REPORT No. 653

A STUDY OF AIR FLOW IN AN ENGINE CYLINDER

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SUMMARY

A 4-stroke-cycle test engine was equipped with a glass cylinder and the air movements within it were studied while the engine was being motored. Different types of air flow were produced by using shrouded intake valves in various arrangements and by altering the shape of the intake-air passage in the cylinder head. The air movements were made visible by mixing feathers with the entering air, and high-speed motion pictures were taken of them so that the air currents might be studied in detail and their velocities measured. Motion pictures were also taken of gasoline sprays injected into the cylinder on the intake stroke.

The photographs showed that: A wide variety of induced air movements could be created in the cylinder; the movements always persisted throughout the compression stroke; and the only type of movement that persisted until the end of the cycle was rotation about the cylinder axis. The velocities of the air currents were approximately proportional to the engine speed and had about the same value whether the flow was orderly or turbulent. Orderly air movements greatly aided the distribution of the sprays about the cylinder.

INTRODUCTION

The performance of spark-ignition engines that spray fuel into the cylinders during the intake stroke is improved when air flow is used to assist the mixing of the fuel and the air. Tests have been made with the N. A. C. A. combustion apparatus (reference 1) to determine the effect of directed air flow on the combustion characteristics of such an engine. The present paper describes apparatus constructed and tests made to study the air movements in an engine cylinder and reports the effects of such movements on the fuel sprays with no combustion taking place. The size and the shape of the cylinder head were the same as those used for the tests of reference 1 and, in both cases, the direction of the air flow was principally controlled by the use of shrouds on the intake valves.

APPARATUS AND TEST METHODS

TEST ENGINE

A steel casting that surrounded and supported a glass cylinder was inserted between the barrel and the head of a single-cylinder test engine. (See figs. 1 and 2.) Four large openings in the steel casting afforded an unobstructed view through the center of the cylinder. The inside surface of the glass cylinder was accurately ground and polished to the same diameter as the engine bore, and its length was equal to the engine stroke. The wall thickness was 0.5 inch. The lower side of the cylinder head was modified to fit the steel casting and,

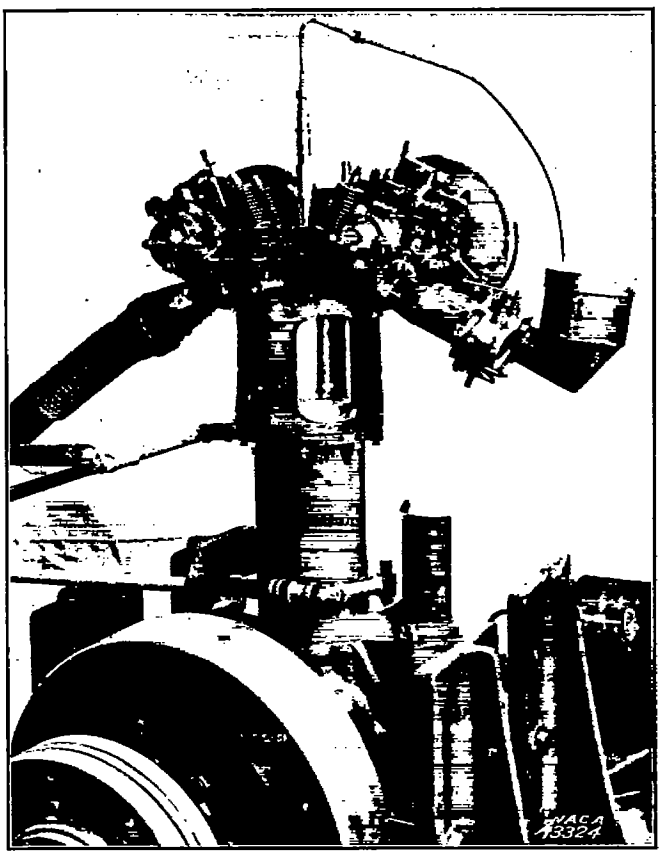


Figure 1.—Test engine with glass cylinder.

when bolted down on the casting, it clamped the glass cylinder firmly in place.

A hollow aluminum extension was fastened on top of the piston, its diameter being 0.032 inch less than the inside diameter of the glass cylinder. This clearance was determined from the height of the extension above the piston pin and the maximum angle of oscillation allowed by the clearance of the main piston in the cylinder bore.

There are two inlet and two exhaust valves in the head, each 2 inches in diameter. Other engine constants are as follows:

Engine bore	5 inches.
Engine stroke	7 inches.
Connecting-rod length	12 inches.
Compression ratio	6.0.
Ridge angle of pent-roof head	130°.
Valve lift	⅜ inch.
Valve timing:	
Inlet opens	15° B. T. C.
Inlet closes	45° A. B. C.
Exhaust opens	50° B. B. C.
Exhaust closes	10° A. T. C.

MEANS OF CONTROLLING DIRECTION OF AIR ENTERING CYLINDER

A set of intake valves was equipped with shrouds that forced the air to flow past one side of the valves and thus imparted definite directions to the incoming

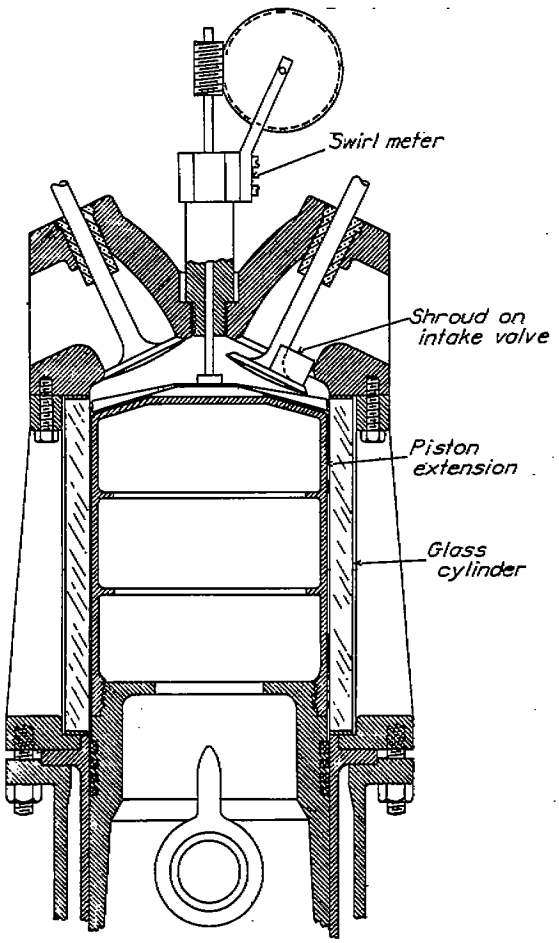


FIGURE 2.—Sketch showing glass cylinder and cylinder head.

air streams. The shrouds were thin brass strips soldered to the valve heads. They normally extended 180° around the head but, for one test, the shroud angle was reduced to 135° and then to 90°. (See figs. 2 and 3.) No means were provided for preventing rotation of the valves, for it was observed that they did not change their positions during the brief test periods.

Another method of controlling the direction of the air as it entered the cylinder was to alter with modeling clay the shape of the intake-air passage in the cylinder head. Figure 4 shows how the passage to one of the intake valves was blocked off and the roof of the passage

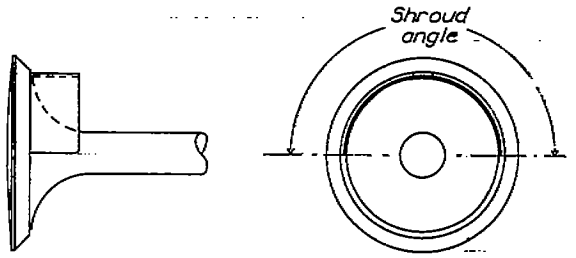


FIGURE 3.—Sketch of shrouded intake valve.

to the other valve was filled in. These changes resulted in the creation of an air swirl in the engine cylinder.

MEANS OF MAKING AIR FLOW VISIBLE IN CYLINDER

Smoke was tried as an indicator of the air movements, but the turbulent flow caused it to become intimately mixed with the air shortly after it entered the cylinder.

Metaldehyde crystals, formed by sublimation and recrystallization in air, were used in some of the pre-

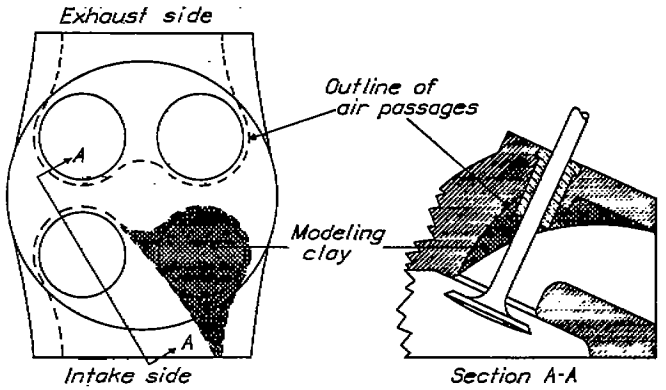


FIGURE 4.—Sketch showing parts of intake-air passage in cylinder head filled with modeling clay.

liminary tests. Although they followed the air better than any other substance tried, they could not be satisfactorily photographed inside the engine nor could individual groups of crystals be identified in successive pictures for the purpose of air-velocity measurements.

The material that proved to be the most satisfactory indicator of air movement was white goose down, cut into short pieces after the heavier pieces had been removed. Its sinking speed in still air averaged about 6 inches per second. It was introduced into the engine at the desired time by a double-barrel intake pipe. One side of this pipe admitted air from the room and the other side was attached to the bottom of a chamber containing the feathers. Butterfly valves in the two barrels were interconnected, one opening as the other closed, so that either air or air mixed with feathers could be admitted to the engine.

PHOTOGRAPHIC EQUIPMENT

The camera used to photograph the feathers was developed in the laboratories of the Eastman Kodak Company (reference 2). The film moves continuously behind the lens; a rotating parallel-sided prism between the film and the lens moves the image in the same direction and at the same rate as the film during the exposure time. The pictures taken for this investigation were made at rates from 1,700 to 2,400 frames per second. The light from a large electric arc was directed through the glass cylinder at right angles to the camera axis, and the side of the glass cylinder farthest from the camera was painted black so that the feathers appeared white against a black background. (See fig. 5.)

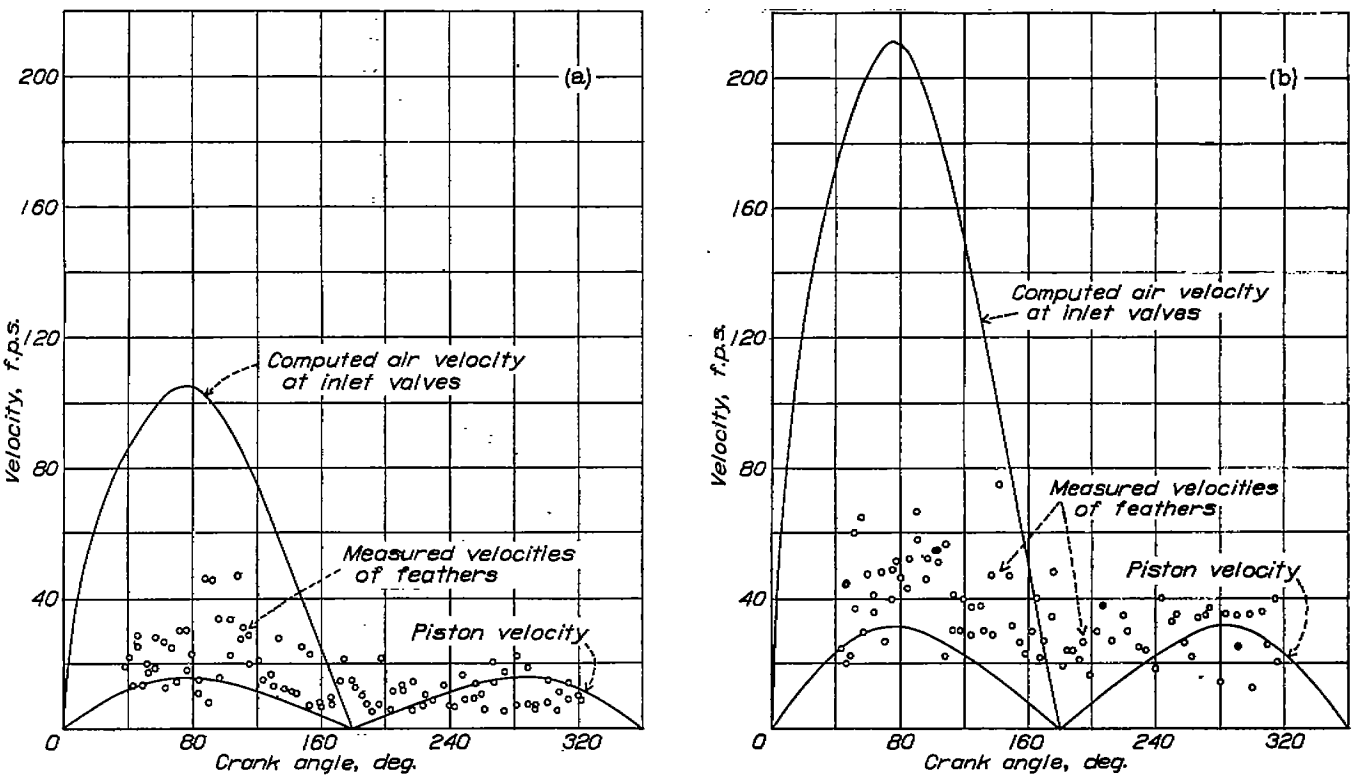
FIGURE 5.—One frame from high-speed motion-picture film showing feathers inside the glass cylinder.

SWIRL METER

A swirl meter was used to indicate the rate of rotation of the air about the cylinder axis. It consisted of four vanes attached to a spindle extending through the center of the cylinder head. (See fig. 2.) The vanes were driven by the rotating air and the number of turns was indicated by a gear driven by a worm on the spindle. Each vane had an area of about 0.42 square inch. End thrust was taken by a ball bearing, and a lap fit around the spindle practically eliminated air leakage.

FUEL-INJECTION EQUIPMENT

The fuel-injection system of the N. A. C. A. spray photographic apparatus (reference 3) was mounted on the engine, and a differential-pressure injection valve was screwed into the spark-plug hole at the center of the cylinder head. (In fig. 2, the swirl meter is shown installed in this hole.) Nozzles of two different types were used. One had four round orifices in a single plane, with diverging axes. The diameter of the two central orifices was 0.018 inch, that of the outer two was 0.010 inch, and the angle between the spray axes was 20°. The other nozzle was of the annular-orifice type, forming a hollow conical spray with an apex angle of 30°.



(a) Engine speed, 500 r. p. m.

(b) Engine speed, 1,000 r. p. m.

FIGURE 6.—Velocities of feathers during the intake and the compression strokes when plain intake valves were used.

TEST METHODS

Separate series of high-speed motion pictures were made to study the air flow as indicated by the movements of the feathers and to study the effect of the air flow on the fuel sprays. Some motion pictures were made of feathers and fuel sprays together, but they were unsatisfactory because the feathers hid the sprays. The swirl meter was not installed on the engine while any of the motion pictures were being made, but separate motoring tests were later made with it. Engine speed was limited to 1,000 r. p. m. because the motion pictures of the feathers became blurred at higher speeds.

When the high-speed motion pictures were projected on a screen at the normal rate of 16 per second, the velocities of the piston and the feathers were reduced to less than 1 percent of their actual velocities. The pictures taken at the various conditions were repeatedly projected and studied.

The velocities of the feathers used to indicate the movements of the air were measured by projecting the motion pictures one at a time onto a piece of paper and marking the successive positions of individual feathers. Velocities were then computed from the movement of the feathers and the time interval between pictures. Although it was impossible under the test conditions to obtain sharply defined photographs of the feathers, there never was any uncertainty in identifying them in successive frames from their relative size and shape. The velocities obtained in this manner are not the true air velocities for two reasons: Motion parallel to the camera axis was neglected; and, in all accelerated movements, the feathers lagged behind the air because of their greater density. The first factor was partly compensated by selecting only the more rapidly moving feathers for measurement or, in the case of orderly air flow, by selecting those moving approximately perpendicular to the camera axis. The inertia of the feathers was probably not a serious factor except in the entering air streams.

MOTION PICTURES SHOWING AIR MOVEMENTS

AIR MOVEMENTS WITH PLAIN INTAKE VALVES

When plain intake valves were used in the engine, the air in the cylinder was in a very agitated and turbulent

state during the intake stroke. Some air movement across the top of the chamber from the intake to the exhaust valves and thence down the cylinder wall was caused by the masking effect of the cylinder wall close to the intake valves, but this flow was very slight compared with the indiscriminate movements. The air movements created during the intake stroke continued throughout the compression stroke, at slowly reducing velocities. By the time the piston had descended far enough on the expansion stroke to reveal the inside of the cylinder (about 40° A. T. C.), most of the turbulence had died out and, during the last two strokes of the cycle, the air movements were mostly due to expansion and expulsion of the air by the piston.

The air in the cylinder always became densely fogged with water vapor early on the expansion stroke. This phenomenon was observed at all engine speeds and on dry days as well as on days of high humidity. It was probably caused by the transfer of heat from the compressed air to the cylinder head and walls during the compression stroke, so that on the expansion stroke the temperature of the air fell below the dew point.

Figure 6 shows the measured velocities of feathers obtained during the intake and the compression strokes of the engine while using plain intake valves. The corresponding crank angles were determined from the positions of the piston extension in each picture. The velocities of the entering air streams at the valve seats were computed, the air being assumed inelastic, and they are also shown in the figure. The great range of velocities during the intake stroke shows how varied the air speed was in different parts of the cylinder at the same time. The higher values were obtained from feathers in the air streams from the intake valves, and the lower values were obtained from feathers in the lower parts of the cylinder where the air had lost much of its entering velocity. The highest feather velocities were less than the computed inlet-air velocities because they were measured 1.5 inches or more from the valve seats. The range of velocities was greatly reduced after the end of the intake stroke, and most of the air motion caused by the entering air streams died out during the expansion and the exhaust strokes.

AIR MOVEMENTS WITH SHROUDED INTAKE VALVES

Tests were made with the shrouded intake valves arranged in the nine different positions shown in figure 7, the shrouds extending 180° around the valves in each case. Arrangements A, B, C, D, and E produced a rotation of all the air in the cylinder about the vertical axis. Arrangement A produced the highest rate of rotation with the least turbulence. Measured velocities of feathers obtained with this valve arrangement are shown in figure 8. The velocities are about twice those obtained with plain intake valves, probably because of the doubled air velocity through the intake valves with 180° shrouds. The range of velocities during the intake stroke was as great as when plain valves were used, although the direction of the air flow was very consistently a rotation about the cylinder axis. The scatter of the test points on the figures showing feather velocities cannot, therefore, be taken as an indication of turbulence. The best method of evaluating turbulence was found to be a careful observation of the motion pictures.

Arrangement C produced almost as high a rate of rotation as A but with slightly greater turbulence.

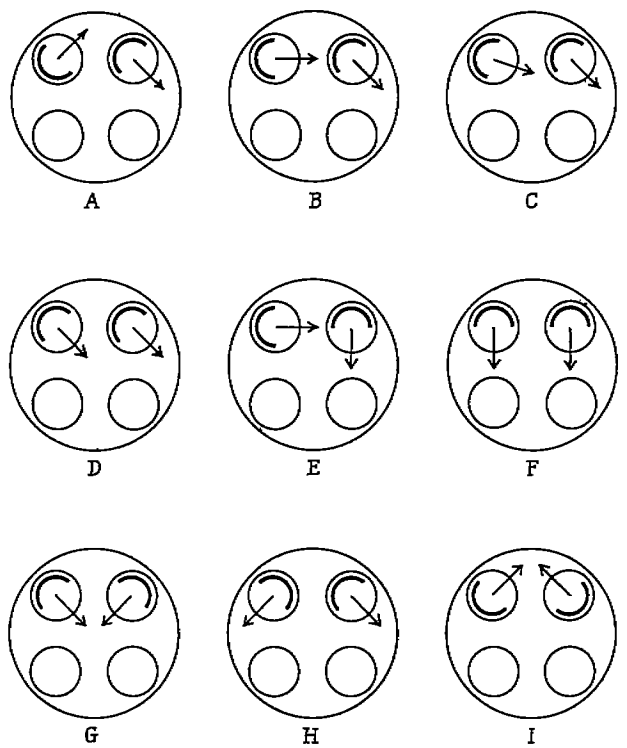


FIGURE 7.—Arrangements of the shrouded intake valves.

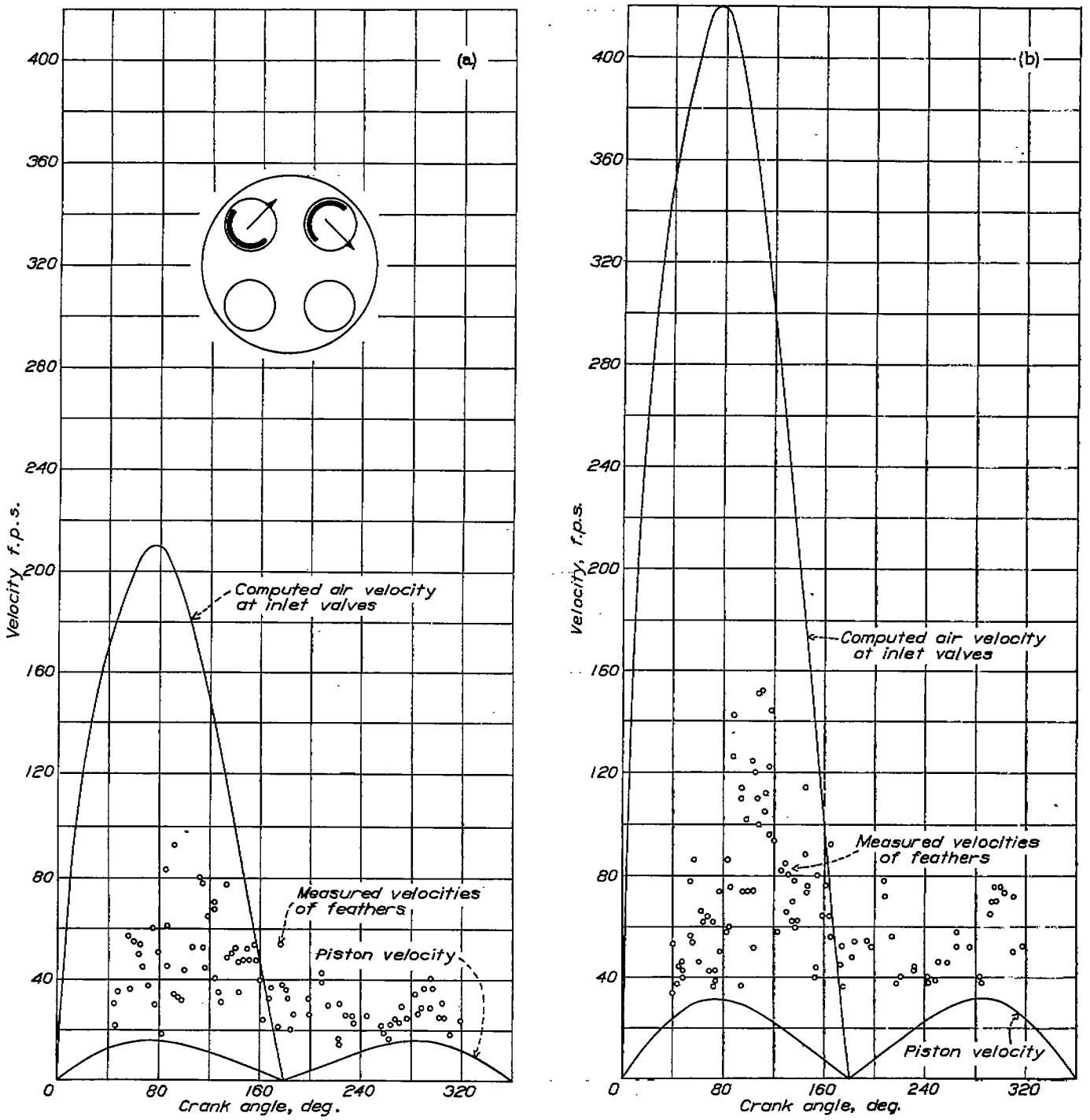
The rates of rotation produced by arrangements B and E were about equal and both were decidedly less than those produced by A and C. The amounts of turbulence were greater, probably because in each case one of the valves discharged air directly toward the other.

With arrangement D, the air movements in the cylinder during the first 140° of the cycle were dominated by the flow from the valve directing air radially inward. After crossing the top of the chamber, this air flowed down along the cylinder wall, back across the top of the piston extension, and then up along the opposite side of the cylinder, thus completing a vertical loop. At the same time, air from the other valve was being directed tangentially, so that a rotary motion was also being built up. During the compression stroke the vertical movement died out, leaving a relatively slow rotation of the entire air charge about the cylinder axis. Turbulence was greater with arrangement D than with any other arrangement producing air rotation about the cylinder axis.

In general, it may be stated that shroud arrangements which result in the greatest rate of air rotation produce the least turbulence and vice versa.

The motion pictures indicated that the air rotated with uniform angular velocity rather than with uniform linear velocity. Of course, the air in the entering streams was at a much higher velocity than the rest, but it soon expended its energy in turbulence or in accelerating the rotation of the air already in the cylinder. Any horizontal rotation set up during the intake stroke always persisted, at a decreasing rate, throughout the compression, the expansion, and the exhaust strokes.

When both of the shrouded intake valves were set to direct the incoming air across the top of the chamber, as in arrangements F, G, and H, the air moved in a vertical loop as previously described. With arrangement F, the loop movement started early on the intake stroke. It was faster and contained less turbulence than the movements with arrangements G or H. Ve-



(a) Engine speed, 500 r. p. m.

(b) Engine speed, 1,000 r. p. m.

FIGURE 8.—Velocities of feathers when shroud arrangement A was used.

locities of feathers measured while arrangement F was used are shown in figure 9. The range of velocities is about the same as that obtained when other valve arrangements were used or when plain intake valves were used at twice the engine speed. With arrangement G, a marked turbulence preceded the loop motion, which did not begin until about the middle of the intake stroke. With arrangement H, there was

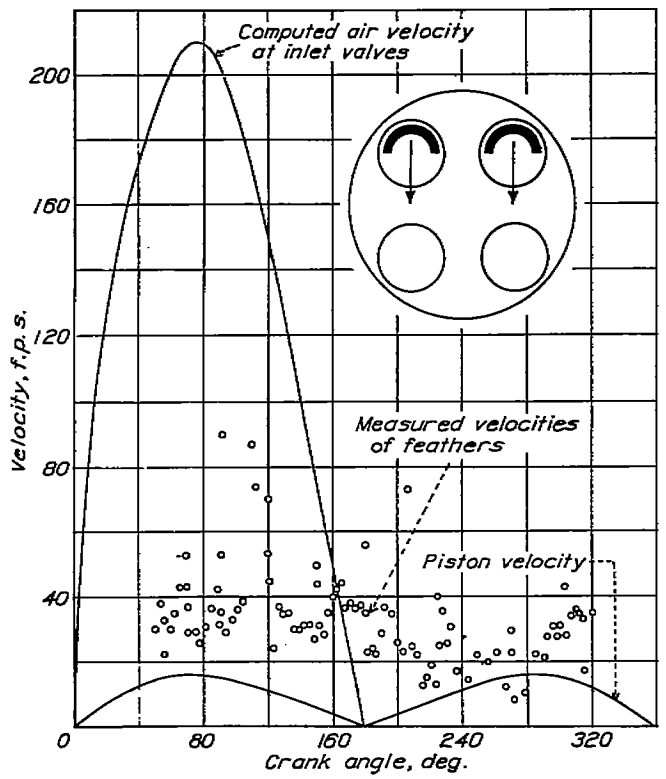


FIGURE 9.—Velocities of feathers when shroud arrangement F was used. Engine speed, 500 r. p. m.

turbulent motion with some parts of the air charge rotating in either direction about the cylinder axis during most of the intake stroke. A slow vertical-loop motion appeared near the end of the intake stroke. Arrangement I also resulted in a slow vertical-loop movement but the direction was the reverse of that with arrangements F, G, and H; that is, the air first descended along the cylinder wall nearest the intake valves, then crossed the top of the piston, and ascended the other side of the cylinder. The loop motion began early on the intake stroke and was accompanied by marked turbulence. With each of the last four arrangements discussed, the vertical-loop movement continued during the compression stroke but was never observed on the expansion and the exhaust strokes.

AIR MOVEMENTS WITH ALTERED INTAKE PASSAGE

When the intake-air passage in the cylinder head was altered as shown in figure 4, all the air entered the cylinder through a single plain valve. The shape of the intake passage caused the entering air stream to pass to one side of the cylinder axis and be slanted downward about 45°. The resulting air movement in the cylinder was complicated. During the intake stroke, the air moved in a loop similar to that described except that, instead of being in a vertical plane, it was slanted across the cylinder. This air movement set up a general rotation of the air charge, which continued to the end of the cycle. Turbulence was general throughout the cylinder during the intake stroke but died out during the compression stroke.

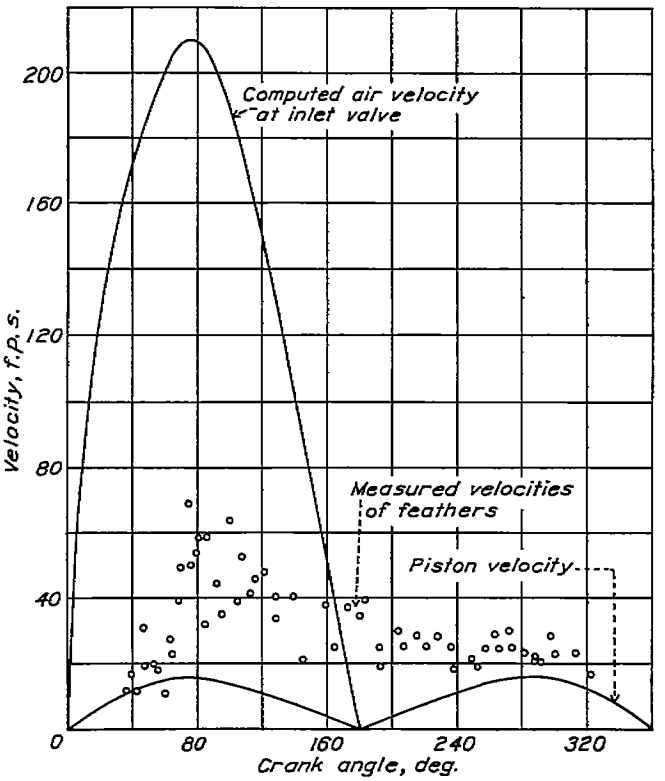


FIGURE 10.—Velocities of feathers after the intake-air passage had been altered. Engine speed, 500 r. p. m.

Velocities of feathers obtained when the altered intake passage was used are shown in figure 10. They are slightly lower than those obtained with shrouded valves in arrangement A.

MEASUREMENT OF THE RATES OF AIR SWIRL

Two methods were used to measure the rates at which the air rotated about the cylinder axis. In one, the high-speed motion pictures were projected onto a screen one at a time and the angular velocities of the feathers were obtained from the time it took them to pass between two vertical lines on the screen, spaced to represent 30° of rotation. A distance of 2 inches was chosen as the mean radius of the rotating feathers because some stereoscopic high-speed motion pictures made with a special attachment on the camera showed that the paths of most of the feathers lay within 1 inch of the cylinder wall. The results of measuring the rates of air swirl in the foregoing manner are shown in figures 11 to 14. The test points were scattered as widely as those in the figures showing velocities of feathers, but they are shown only in figure 14, which contains a single test condition. The entire 4-stroke cycles are represented, the dashed portions of the

curves being the regions near top center where the inside of the cylinder was not visible.

The second method used to measure rates of air rotation was to obtain with a stop watch the time required for several hundred turns of the swirl meter. This method is considered less reliable than the photographic method because of the inertia and the friction of the rotating parts and because it measures the swirl in only a small part of the chamber. It was used, however, mostly as a check on the other tests, and the conclusions given at the end of this report are based mostly on the results of the photographic method.

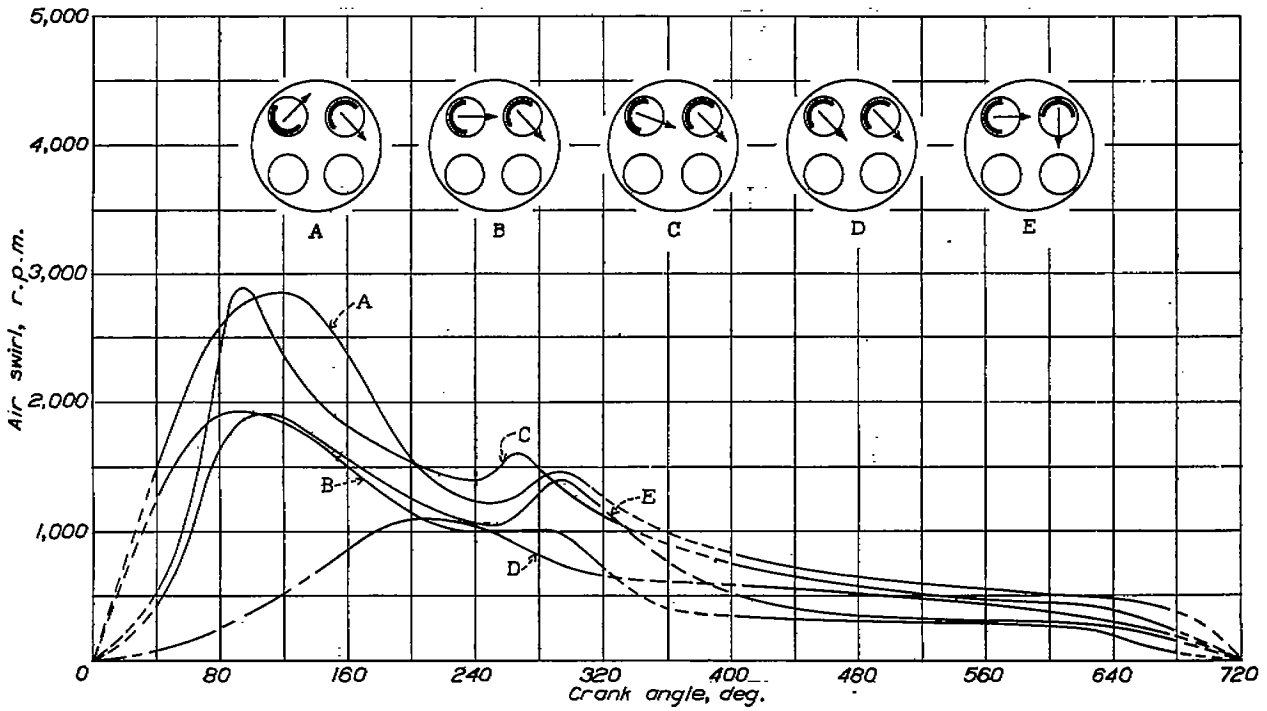


FIGURE 11.—Effect of shrouded intake-valve arrangement on rate of air swirl. Engine speed, 500 r. p. m.

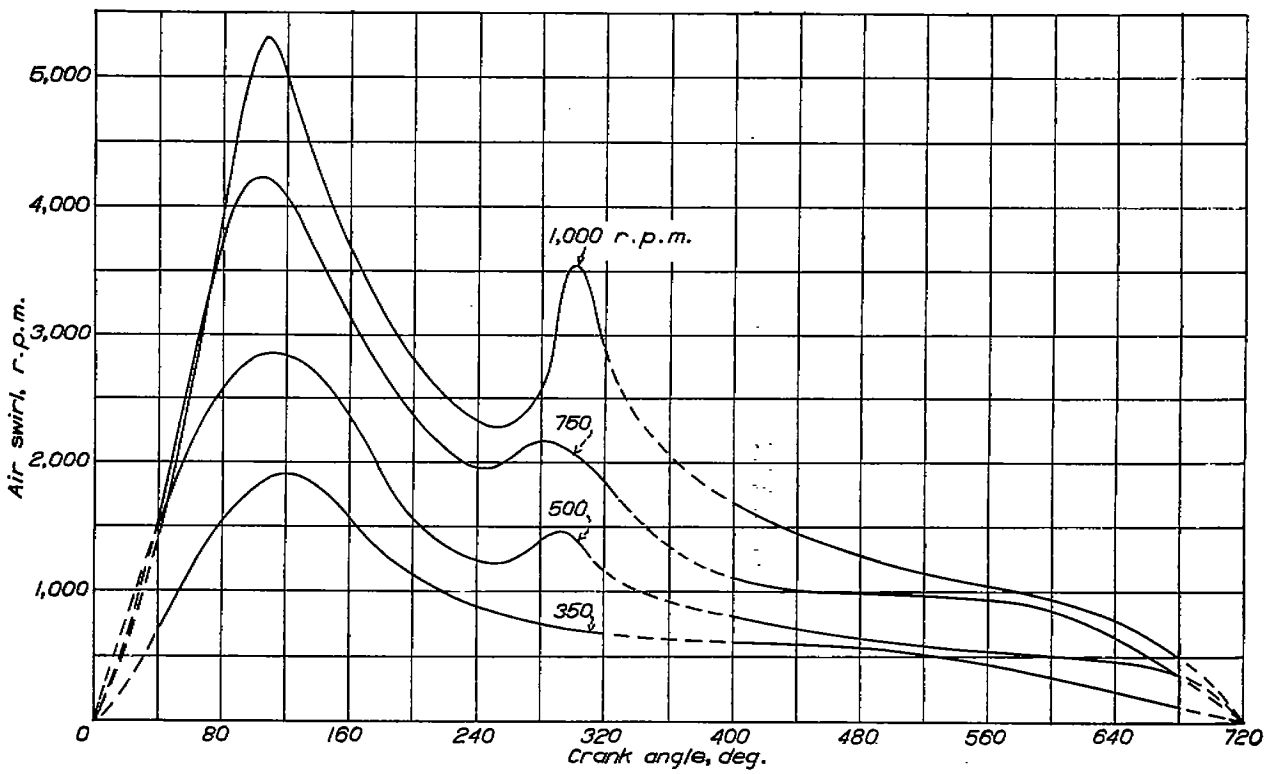


FIGURE 12.—Effect of engine speed on rate of air swirl when shroud arrangement A was used.

Table I gives the mean swirl rates obtained by integrating the curves in figures 11 to 14 and also gives the results of the swirl-meter tests. The meter usually gave a higher mean rate than the photographic method, probably because the rotating vane of the meter was close to the intake valves where the air velocity was high.

TABLE I

MEAN SWIRL RATES

Condition causing swirl	Shroud angle (deg.)	Engine speed (r. p. m.)	Mean swirl rate (r. p. m.)	
			Photographic method	Swirl meter
Shrouds, Arrangement: A	180	500	1,100	1,340
B			700	1,280
C			950	720
D			--------	330
E			750	1,090
A	180	350	700	910
		500	1,100	1,340
		750	1,600	2,140
		1,000	2,000	2,960
	180	500	1,100	--------
	135		950	--------
	90		650	--------
Altered intake passage	--------	500	850	1,060

Variations in swirl rate with crank angle, when the shrouded intake valves were used in arrangements A to E, are shown in figure 11. With each arrangement except D, the swirl rate was greatest at about 110 crank degrees after the beginning of the intake stroke, dropped to about half the maximum value at 250 crank degrees, then slightly increased while the piston was moving most rapidly on its compression stroke, and finally decreased slowly for the rest of the cycle. Valve arrangement A gave the highest mean swirl rate, and arrangement D gave the lowest. As explained earlier, the air movements with arrangement D were dominated during the first 140 crank degrees by air from the radially set valve. Although rotation was slowly building up during this period, it could not be measured from the movements of the feathers; this part of the curve in figure 11 is therefore given as a broken line.

The effect of engine speed on the rate of air swirl, when shroud arrangement A was used, is shown in figure 12. Swirl rates were approximately proportional to the engine speed, the maximum rate being about 5.5 times the engine speed and the mean rate being about twice the engine speed.

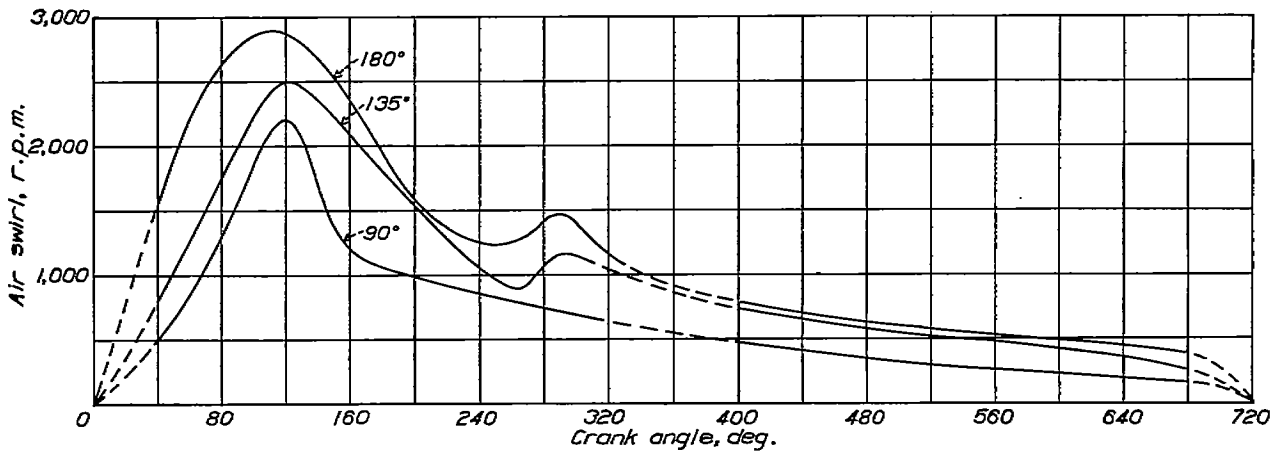


FIGURE 13.—Effect of shroud angle on rate of air swirl when shroud arrangement A was used. Engine speed, 500 r. p. m.

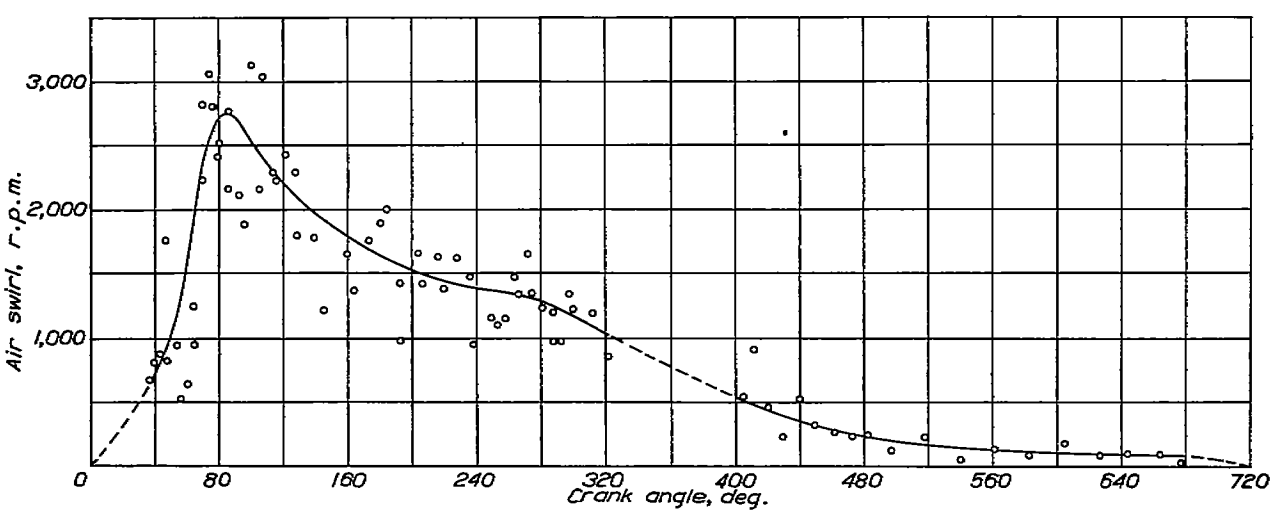


FIGURE 14.—Air swirl created by altering shape of intake-air passage. Engine speed, 500 r. p. m.

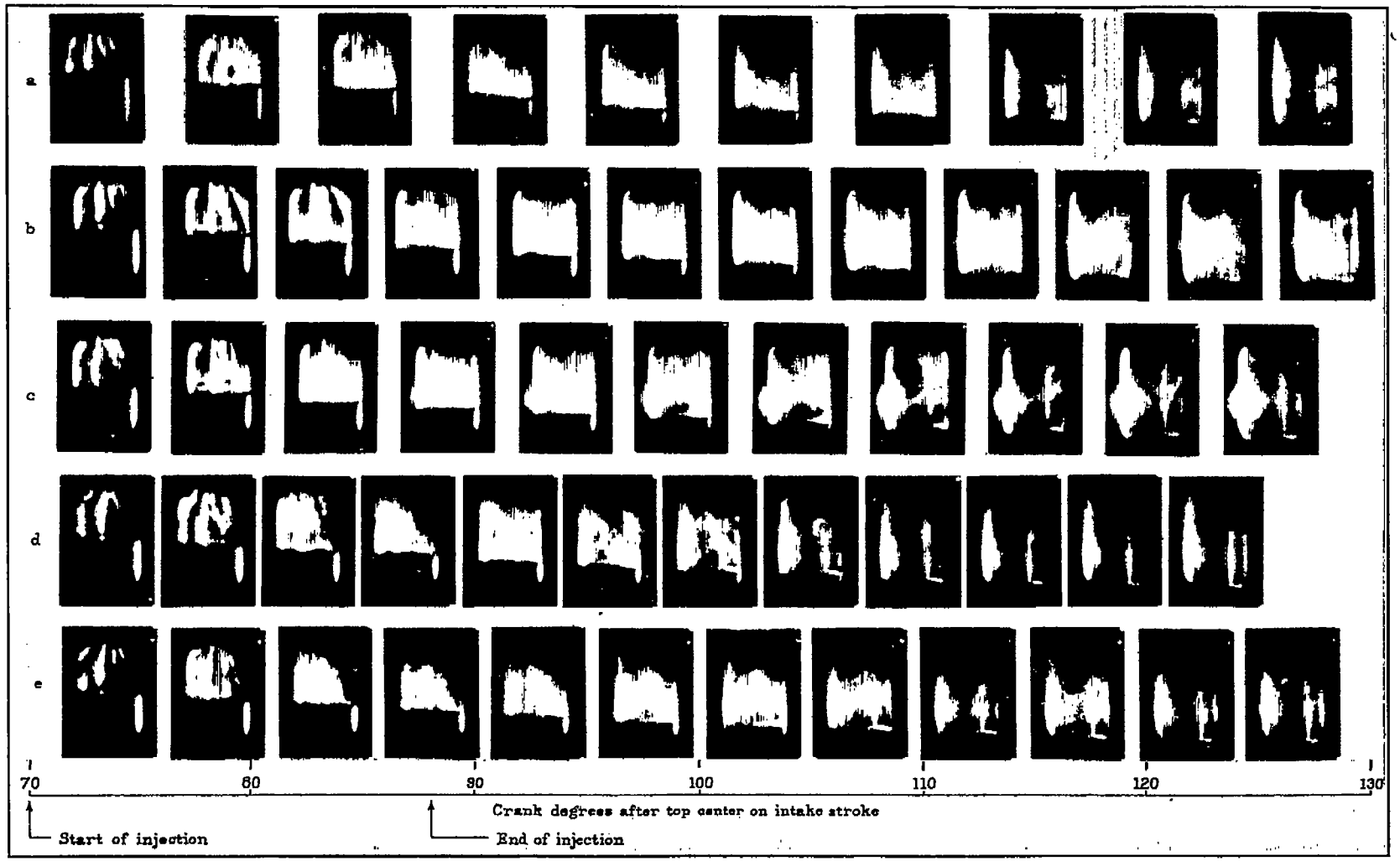


FIGURE 15.—High-speed motion pictures of sprays from the 4-orifice nozzle using different intake conditions and fuels. (a) Plain valves, gasoline spray; (b) shrouded valves in arrangement A, gasoline spray; (c) shrouded valves in arrangement F, gasoline spray; (d) altered intake passage, gasoline spray; (e) altered intake passage, Diesel-fuel spray.

FIGURE 16.—High-speed motion pictures of sprays from the annular-orifice nozzle using different intake conditions and fuels. (a) Plain valves, gasoline spray; (b) shrouded valves in arrangement A, gasoline spray; (c) shrouded valves in arrangement F, gasoline spray; (d) altered intake passage, gasoline spray; (e) altered intake passage, Diesel-fuel spray.

The effect of decreasing the angular extent of the intake-valve shrouds from 180° to 135° and then to 90°, while shroud arrangement A was used, is shown in figure 13. Table I indicates that the mean swirl rates were roughly proportional to the shroud angle. Figure 14 shows how the swirl rate changed when the intake-air passage was altered. The maximum rate of swirl came at about 85 crank degrees after the beginning of the intake stroke, earlier than when shrouded intake valves were used; and the swirl rate during the last half of the cycle was very low.

EFFECT OF AIR MOVEMENT ON FUEL SPRAYS

TEST CONDITIONS

High-speed motion pictures were taken of sprays from the 4-orifice nozzle and from the annular-orifice nozzle injected into the cylinder on the intake stroke. Injection began at 70° A. T. C. in each case and lasted 18 crank degrees with the 4-orifice nozzle and 70 crank degrees with the annular-orifice nozzle. An injection pressure of 2,000 pounds per square inch was used with both nozzles, and the amount of fuel injected was approximately equivalent to full-load fuel quantity. Two fuels were used, aviation gasoline and a high-grade automotive Diesel fuel. The Diesel fuel was used at only one condition, so the following description of results refers to gasoline sprays unless it is otherwise stated. Neither fuel was ignited, but the penetration, the distribution, and the rate of vaporization of the sprays were studied from the motion pictures. Four air-intake conditions were used at an engine speed of 500 r. p. m., as follows: with plain intake valves, with shrouded intake valves in arrangements A and F, and with the intake passage altered.

SPRAYS FROM THE 4-ORIFICE NOZZLE

Some of the motion pictures of the 4-orifice sprays are reproduced in figure 15. Only every third picture taken is shown, and they have been spaced to fit a uniform scale of crank degrees. The penetration of the sprays was unaffected by the air movements in the cylinder, the tips of the two inner sprays reaching the piston about 5 crank degrees after the start of injection in each case. Most of the fuel impinged on the piston or the cylinder walls, showing that the orifices were too large or the injection pressure too great. The central parts of the four jets were not deflected by even the most rapid air movements; but the fine mist in the spray envelopes, and also the mist formed by impingement on the piston, was picked up and distributed by the air currents. When shroud arrangement A was used, the mist was well distributed in the lower part of the cylinder where most of the fuel went, but it failed to mix with the air in the upper part of the cylinder. When shroud arrangement F was used, the mist was carried to the upper part of the cylinder, leaving the center of the cylinder relatively "lean." Altering the intake-air passage in the engine head seemed to be the most effective way to secure rapid and complete mixing of the fuel and the air in the cylinder, probably because this change resulted in air movements having both horizontal and vertical components and also containing much small-scale turbulence.

SPRAYS FROM THE ANNULAR-ORIFICE NOZZLE

The penetration of sprays from the annular-orifice nozzle was markedly affected by air movements in the cylinder. (See fig. 16.) With plain intake valves, the sprays reached the piston about 20° after the start of injection. With shrouded intake valves in arrangement A, the spray never quite reached the piston; but, with shroud arrangement F, it reached the piston in 25 crank degrees. When the intake passage in the head was altered, it took the spray 110 crank degrees to reach the piston, and by then it had been well broken up by the air currents. The lack of penetrating power in this type of spray is well illustrated by the fact that the sprays were deflected by even the slow vertical-loop movement obtained with plain intake valves, caused by the partial masking effect of the nearby cylinder wall. The air movements obtained with shrouded valves and with the altered intake passage distributed all the fuel in the conical sprays about the cylinder in much the same way that they distributed the mist surrounding the sprays from the 4-orifice nozzle.

COMPARISON OF GASOLINE AND DIESEL-FUEL SPRAYS

Diesel-fuel sprays were used only with the altered intake passage. In this case their appearance and behavior were about the same as gasoline sprays. A failure of part of the apparatus terminated the test program before additional pictures of Diesel-fuel sprays could be taken.

CONCLUSIONS

The results of the experiments described in this report may be summed up as follows:

1. Air movements created in the engine cylinder during the intake stroke continued throughout the compression stroke and were a distinct aid to the distribution of gasoline sprays injected into the cylinder.

2. The velocities of induced air movements were approximately proportional to the engine speed and about inversely proportional to the flow area at the intake valves. They were about the same whether the air flow was orderly or turbulent.

3. The use of shrouded intake valves set to direct the incoming air tangentially caused the air to rotate rapidly about the cylinder axis. The maximum rate of rotation was reached at about 110 crank degrees after the beginning of the intake stroke, and the rotation continued until the end of the exhaust stroke.

4. When shrouded intake valves were set to direct the incoming air across the tops of the cylinders, the air moved in vertical loops and the movement died out at the end of the compression stroke.

5. The use of a single plain intake valve with its manifold shaped to direct the incoming air tangentially resulted in a rotation of the air accompanied by considerable turbulence and some vertical air movements.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *September 15, 1938.*

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