the brake performance at 1,500 r.p.m. is slightly better at low fuel quantities with tangential air flow it is decidedly poorer over the remaining range, but the indicated performance is slightly better even in the upper range of fuel quantities.

These data show that the friction horsepower when motoring at 1,500 r.p.m. was 28 per cent higher with the tangential air flow throat than with the straight throat. This increase resulted from the greater friction losses in the throat passage. Also, the volumetric efficiency dropped from 91.0 per cent to 85.5 per cent so that 5.5 per cent less air was available for combustion. These two losses are the ones most apparent in all schemes for using air flow and although the values may be high in this particular case, since induction as well as compression is through the throat, it is reasonable to expect such losses to be even greater under power than they are while motoring. Another loss that is not quite so apparent became evident when the heat losses to the cooling water were determined.

For motoring, the amount of heat lost to the cooling water amounted to 6.4 per cent of the friction horsepower for the tangential air flow condition and amounted to 4.5 per cent without the tangential air flow. The actual amount of heat lost was 74 per cent greater with the tangential air flow than without it. This amount could also be expected to increase when under power because of the higher pressures and temperatures involved.

The magnitude of the losses led to the abandonment of this method of air flow utilization with this cylinder head. The results agree in part with the results of Alexander's work (reference 10), on a larger but similar cylinder at lower speeds, in that some methods of using air flow may cause a decrease in engine performance.

With an understanding of the losses involved, the greater significance of these curves (fig. 5) is evident. The b.m.e.p. curves show that at the higher fuel quantities there is not a sufficient return in power for the energy required by the air flow although the i.m.e.p. curves indicate that a good combustion efficiency is maintained. Both maximum-cylinder-pressure curves remain within reasonable limits although the one with the air flow is higher. The most noteworthy of the fuel-consumption curves is the indicated fuel consumption with air flow because it is nearly a straight line and indicates a more nearly uniform combustion efficiency than without air flow.

Although at small loads the dispersion of the spray became poor, the air flow was sufficient to aid mixing and make both the brake and indicated fuel consumption better than without air flow.

CONCLUSIONS

Any of the three types of air flow may be used advantageously since, if correctly directed and used with the proper spray, the air flow will be effective as a means of causing intimate mixing of fuel and air.

The methods of measuring air flow have given incomplete and only approximate data insufficient to design engines to use air flow efficiently. Methods should be developed to give more exact data of air flow direction and velocity throughout the combustion chamber and cylinder and throughout the entire cycle, not only to allow more efficient use of the air flow but also to aid the analysis of engine performance.

The utilization of air flow is influenced by such factors as throttling and damping which must be taken into account if the benefits to be derived are not to be overbalanced by the volumetric, friction, and thermal losses incurred. However, the results of engine tests indicate that proper coordination of air flow and fuel spray will result in better engine performance. The mixing and combustion of fuel and air by means of air flow should be more complete and uniform than when effected by spray dispersion alone.

National Advisory Committee for Aeronautics,
Langley Memorial Aeronautical Laboratory,
Langley Field, Va., March 10, 1932.

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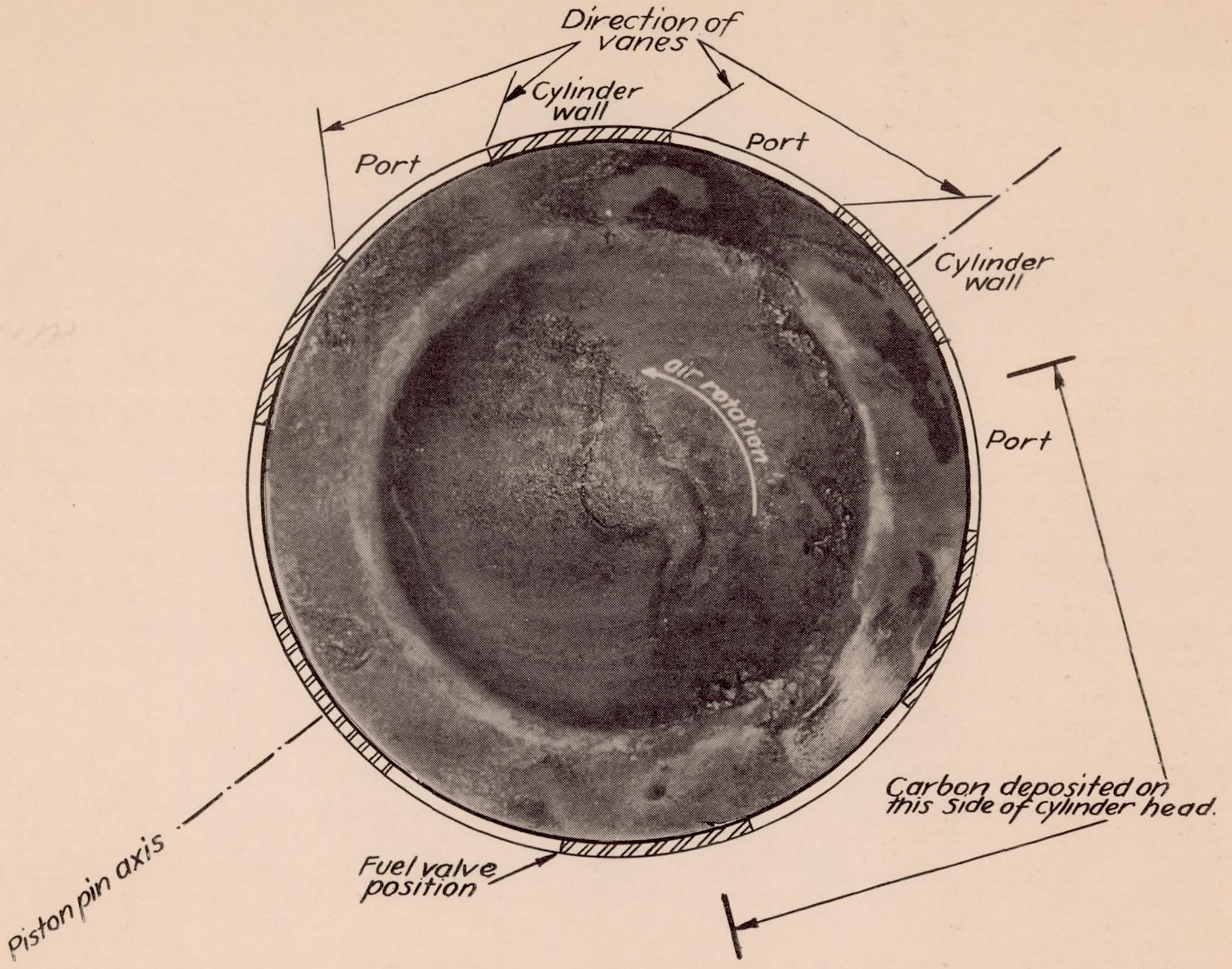
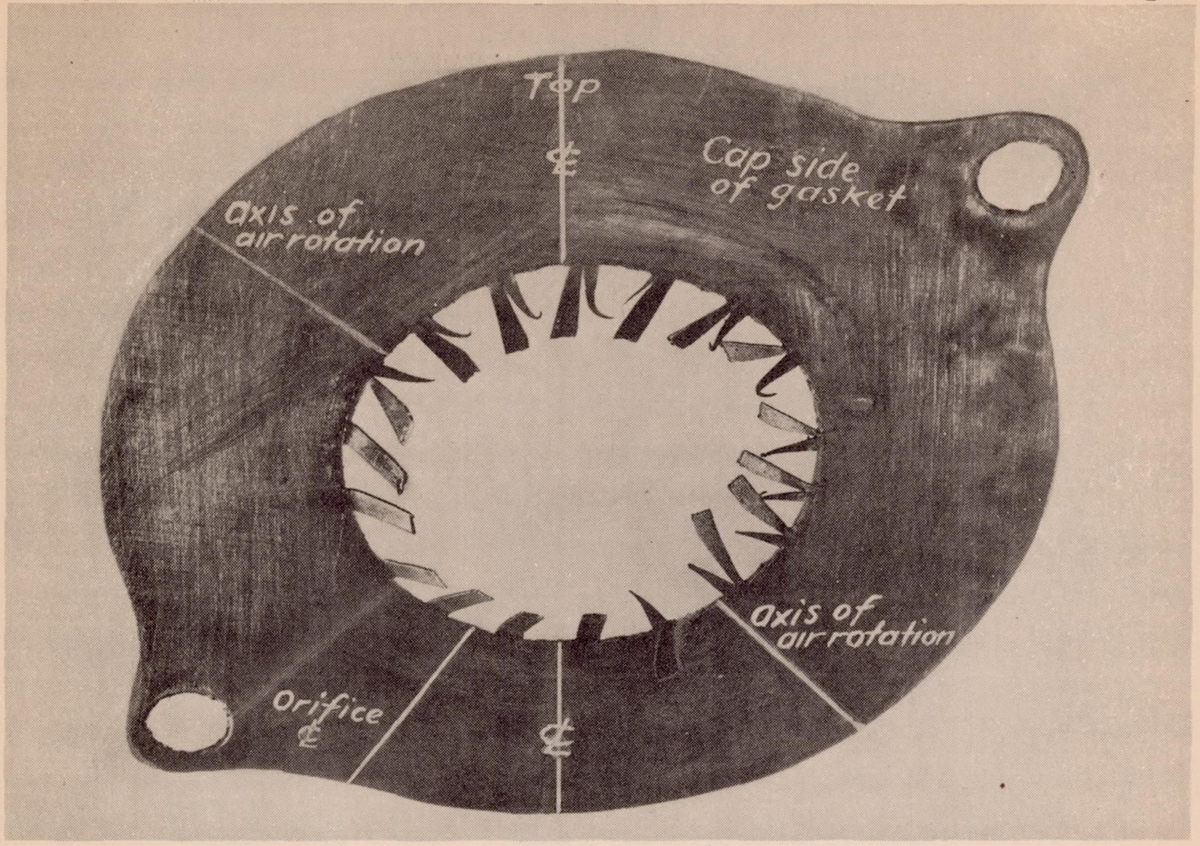


Fig.1 Carbon formation on cupped piston crown indicating induced and residual air flow.



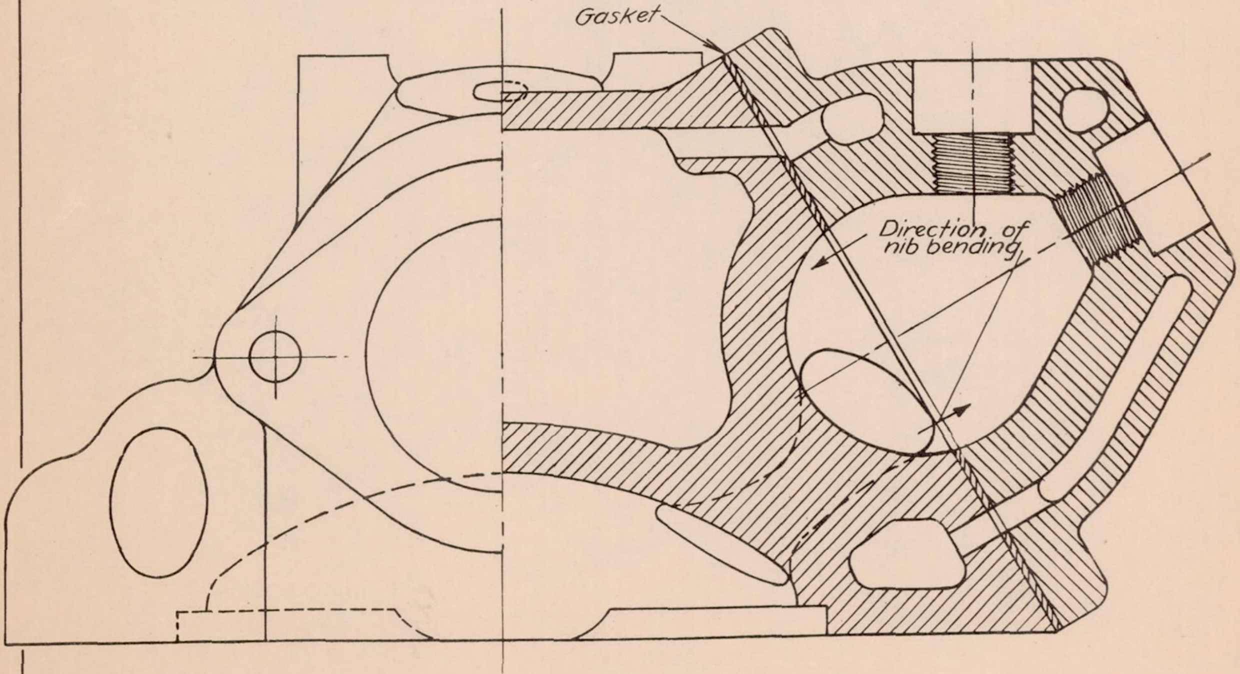


Fig.2 Copper gasket (above) with nibs bent by forced air flow in precombustion chamber of N.A.C.A. cylinder head. No.3 (below).

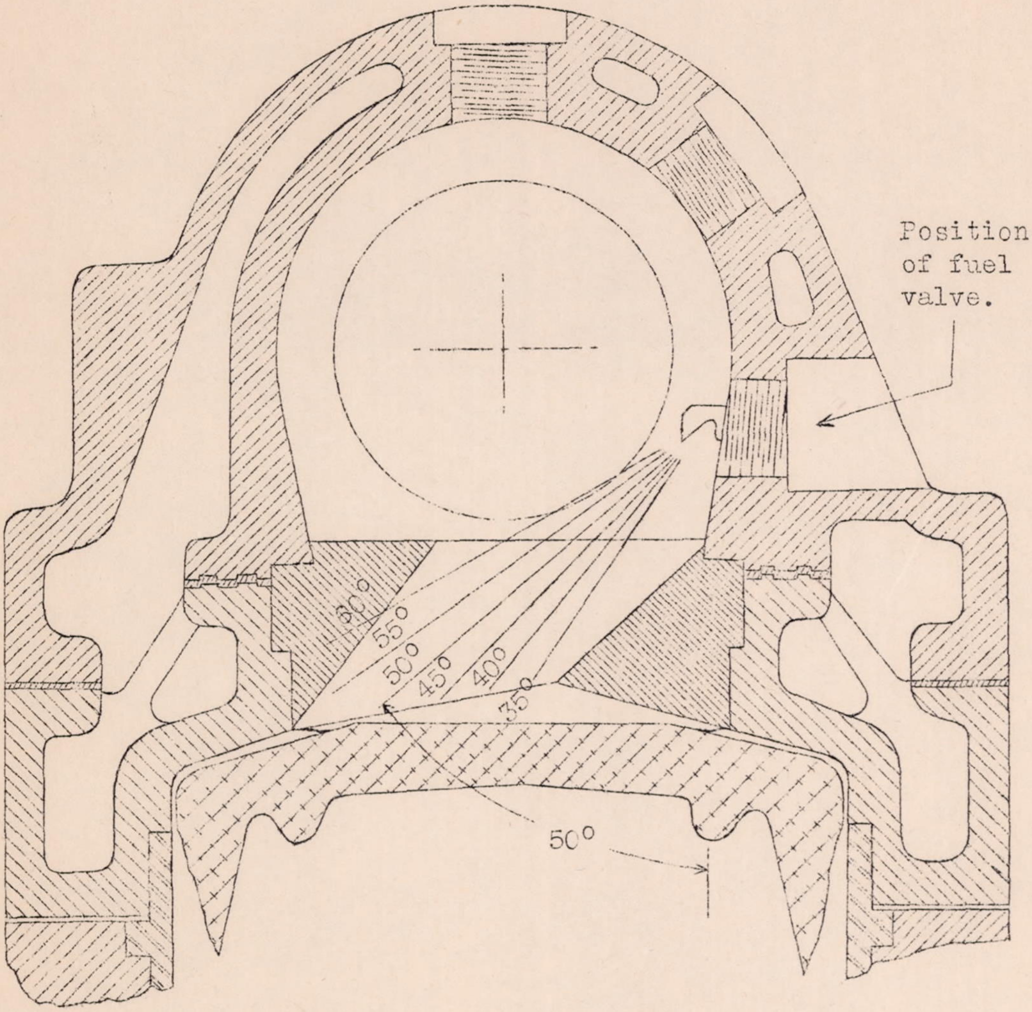


Fig.3

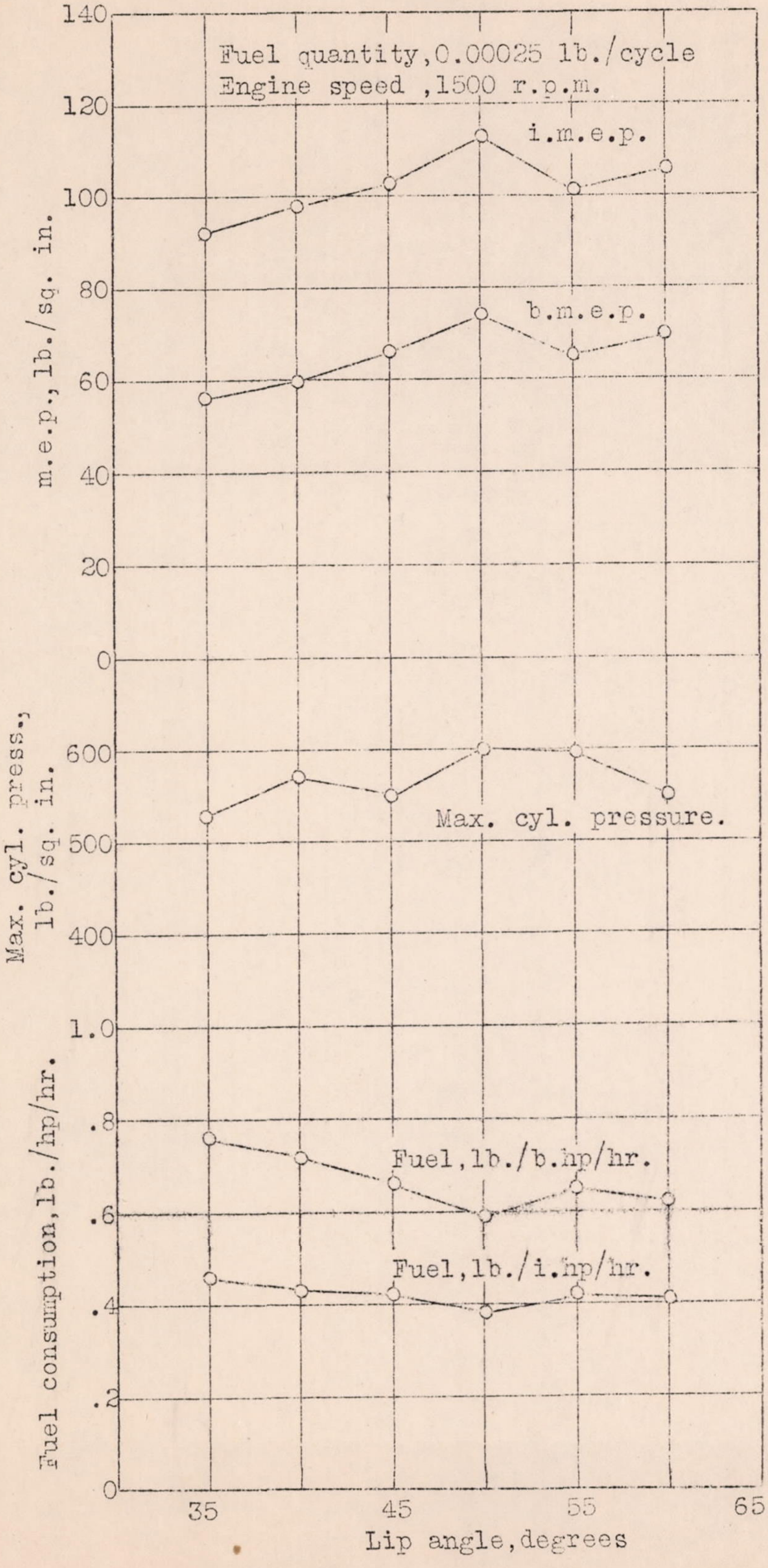


Fig.4 Effect of lip angle on engine performance.

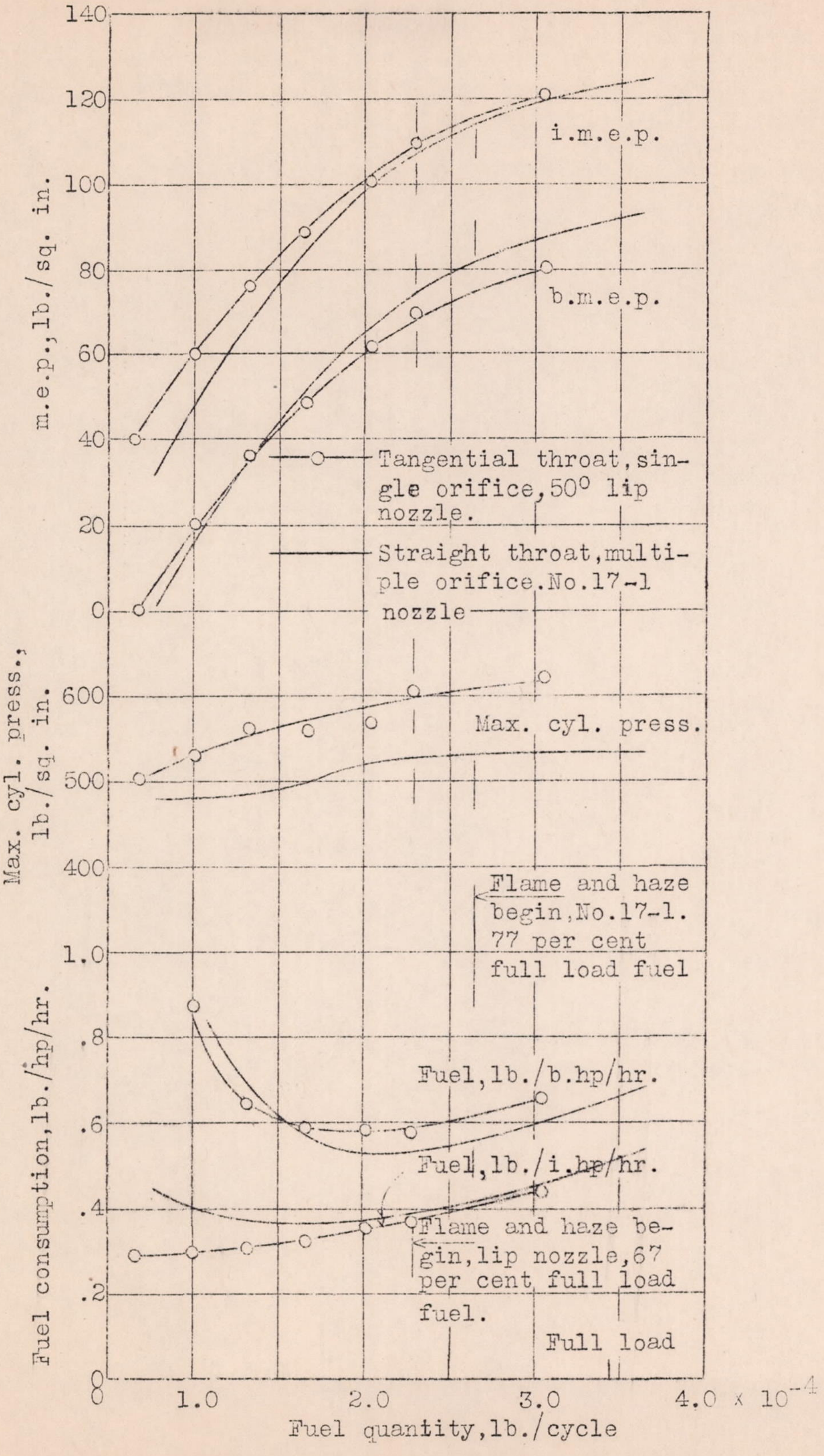


Fig.5 Effect of load on engine performance.