# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 588

# FUEL SPRAY AND FLAME FORMATION IN A COMPRESSION-IGNITION ENGINE EMPLOYING AIR FLOW

By A. M. ROTHROCK and C. D. WALDRON

1937

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# AERONAUTIC SYMBOLS

## 1. FUNDAMENTAL AND DERIVED UNITS

| | Symbol | Metric | | English | |
|---|---|---|---|---|---|
| | | Unit | Abbreviation | Unit | Abbreviation |
| Length | $l$ | meter | m | foot (or mile) | ft. (or mi.) |
| Time | $t$ | second | s | second (or hour) | sec. (or hr.) |
| Force | $F$ | weight of 1 kilogram | kg | weight of 1 pound | lb. |
| Power | $P$ | horsepower (metric) | | horsepower | hp. |
| Speed | $V$ | kilometers per hour<br>meters per second | k.p.h.<br>m.p.s. | miles per hour<br>feet per second | m.p.h.<br>f.p.s. |

## 2. GENERAL SYMBOLS

| | |
|---|---|
| $W$, | Weight $= mg$ |
| $g$, | Standard acceleration of gravity $= 9.80665$ m/s$^2$ or 32.1740 ft./sec.$^2$ |
| $m$, | Mass $= \frac{W}{g}$ |
| $I$, | Moment of inertia $= mk^2$. (Indicate axis of radius of gyration $k$ by proper subscript.) |
| $\mu$, | Coefficient of viscosity |
| $\nu$, | Kinematic viscosity |
| $\rho$, | Density (mass per unit volume) |
| | Standard density of dry air, 0.12497 kg-m$^{-4}$-s$^2$ at 15° C. and 760 mm; or 0.002378 lb.-ft.$^{-4}$-sec.$^2$ |
| | Specific weight of "standard" air, 1.2255 kg/m$^3$ or 0.07651 lb./cu.ft. |

## 3. AERODYNAMIC SYMBOLS

| | |
|---|---|
| $S$, | Area |
| $S_w$, | Area of wing |
| $G$, | Gap |
| $b$, | Span |
| $c$, | Chord |
| $\frac{b^2}{S}$, | Aspect ratio |
| $V$, | True air speed |
| $q$, | Dynamic pressure $= \frac{1}{2}\rho V^2$ |
| $L$, | Lift, absolute coefficient $C_L = \frac{L}{qS}$ |
| $D$, | Drag, absolute coefficient $C_D = \frac{D}{qS}$ |
| $D_o$, | Profile drag, absolute coefficient $C_{D_o} = \frac{D_o}{qS}$ |
| $D_i$, | Induced drag, absolute coefficient $C_{D_i} = \frac{D_i}{qS}$ |
| $D_p$, | Parasite drag, absolute coefficient $C_{D_p} = \frac{D_p}{qS}$ |
| $C$, | Cross-wind force, absolute coefficient $C_C = \frac{C}{qS}$ |
| $R$, | Resultant force |
| $i_w$, | Angle of setting of wings (relative to thrust line) |
| $i_t$, | Angle of stabilizer setting (relative to thrust line) |
| $Q$, | Resultant moment |
| $\Omega$, | Resultant angular velocity |
| $\rho\frac{Vl}{\mu}$, | Reynolds Number, where $l$ is a linear dimension (e.g., for a model airfoil 3 in. chord, 100 m.p.h. normal pressure at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord, 40 m.p.s. the corresponding number is 274,000) |
| $C_p$, | Center-of-pressure coefficient (ratio of distance of *c.p.* from leading edge to chord length) |
| $\alpha$, | Angle of attack |
| $\epsilon$, | Angle of downwash |
| $\alpha_o$, | Angle of attack, infinite aspect ratio |
| $\alpha_i$, | Angle of attack, induced |
| $\alpha_a$, | Angle of attack, absolute (measured from zero-lift position) |
| $\gamma$, | Flight-path angle |

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Langley Memorial Aeronautical Laboratory

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# REPORT No. 588

# FUEL SPRAY AND FLAME FORMATION IN A COMPRESSION-IGNITION ENGINE EMPLOYING AIR FLOW

By A. M. Rothrock and C. D. Waldron

## SUMMARY

*The effects of air flow on fuel spray and flame formation in a high-speed compression-ignition engine have been investigated by means of the N. A. C. A. combustion apparatus. The process was studied by examining high-speed motion pictures taken at the rate of 2,200 frames a second. The combustion chamber was of the flat-disk type used in previous experiments with this apparatus. The air flow was produced by a rectangular displacer mounted on top of the engine piston. Three fuel-injection nozzles were tested: a 0.020-inch single-orifice nozzle, a 6-orifice nozzle, and a slit nozzle. The air velocity within the combustion chamber was estimated to reach a value of 425 feet a second.*

*The results show that in no case was the form of the fuel spray completely destroyed by the air jet although in some cases the direction of the spray was changed and the spray envelope was carried away by the moving air. When the fuel distribution within the combustion chamber was particularly poor, the volume in the chamber reached by the flame was considerably increased by the air flow. When the distribution was reasonably good, there was little change in the distribution of the flame. It was found that the air movement set up during the induction of air through ports in the cylinder liner, under a pressure difference of 26 inches of Hg, could be controlled so as materially to aid the air flow set up during the last portion of the compression stroke.*

## INTRODUCTION

The distribution of the fuel in the combustion chamber of a compression-ignition engine can be regulated to some extent by the design of the combustion chamber, by the design of the fuel-injection nozzle, and by the use of air flow. The N. A. C. A. has been conducting investigations of all three methods, singly and in combination. Tests have been conducted with single-cylinder engines and with special apparatus, by which data unobtainable on the engine may be procured.

With a special high-speed motion-picture camera operating at speeds from 2,000 to 2,400 frames a second in conjunction with the N. A. C. A. combustion apparatus, investigations have been made of some of the effects of injection advance angle, air-fuel ratio, and nozzle design on the combustion process. (See references 1, 2, and 3.) Data obtained by the N. A. C. A. on the effects of combustion-chamber shape and of air flow on combustion in a single-cylinder compression-ignition engine have been published in references 4 to 8. In order to explain further the results obtained in these tests and to coordinate the researches on the combustion apparatus with the engine tests, a program of tests was originated to study the effect of air movement preceding and during the combustion process. In the present tests it was desirable not only to photograph the fuel spray and flame formation in the combustion chamber of the N. A. C. A. combustion apparatus but also to photograph the air movement.

Any method employed for photographing the air movement must not disturb the normal operation of the apparatus, for by so doing the variables under investigation are changed. This condition immediately eliminates methods using such materials as light metal projections or strings to show the direction of the air flow. The use of aluminum dust or some such material was discarded because of its possible effects on combustion. A partial solution of the problem was found in the use of "schlieren" or "striae" photography (reference 9).

## METHODS AND APPARATUS

The N. A. C. A. combustion apparatus has been described in references 1 to 3. A diagrammatic sketch showing the engine cylinder, the combustion chamber,

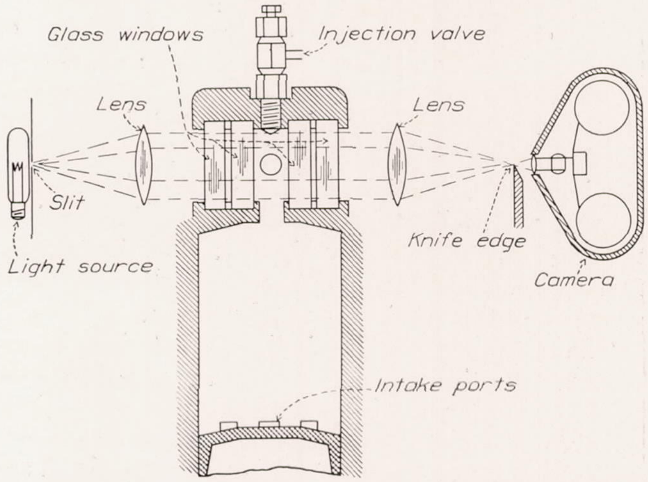
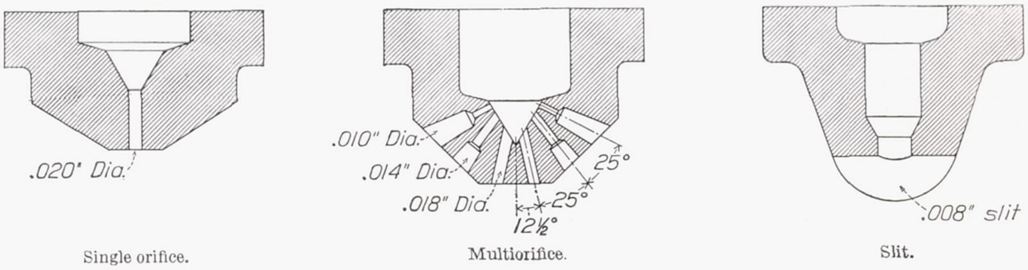


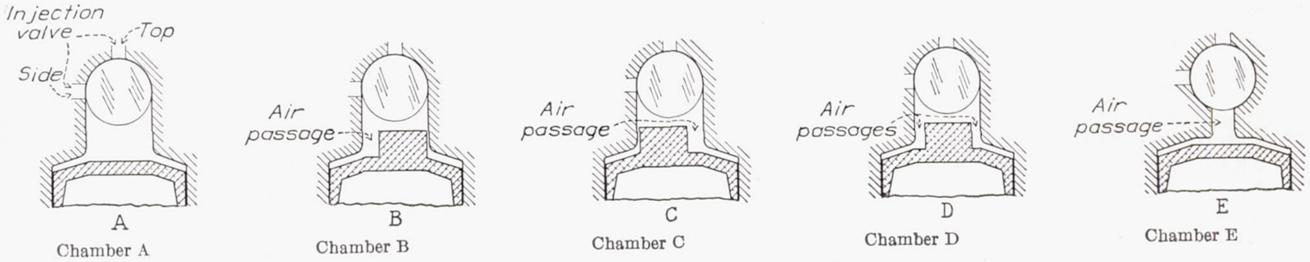
Figure 1.—Diagrammatic sketch of the N. A. C. A. combustion apparatus with schlieren equipment.

and the schlieren optical arrangement is shown as figure 1. The air movement, the fuel injection, and the flame spread were photographed through the 2½-inch-diameter glass windows forming the sides of the flat-disk combustion chamber. A 750-watt projection lamp was placed behind the slit as indicated in the diagram. The slit was placed at the focus of the first lens so that parallel light was transmitted through the combustion chamber to the second lens. The knife edge was located at the image of the slit and in such a position that two-thirds of the slit image was intercepted by the knife edge. The image of the combustion chamber was focused on the motion-picture film. Any local change in the index of refraction of the medium between the two lenses caused a deflection in the parallel light rays. This deflection caused the light rays to strike either below or above the original point in the image of the slit. Therefore, a change in the index of refraction of a part of the medium between the lenses resulted in light or dark areas being formed on the motion-picture film in the image of the combustion chamber. Because any air movement in the combustion chamber is accompanied by local changes in the index of refraction of the air, the air movement showed up as light and dark streaks in the image recorded on the photographic film. The image of the fuel-spray silhouette and of the combustion was photographed on the film in the usual manner.



Single orifice. Multiorifice. Slit.

FIGURE 2.—Nozzles tested.



Chamber A Chamber B Chamber C Chamber D Chamber E

FIGURE 3.—Combustion-chamber shapes tested.

The test procedure was similar to that given in reference 3. No time-pressure records are presented in the present report, although they were taken for each test condition. Such records have been presented in references 1, 2, and 3. As has been previously stated, these records, although giving the general course of the combustion, are not sufficiently accurate to permit close comparisons to be made of the indicated mean effective pressures developed by the engine.

Three fuel-injection nozzles (fig. 2) were tested: a 0.020-inch single-orifice nozzle, a 6-orifice nozzle, and a slit nozzle. These nozzles were chosen from those used in the investigation of the effect of nozzle design on combustion (reference 3). The fuel oil was the same as that used in the tests reported in references 1, 2, and 3.

The following test conditions were maintained constant:

| | |
|---|---|
| Engine bore__________inches__ | 5 |
| Engine stroke__________do____ | 7 |
| Engine speed__________revolutions per minute__ | 1, 500 |
| Engine-jacket coolant temperature (outgoing)_°F__ | 150 |
| Engine compression ratio (based on total stroke)_ | 14. 1 |
| Air-fuel ratio (except as otherwise stated)________ | 17 |
| Start of injection____crankshaft degrees B. T. C__ | 15 to 20 |

A flat-disk combustion chamber was used with a rectangular displacer as adapted by Moore and Foster (references 7 and 8). The displacer was mounted on the engine piston to produce an air flow of high velocity within the combustion chamber. The displacer was arranged so that it could be mounted at either side or directly in the center of the piston, as shown in figure 3. In this manner an air jet could be directed along either or both ends of the combustion chamber. In one test the displacer was removed and a central oval orifice installed in the center of the chamber throat (fig. 3E). The areas between the displacers and the edges of the combustion chamber and of the orifice in combustion chamber E were such that the velocity approximated the value which gave the best performance in the tests presented in reference 7. The velocity of the air as it entered the combustion chambers was estimated according to the method given in reference 7 and is shown in figure 4 as a function of the crank angle. Combustion chamber A has a width between the glass windows of 0.78 inch and the others a width of 1.01 inches. This variation in width was necessary to maintain a constant compression ratio.

In the tests with the single-orifice nozzle the manifold around the inlet ports of the engine had a single opening in the plane of the combustion-chamber disk on the side in which the injection valve was mounted, and the air entered the cylinder with a definite whirling motion. In the tests with the multiorifice nozzle this manifold was removed so that the air could enter symmetrically with respect to the cylinder. In the tests with the slit-orifice nozzle the same arrangement was used and additional runs were made with the intake ports blocked on first one and then the other side of the cylinder.

## RESULTS AND DISCUSSION

The estimated air flow (fig. 4) shows that, as the displacer entered the combustion chamber, the air velocity quickly reached a value of 400 feet a second. The rate of velocity increase became successively less and a maximum of 420 feet a second was reached at about 25 crankshaft degrees B. T. C. The velocity then decreased to zero at top center. With combustion chamber E a maximum velocity of 435 feet a second was reached at 33° B. T. C. With combustion chamber A the velocity reached a maximum of 120 feet a second at about the same piston position that the maximum was reached with the displacer. These velocities with the restriction are those estimated for the air as it entered the combustion chamber at the narrowest section. As the air passed from this orifice into the chamber proper there was, of course, a certain amount of expansion of the jet and a certain amount of turbulence was also created. In addition, there was the effect of any air flow produced during the induction of the air through the ports into the displacement volume. The conditions under which the air is inducted are comparable with those existing in a highly supercharged engine because, as was shown in reference 1, the pressure differential between the displacement volume and the intake manifold at the time the piston uncovered the intake ports was approximately 26 inches of Hg.

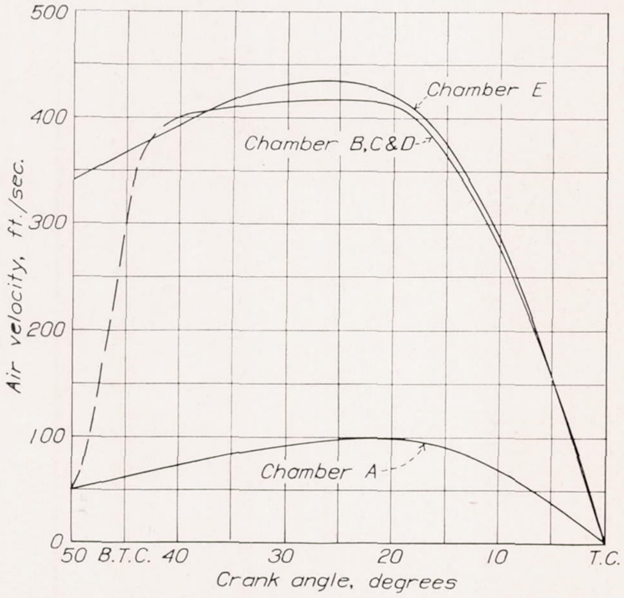


FIGURE 4.—Air velocity through throat connecting displacement volume and combustion chamber.

The photographs showed that two types of air flow might occur in the combustion chamber. The first was a mass rotation of the air as a whole and the second was the occurrence of a vortex traveling around the combustion chamber. The first type is not visible unless the motion pictures are projected, the individual photographs showing only light and dark areas in the combustion gases. The vortex occurred most often with combustion chamber A. Occasionally a vortex was produced in combustion chamber D (fig. 5). In the photographic prints reproduced in this report, mass movement of the air as a whole is indicated by the deflection of the fuel spray. A description of the flow as visualized when the motion pictures were projected and also as interpreted from the spray shapes is also included. For assistance in the analysis of the results, line drawings of the combustion chambers with arrows indicating the air movement are included with the enlargements from the motion-picture films. The enlargements show the fuel spray from the start of injection and the first three or four photographs of the combustion.

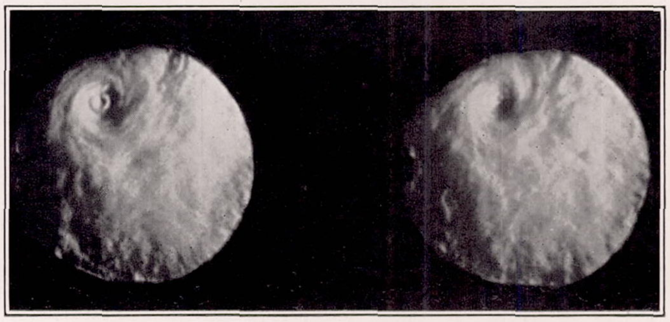


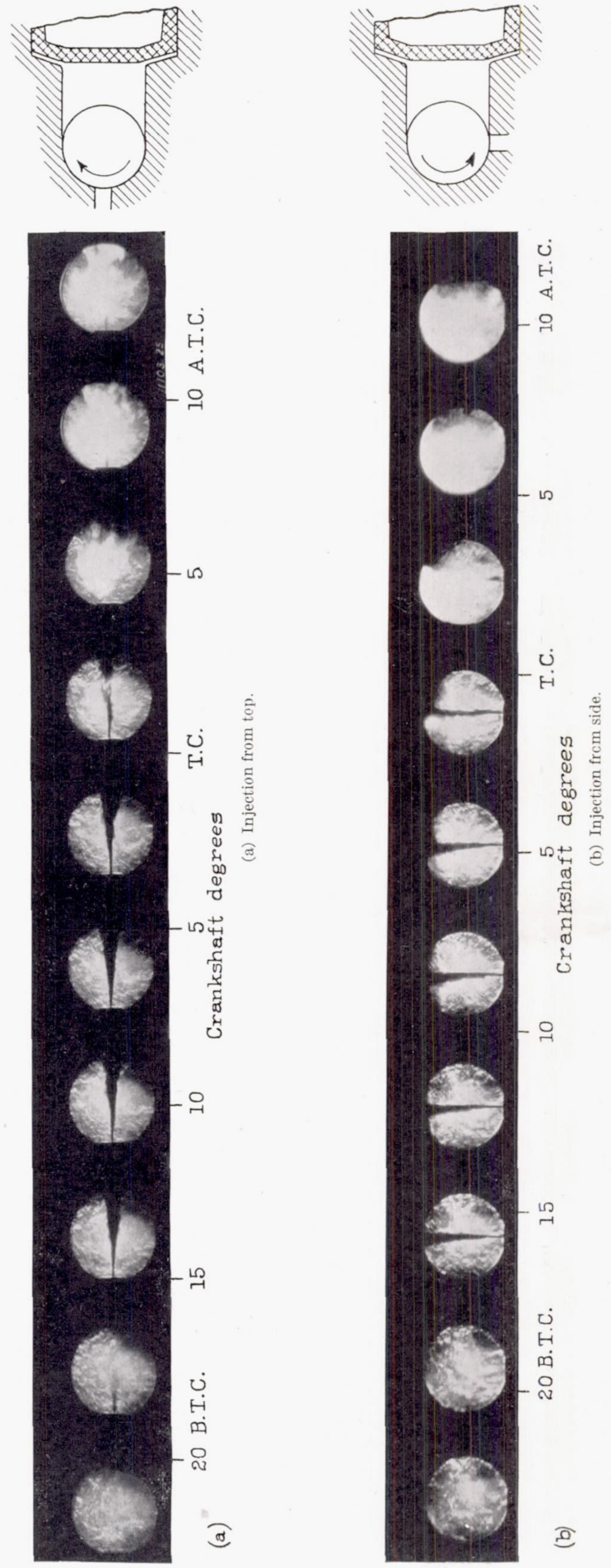
FIGURE 5.—Air vortex in combustion chamber D.

The effect of some air movement on the fuel sprays in combustion chamber A was observed in the results presented in both references 2 and 3. The photographs showed that the spray tips were twisted first to the right and then to the left as the sprays proceeded across the combustion chamber. In the present tests this motion was found to be caused by the vortex (fig. 5) moving around the combustion chamber, generally clockwise in the results reported herein and counterclockwise in the results shown in references 2 and 3. (This difference in directional rotation does not actually occur in the engine. Because of space limitations it was necessary to reflect the light through 90° in this schlieren set-up. Therefore, results showing clockwise rotation in these photographs correspond to a counterclockwise rotation in the previous results.) The vortex was apparently caused by the air movement set up as the air entered the displacement volume through the inlet ports. It has been shown in reference 3 that this flow caused the flame to predominate on the leeward side of the spray.

**Single-orifice nozzle.**—With the injection valve mounted in the top (fig. 6 (a)) of combustion chamber A, the single fuel spray penetrated across the visible portion of the chamber. Because of the relationship of the injection-nozzle area to the other injection-system dimensions there was a secondary discharge of the fuel following the first stop of injection. The photographs indicate that this secondary discharge penetrated through the already burning gases. When the injection valve was mounted in the side (fig. 6 (b)) the spray penetrated across the chamber and impinged on the opposite wall. In this case there is visible a slight upward bending of the spray caused by the entering air. Combustion started at the chamber wall. In neither case did the flame spread throughout the chamber. With the injection valve mounted in the side, the motion pictures show that the combustion was followed by a cloud of smoke, which seemed to roll backward from the section of the chamber wall that was struck by the spray core.

The arrows indicate that in one case the general air movement was clockwise and in the other case counterclockwise, but the reason for this apparent occasional reversal of the flow is not known. In no case was it sufficient to have much effect on the fuel spray or flame formation.

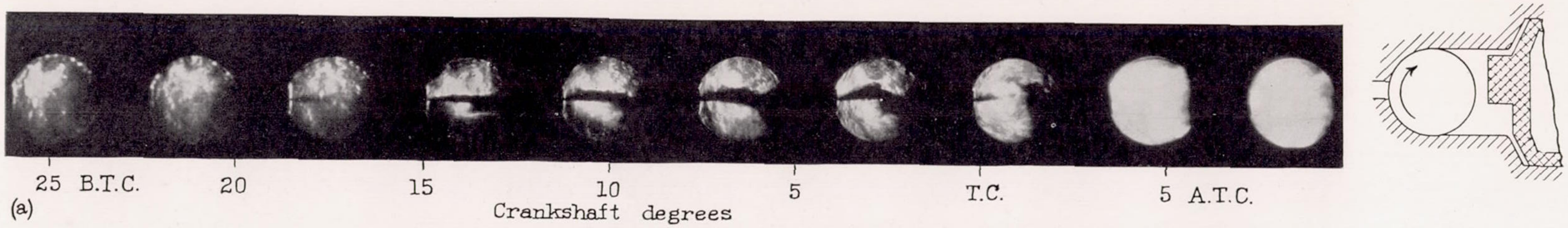
Combustion chamber B showed a marked difference from chamber A both in the fuel spray and the flame formation (fig. 7). The motion pictures showed that the rotation of the air caused by the displacer, being in the same direction as that produced during the induction of the air, was in the form of a mass rotation of the air in a clockwise direction as compared with the rotating vortex obtained without the displacer. In the upper half of the visible portion of the chamber the spray is shown blown to the right, and in the lower half to the left. In the seventh photograph of figure 7 (a) (3° B. T. C.) the center of the rotating air is well marked by the spray formation. The flame filled the chamber reasonably well and a decided improvement in mixing over that obtained without the piston displacer is noted. When the injection valve was mounted in the side (fig. 7 (b)), the fuel-spray core was directed upward so that there was little impingement on the opposite wall of the combustion chamber and very little smoke was visible. The downward motion of the air on the right-hand side of the chamber did not have much apparent effect on the spray. Again the cham-



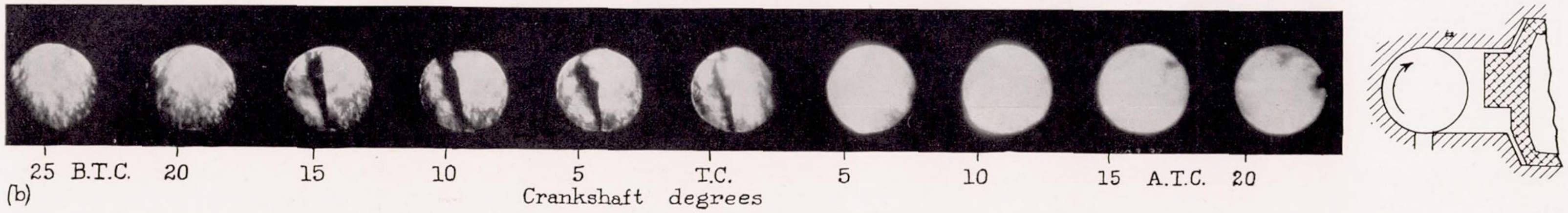
(a) Injection from top.

(b) Injection from side.

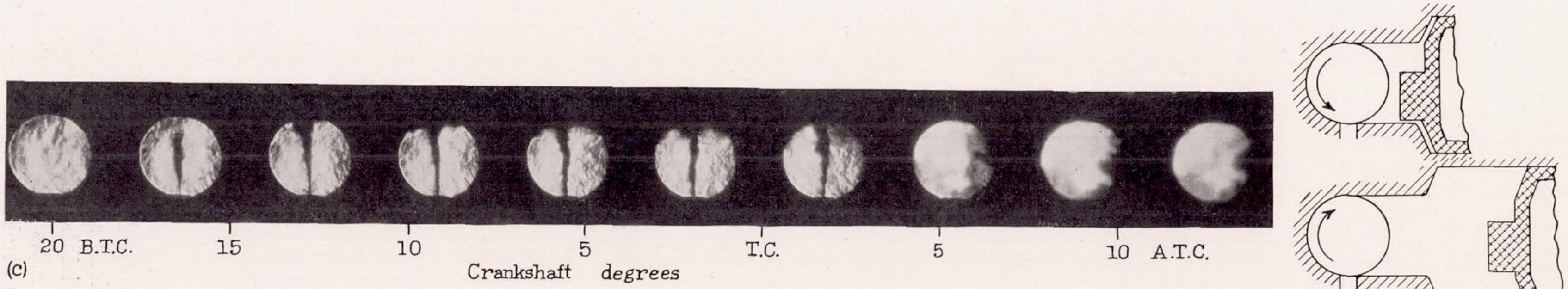
FIGURE 6.—Fuel sprays and combustion with chamber A.



(a) Injection from top of cylinder B.



(b) Injection from side of cylinder B.



(c) Inection from side of cylinder C.

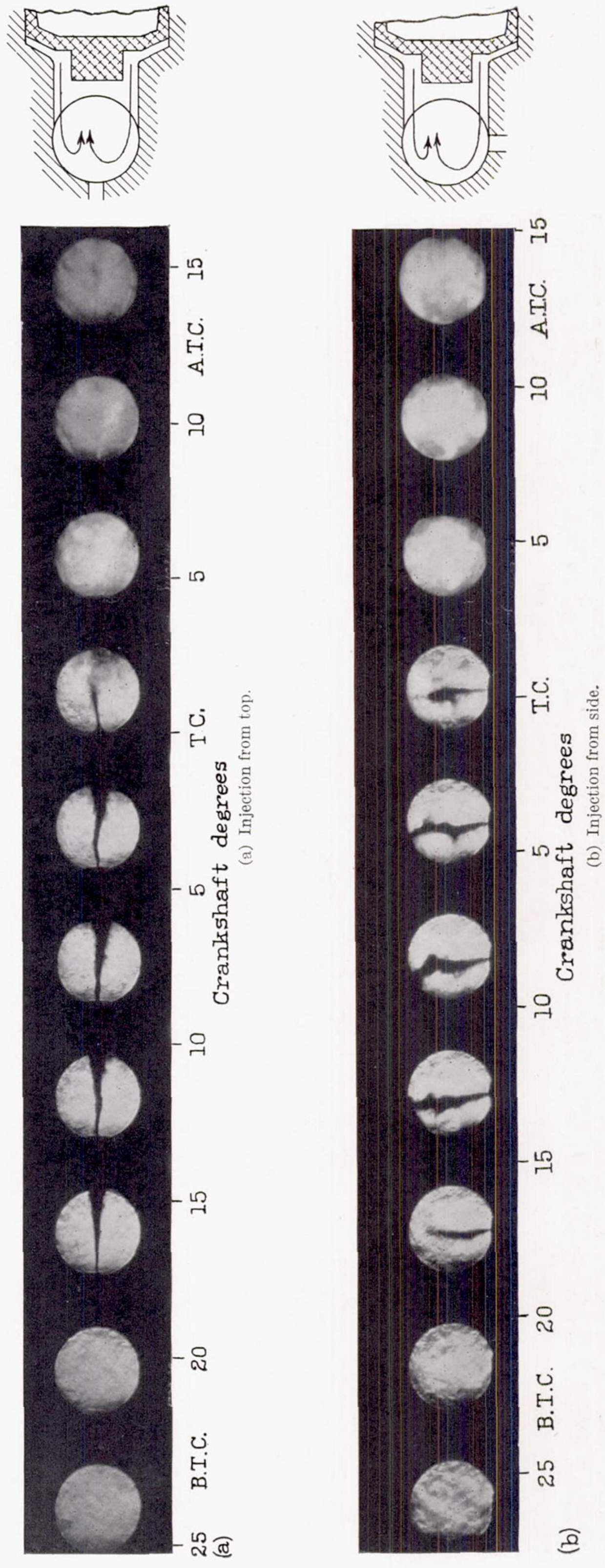
FIGURE 7.—Fuel spray and combustion with chambers B and C.

ber was fairly well filled with flame. In neither case was the spray core destroyed by the moving air, although the envelope was swept away from the core. The results show that, even in the highly heated air of the combustion chamber, high air velocities do not destroy the core of the spray but nevertheless materially aid in the mixing of the fuel and air.

With combustion chamber C the air rotation produced in the combustion chamber by the displacer was in the opposite direction to that produced by the induction of the air (fig. 7 (c)). The motion pictures show that the air first rotated clockwise and then, as the displacer entered the combustion chamber, the air suddenly changed direction and made a rotation in the counterclockwise direction. As a result of this change of motion, much of the energy of the moving air was lost so that the effect on the fuel spray was considerably less than was the case with combustion chamber B. The spray impinged on the wall of the chamber as it did when no displacer was employed and there was considerable smoke. There is little evidence that with this arrangement the air flow produced beneficial results. The test illustrates the fact that, when designing a combustion chamber to produce a certain type of air flow, extreme care must be taken to insure that the desired results are not nullified by air movements set up by the induction of the air into the displacement volume.

When combustion chamber D was employed (fig. 8), the movement of the air as a whole was hard to distinguish. The rotation of the air before the displacer entered the combustion chamber was still clockwise but it seemed to predominate in the right-hand section of the chamber. With the fuel being sprayed in from the top of the chamber, there was little apparent effect from the air flow. The spray tended to have a somewhat sinuous motion as it penetrated through the combustion air. The flame showed but slightly better distribution than was obtained without the displacer. When the spray was injected from the side, the effect of the air movement was quite noticeable. As the spray first issued from the injection nozzle it was blown upward by the air jet. Its direction was then changed slightly so that it again traveled in a horizontal direction but, as the issuing fuel jet became more dense and the air velocity decreased, the spray core maintained a straight course inclined upward to the horizontal. The downward movement of the air in the center of the chamber is noticeable in the photograph taken at 4° B. T. C. In this frame the spray shows the effects of the air blowing up along the side walls of the chamber and down in the right center. The flame spread throughout most of the visible portion of the chamber but there was still considerable smoke during the expansion stroke.

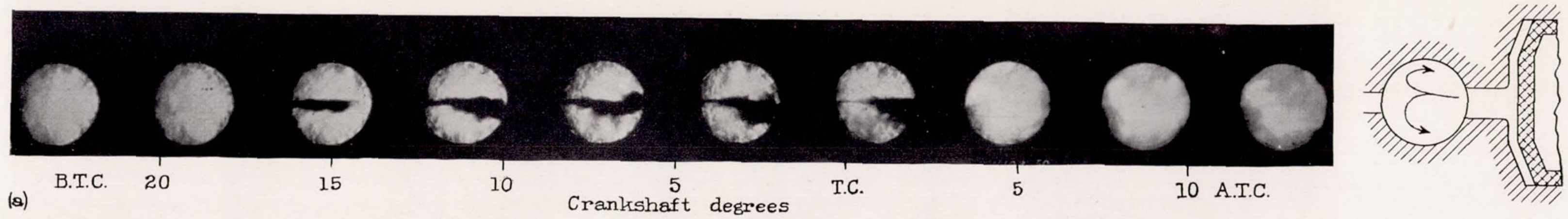
With combustion chamber E it appeared that the air divided in the center of the chamber, rotating in a clockwise direction in the right half and a counterclockwise



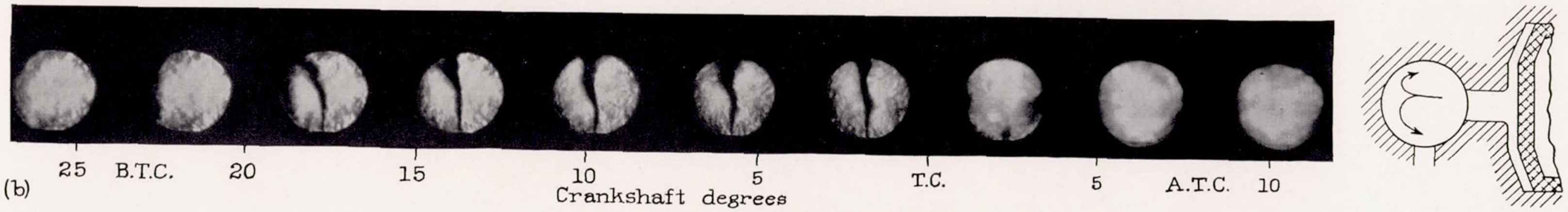
(a) Injection from top.

(b) Injection from side.

FIGURE 8.—Fuel spray and combustion with chamber D.

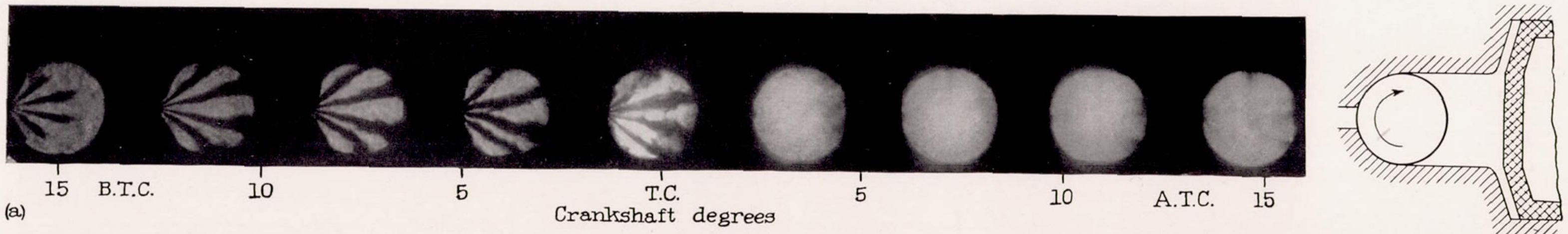


(a) Injection from top.

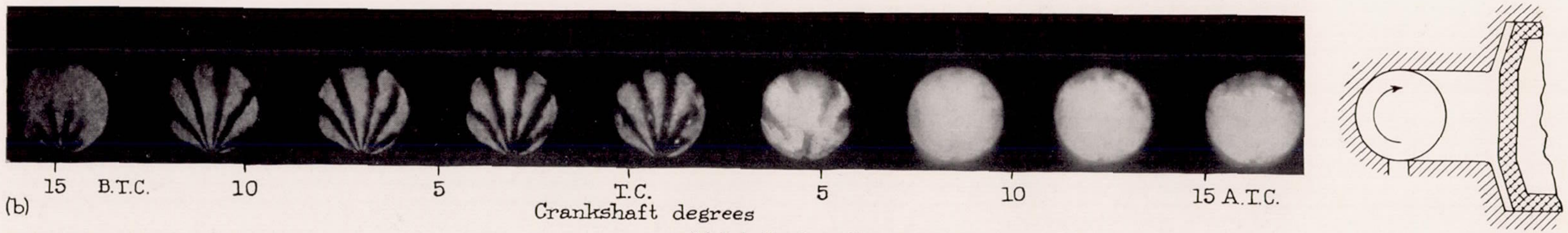


(b) Injection from side.

Figure 9.—Fuel sprays and combustion with chamber E.

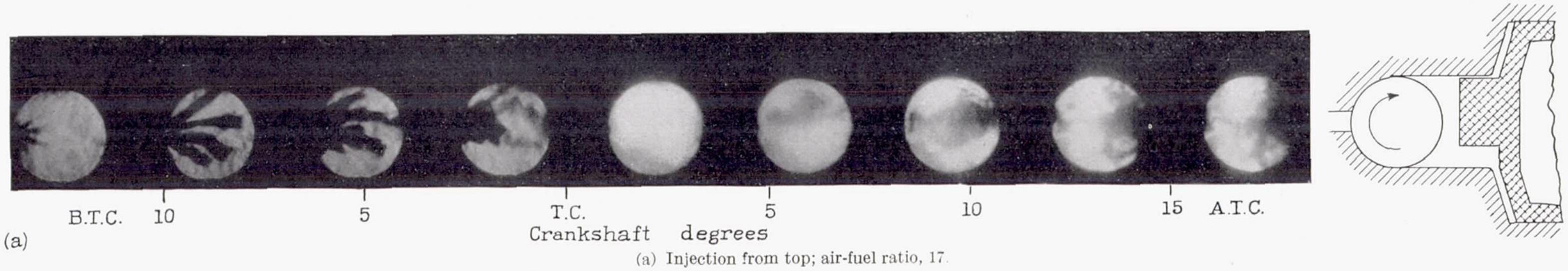


(a) Injection from top.

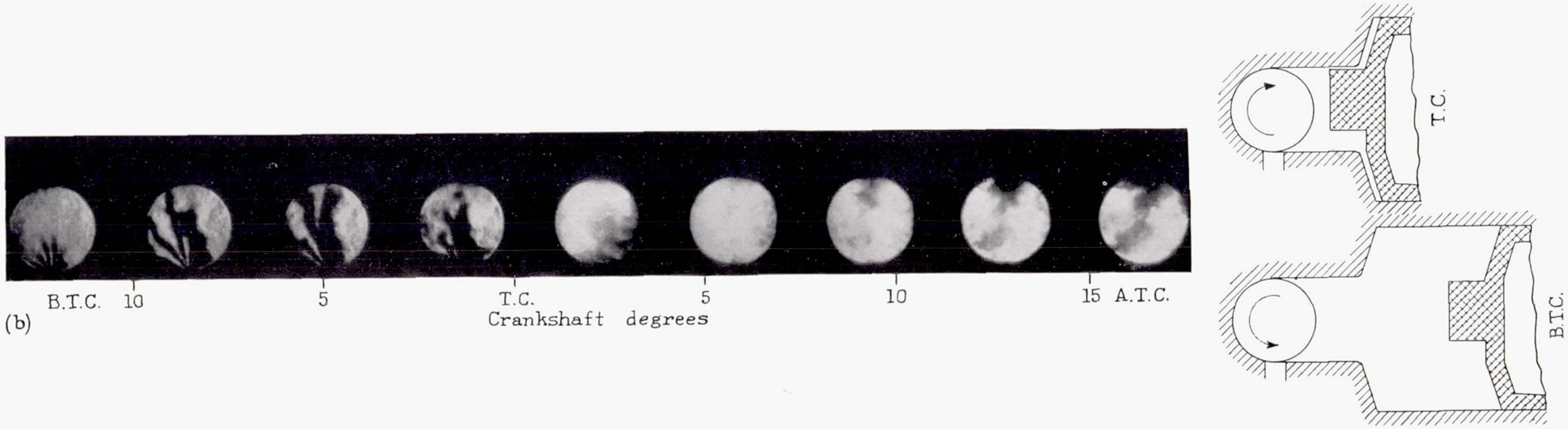


(b) Injection from side.

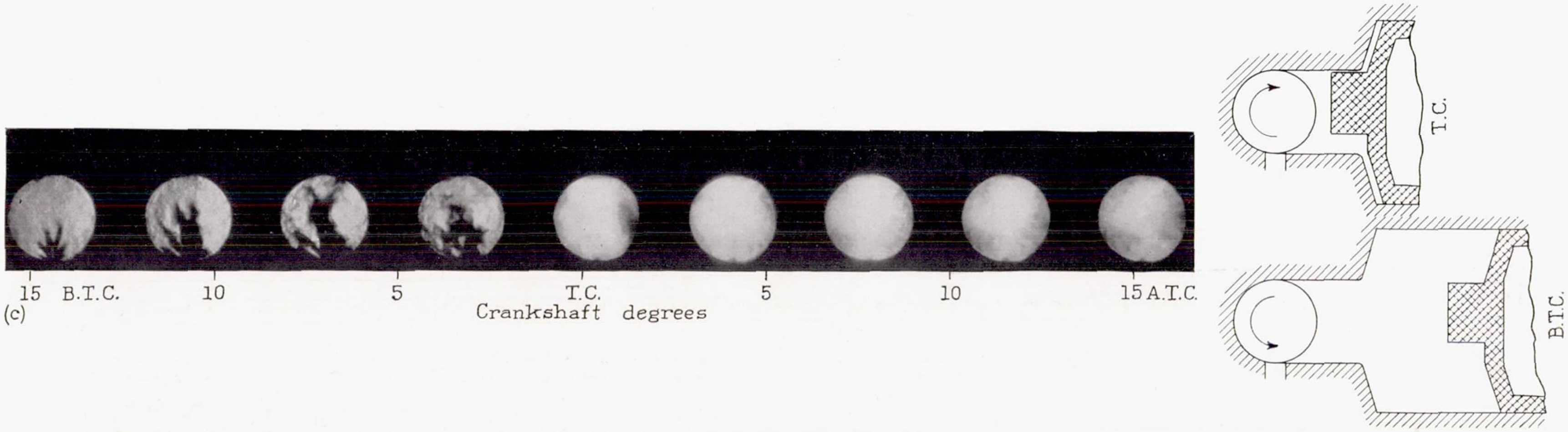
Figure 10.—Fuel sprays and combustion with multiorifice nozzle and chamber A.



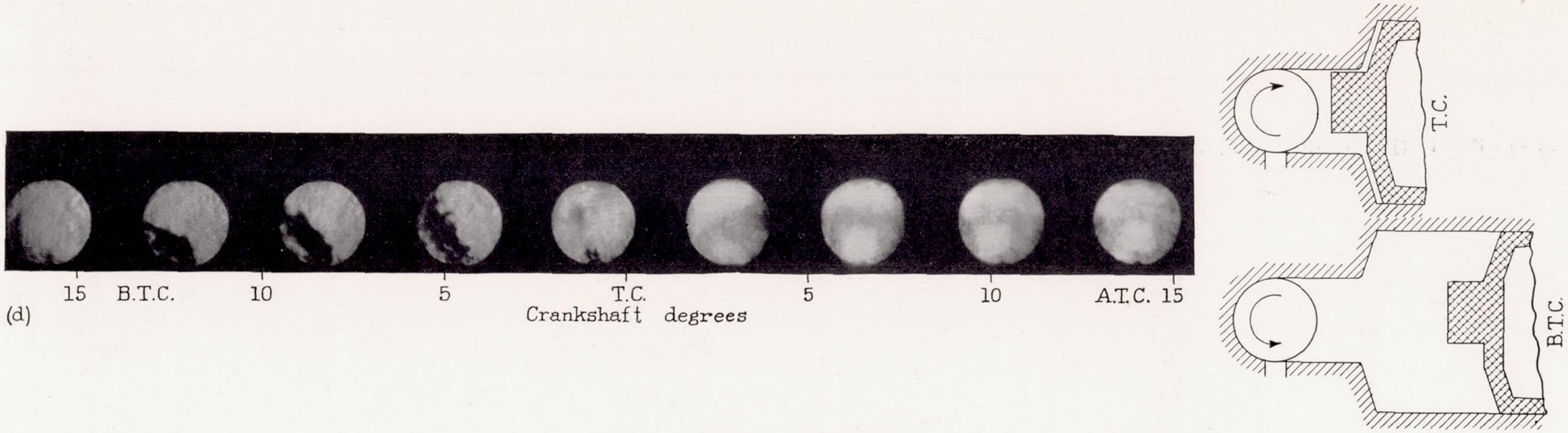
(a) Injection from top; air-fuel ratio, 17.



(b) Injection from side; air-fuel ratio, 17.

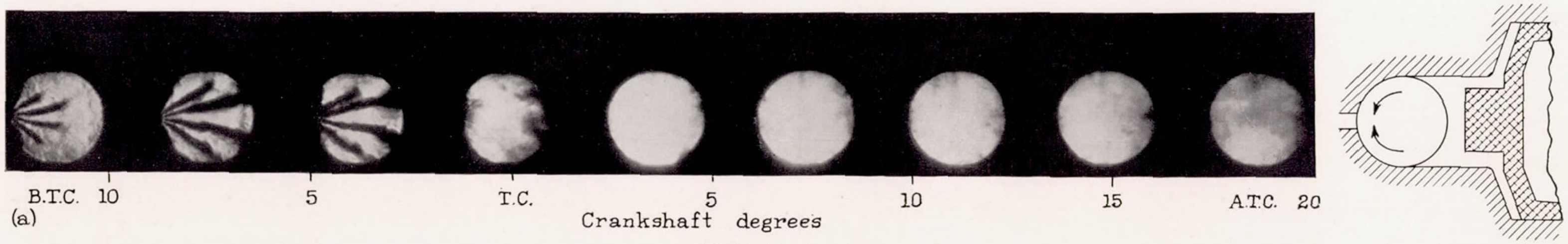


(c) Injection from side; air-fuel ratio, 33.

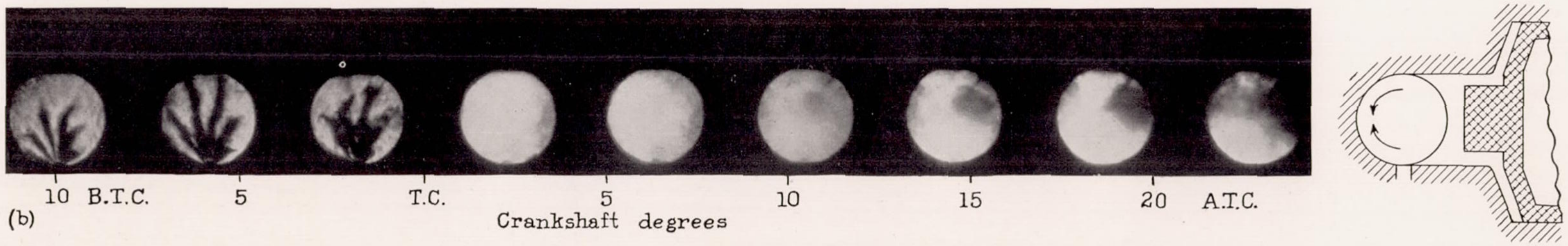


(d) Injection from side; air-fuel ratio, 65.

FIGURE 11.—Effect of air flow on the fuel sprays and combustion at different air-fuel ratios. Multiorifice nozzle and chamber B.



(a) Injection from top.



(b) Injection from side.

FIGURE 12.—Fuel sprays and combustion with multiorifice nozzle and chamber D.

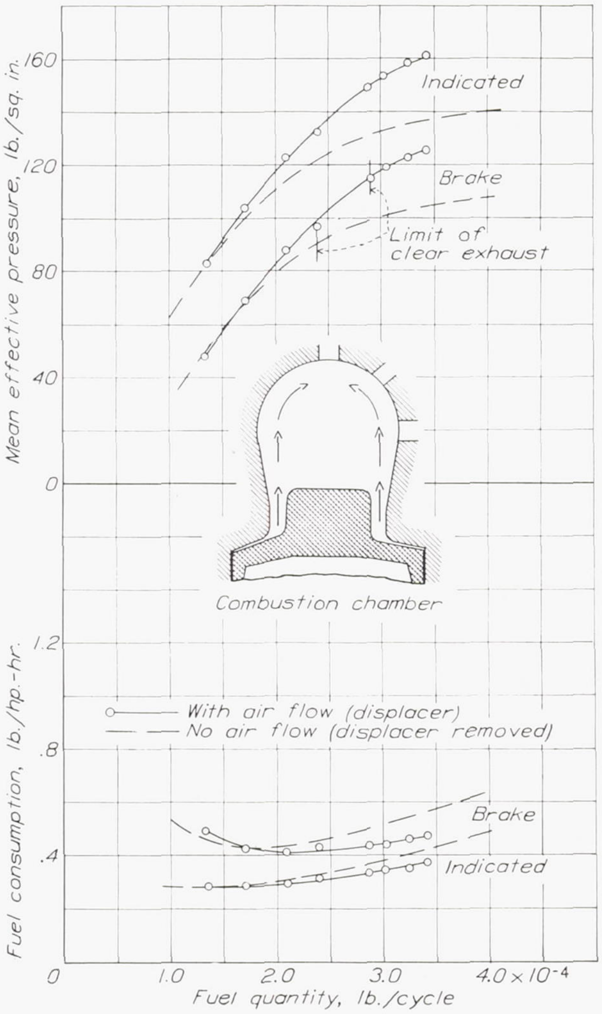


FIGURE 13.—Comparison of performance with and without air flow (reference 7).

direction in the left half (fig. 9). With the injection valve mounted in the top of the spray chamber the spray penetration was decreased by the air jet directed against it. Also the air movement was such that the spray envelope was blown to the left-hand side of the chamber. This deflection is quite noticeable in the photograph obtained 1° A. T. C. The mixing of the fuel and air was not particularly good. The results appeared to be little better than with combustion chamber A. When the injection valve was mounted in the side of the combustion chamber, the spray was deflected upward when it met the incoming air jet about midway across the combustion chamber. The spray impinged on the opposite wall of the chamber and was there blown downward by the air swirl in that half of the chamber. The flame spread to a somewhat greater area than was the case with the spray entering at the top of the chamber, but considerable air was still not reached by the fuel. Again the chamber was partly filled with a dense smoke during the expansion stroke.

**Multiorifice nozzle.**—The multiorifice nozzle was designed according to the proportionality principle discussed in reference 6. Engine tests (reference 7) have shown that in the type of combustion chamber tested the multiorifice nozzle which gave the best performance with the quiescent combustion chamber also gave the best performance with the same combustion chamber used in conjunction with the displacer piston.

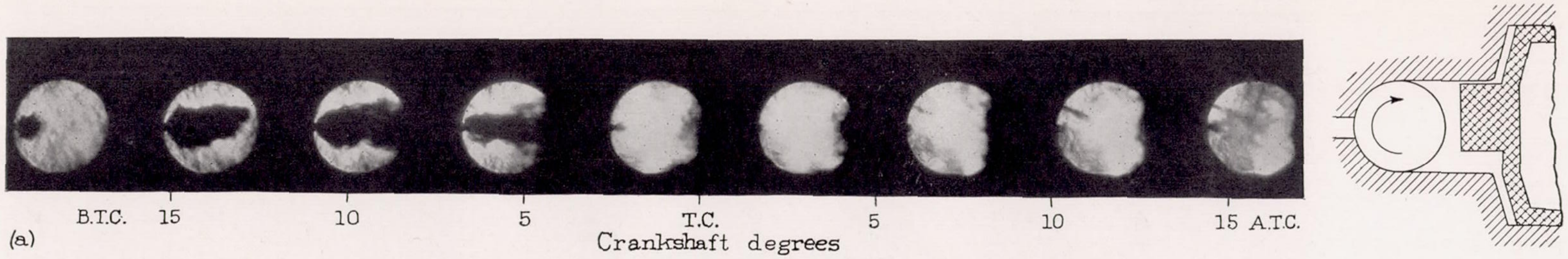
In the tests with the multiorifice nozzle the inlet manifold around the ports was removed. The vortex that appeared when the manifold was in place did not occur so often when the manifold was removed. With the injection valve mounted in the top of chamber A (fig. 10 (a)) the individual sprays penetrated through the highly heated dense air, the side sprays impinging on the combustion-chamber walls. The flame filled the visible portion of the combustion chamber. When the injection valve was mounted in the side of the chamber (fig. 10 (b)), some of the fuel sprays impinged on the opposite wall of the chamber but not with the intensity that accompanied the impingement of the spray from the single 0.020-inch orifice. The two sprays directed toward the entrance throat were definitely deflected upward. The flame again filled the combustion chamber and, although there was some smoke visible on the expansion stroke, it was not so dense as in the case with the single 0.020-inch orifice.

With the nozzle mounted in the top of combustion chamber B (fig. 11 (a)) the sprays from the 0.014- and 0.018-inch orifices on the side of the chamber toward the air jet were deflected to the right by the air movement across the top of the chamber, as they left the nozzle, and to the left nearer the bottom of the chamber because of the upward movement of the air in this portion. The sprays on the other side of the combustion chamber showed less movement although they were somewhat bent. On this side of the chamber the air flow had been decreased because of its greater distance from the displacer passage and also because the air flow had already lost some of its energy in deflecting the first sprays through which it passed.

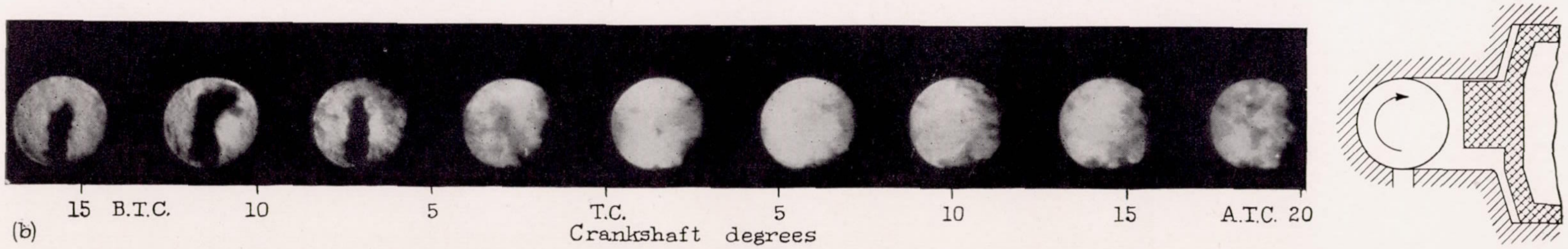
With the injection nozzle mounted in the side, the effects of the air movement are visible during the entire injection period. The sprays are all deflected upward as they enter the chamber. The envelopes and, in some cases, the spray cores are deflected downward when they reach the opposite side of the chamber.

Projection of the film containing the photographs shown in figure 11 showed that in three cases there was a reversal of rotation of the air flow even though the intake manifold had been removed. The reversal was not so violent, however, as it was with the manifold.

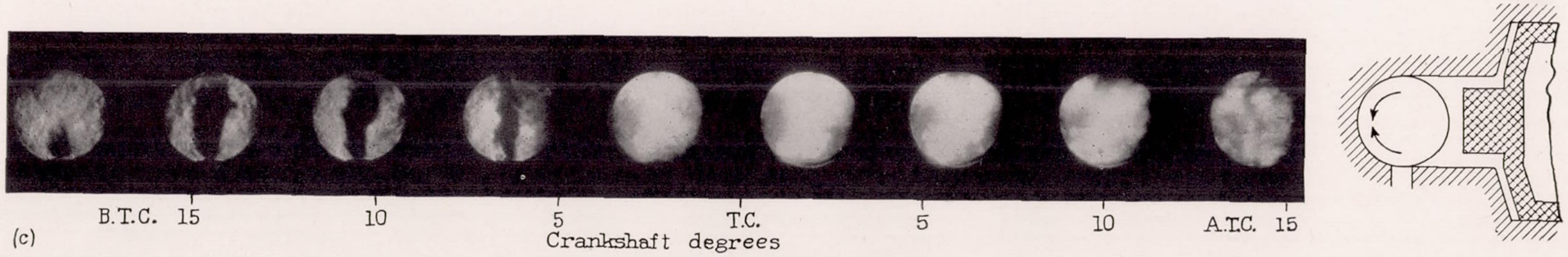
In figures 11 (c) and (d) are shown the results of tests made with air-fuel ratios of 33 and 65, respectively. A comparison of these photographs with those obtained at an air-fuel ratio of 17 shows that, as the fuel quantity was decreased and consequently the energy in the injected spray was decreased, the rotating air turned the fuel jets through a larger angle so that the sprays were forced to the upper left-hand quadrant of the chamber. With the air-fuel ratio of 65 the flame is



(a) Injection from top of chamber B.

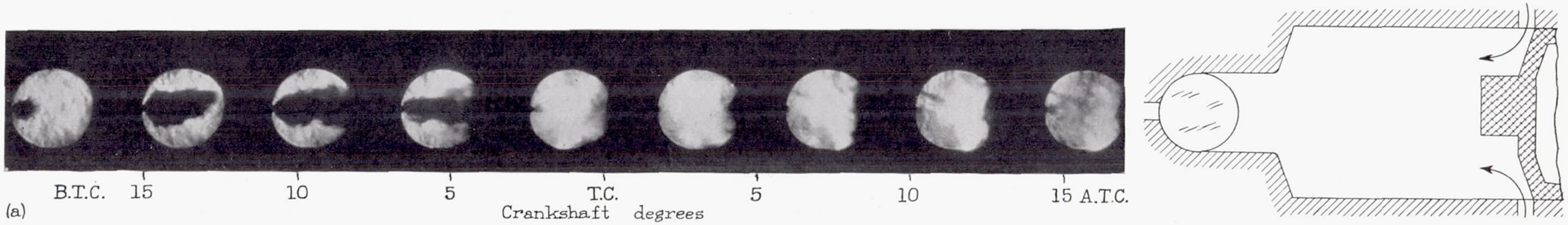


(b) Injection from side of chamber B.

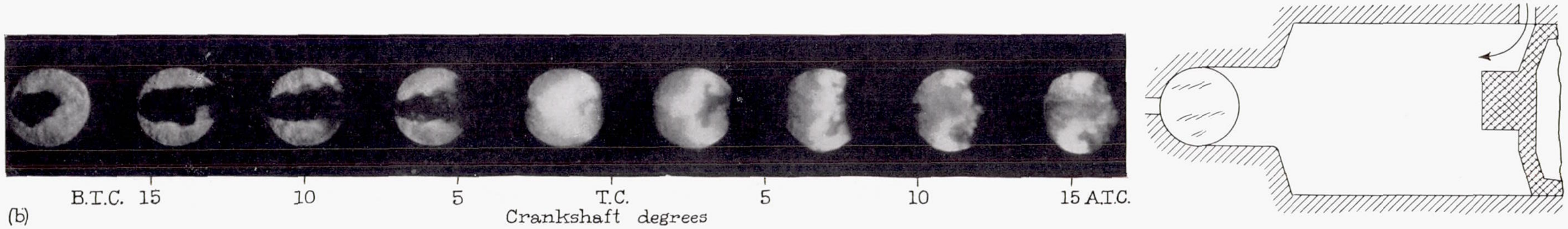


(c) Injection from side of chamber D.

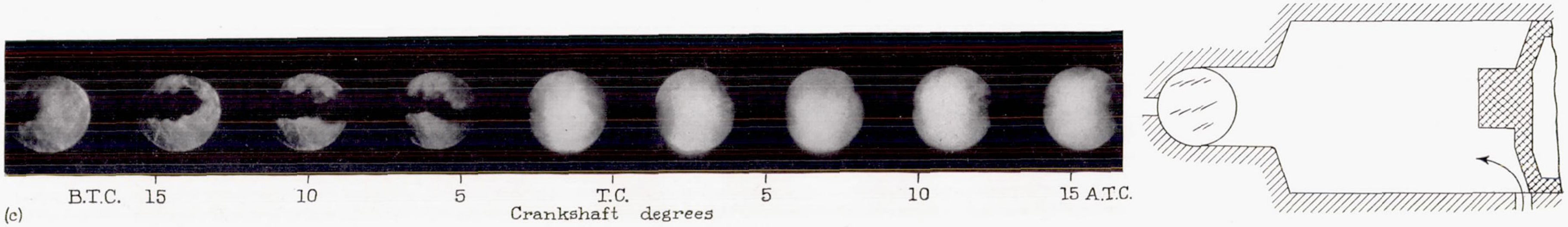
FIGURE 14.—Fuel sprays and combustion with slit nozzle



(a) Air flow from both sides.



(b) Air flow from right only.



(c) Air flow from left only.

FIGURE 15.—Effect of inlet-port arrangement on fuel spray and flame formation. Slit-orifice nozzle; combustion chamber B; injection from top.

visible in two separate sections. One section extends along the right-hand side of the chamber and the other is in the region surrounding the fuel-injection nozzle. In this case the fuel from the main discharge has apparently been carried to the opposite side of the combustion chamber by the moving air and so forms a stratified charge in this area. The small secondary discharge visible in the photograph taken just before top center was not blown away because of the decrease in the air velocity. The original of this strip of film shows that these two flame areas did not combine. The results therefore prove that, even with high air velocities in the combustion chamber, it is possible to maintain a stratified charge of the fuel and air. For this reason it is believed that in engines employing air flow there should be no difficulty in idling the engine. It is probable that in certain cases where special adapters have been used in the air-induction system to change the air flow for idling conditions, the trouble has not been with the air movement but with the idling characteristics of the fuel-injection system.

The results obtained with combustion chamber D and the multiorifice nozzle are shown in figure 12. With the fuel being injected from the top (fig. 12 (a)) of the chamber, the sprays appeared quite similar to those in chamber A. With the fuel being injected from the side (fig. 12 (b)) of the chamber, the sprays show that there was a clockwise rotation of the air in the left-hand side of the chamber and a counterclockwise rotation in the right-hand side of the chamber. The air flow did not have much directional effect on the fuel sprays as a whole except to concentrate them more in the top of the chamber. Engine tests (fig. 13) reported in reference 7 of a similar combustion chamber have shown that this arrangement gives an appreciable increase in power over the quiescent combustion chamber without the displacer piston.

**Slit nozzle.**—In the test conducted by Lee of the distribution within different types of fuel sprays (reference 10) it was shown that the distribution within the spray from a slit nozzle was comparatively good but that the dispersion of the spray, that is, the total volume included in the spray, was insufficient and consequently the air-fuel ratio within the spray was too low. The suggestion was made that this type of spray could most beneficially be used with some form of air flow in the combustion chamber. The results in figure 14 show that, even with the air velocities used in the present tests, the energy was insufficient to break up the fuel spray. A comparison of figure 14 with figures 11 and 12 indicates that the spray from the slit-orifice nozzle was less affected than those from the multiorifice nozzle. The conclusion is drawn that because of the large cross-sectional area presented to the air flow the spray from the slit-orifice nozzle tends to damp the air movement to a greater extent than do those from the multiorifice nozzle. With the fuel being injected from the side (fig. 14 (b)) in combustion chamber B, the air-flow effects are more noticeable than is the case when the fuel is injected from the top (fig. 14 (a)).

A direct comparison cannot be made between the results shown in figure 14 and those in figures 7 and 8 because of the difference in the air-intake system. Tests were therefore run with the slit-orifice nozzle in chamber B in which the inlet ports were blocked first on one side and then on the other (fig. 15). At the right of each of the three photographic strips a line drawing shows which inlet ports remained opened and which were closed. The three ports on each side of the engine cylinder are represented by the single opening. Figure 15 (a) shows the results obtained with the ports opened on both sides, the same photographs being shown in figure 14. When the inlet ports on the cylinder side adjacent to the displacer were opened and those on the other side blocked, a counterclockwise rotation of air was produced in the combustion chamber, that is, a rotation opposed to the air movement produced by the displacer. Although this counterclockwise rotation was stopped before the start of the injection of the fuel, a rotation of the air in the opposite direction was not visible and the fuel spray shows no indication of such a reversal. As was the case in the results presented in figure 7 (c), the air flow induced during the induction period opposed that purposely induced during the last part of the compression stroke and nullified its effects. With the air-inlet ports arranged as shown in figure 15 (c), the air swirl produced during the induction period assisted that produced by the piston displacer and the maximum effect of the air flow was obtained.

## GENERAL SIGNIFICANCE OF TEST RESULTS

In previous tests (references 3 and 10) it had been concluded that with high-dispersion fuel-injection nozzles the lack of spray penetration must be assisted by air flow. The present tests have shown that with the nozzles now generally employed and with the injection pressures commonly used, it is difficult to obtain a good mixture of the air and fuel even with air flow. The question that naturally follows is: How is the compression-ignition engine to be designed so as to give the power outputs together with the fuel economy inherent in the high compression ratio? It was concluded in reference 3 that the chief obstacle to obtaining this high performance is the slow rate of diffusion of the fuel vapors. The results presented in this report support this conclusion. In the use of air flow to assist diffusion, the air must blow through the fuel jet and continually pick up the vapors from the jet. If the air and the fuel rotate about the chamber as a unit, the mixing of the two is not necessarily improved. It is necessary to have a continual intermixing of the fuel and air taking place within the combustion chamber. In addition to the controlled air flow, the purpose of which is to destroy the fuel jet, it is desirable and probably necessary to have numerous small eddies throughout the combustion chamber. The production of such an air flow presents a difficult problem, and the development of a method to measure it is probably even more difficult. Whether or not the use of such flow will actually increase the initial rate of heat exchange from the air is questionable. Such an effect has been indicated, however, by the decreased ignition lags in engine tests at this laboratory with the displacer piston. Test results presented by Selden and Spencer (reference 11) have shown that the rate of heat exchange between the injected fuel and the air is not much affected by low air velocities. An extensive discussion of the effects on engine performance of air flow produced by combustion chambers of different design has been presented by Alcock in reference 12.

In both the present tests and those discussed in reference 2 it has been shown that stratification of the charge occurs in the compression-ignition engine; it has not been shown whether or not such stratification is necessary. When spark ignition is employed as in the conventional carburetor engine, it is known that the flame will not propagate across the combustion chamber unless the air-fuel ratio is less than approximately 20. In this case the combustion of each successive portion of the fuel is brought about by the heat from the combustion of the preceding portion of fuel. In the compression-ignition engine, in which the number of ignition sources is infinite, no tests have been conducted to determine to what extent the air-fuel ratio affects the flame spread. Although it is probable that each source of combustion does propagate flame in the normal manner, it is also certain that new sources of ignition are continually being formed. It is therefore believed that, although stratification does occur in the compression-ignition engine, it is not of so much importance at high air-fuel ratios as would be the case in a spark-ignition engine attempting to run on mixtures with an air-fuel ratio greater than necesssary to support flame propagation.

Since the present tests do not show much difference in the appearance of the flame using the multiorifice nozzle with and without the air flow and since those presented in references 7 and 8 show that a considerable improvement in engine performance is gained by the use of air flow under similar conditions, it can be concluded that the chief effect of the air flow in those cases in which the distribution is reasonably good is not on the direction and penetration of the fuel sprays but on the intermixing of the air and fuel by the numerous small eddies. This conclusion is strengthened by the fact that in references 7 and 8 it was shown that the nozzle which gave the best performance with the air flow was the one which gave the best performance in the quiescent combustion chamber.

An examination of the results presented in this report and those presented in references 1 to 3 gives an indication of the rate of diffusion of the fuel vapors but does not indicate the rate of heat exchange between the air and the injected fuel. The test results presented in reference 11 show that the rate of heat exchange is high from the instant injection starts. Tests have been conducted at this laboratory on methods of increasing the effectiveness of this heat exchange, first, by heating the engine jacket (reference 1) and, second, by heating the fuel to a high temperature before injection (reference 13). In neither case was there any appreciable improvement in the engine performance except for a shortening of the ignition lag with its consequent smoother engine operation, indicating that the rate of heat exchange is sufficiently fast under normal operating conditions.

Efforts to improve the atomization of the fuel jet have not shown any marked improvement in engine performance over that obtained with the atomization already realized with the conventional injection systems. In a series of tests conducted at this laboratory (reference 14) a jet of high-velocity air was directed through the fuel spray as it left the injection valve. Tests conducted by the methods described in reference 14 showed that the combination air-fuel injection decreased the mean diameter of the fuel drops and, when the fuel was injected into the atmosphere, it was found that the combination of the air and fuel jet burned with a much fiercer flame than did that of the fuel jet alone. Nevertheless, when the combination air-fuel injection was used in the engine, there was no appreciable gain in engine performance. As a result of these tests it was concluded that the atomization in the conventional hydraulic injection system is sufficient to result in good combustion provided that the fuel is correctly distributed.

Analysis of the results presented in this report, together with those in the references, leads to the conclusion that the factor about which more information should be obtained is the actual air-fuel ratio at each instant throughout the combustion chamber during the injection and combustion period. These ratios are the determining factors that control the performance of the engine. At present it is known that the air-fuel ratio is extremely uneven and that as a result of this unevenness too much of the fuel is burned late on the expansion stroke and, consequently, at a low cycle efficiency. Not only must the combustion efficiency of the engine be improved (by combustion efficiency is meant the percentage of the total fuel injected that is burned between the start of the fuel injection and the completion of the power stroke) but the time at which this burning occurs must also be controlled to a greater extent than is done in present-day designs.

## CONCLUSIONS

The analysis of the data on the effect of air flow on fuel spray and flame formation has led to the following conclusions:

1. In the combustion chamber of the compression-ignition engine, air velocities as high as 400 feet a second were not sufficient to destroy the core of a fuel spray from a single round-hole orifice.
2. Air velocities of 400 feet a second were sufficient to change materially the direction and distance of the spray-core penetration and to blow aside the envelopes of sprays from a single round-hole orifice.
3. As the air-fuel ratio was increased the effect of the air flow on the fuel sprays was increased.
4. With fuel-injection nozzles giving poor fuel distribution within the combustion chamber, air flow increased the volume in the combustion chamber reached by flame.
5. With a fuel-injection nozzle giving good distribution, air flow did not result in much change in the spread of the flame although engine tests showed a large increase in performance.
6. High-distribution nozzles such as the slit nozzle did not show much more effect from air flow than did the sprays from round-hole orifices.
7. High-distribution nozzles damped the air flow considerably.
8. When air flow is employed in a combustion chamber, care should be taken that the motion of the air set up during the induction period is not such as to oppose the desired air flow produced at the end of the compression stroke.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *November 25, 1936.*

## REFERENCES

1. Rothrock, A. M., and Waldron, C. D.: Some Effects of Injection Advance Angle, Engine-Jacket Temperature, and Speed on Combustion in a Compression-Ignition Engine. T. R. No. 525, N. A. C. A., 1935.
2. Rothrock, A. M., and Waldron, C. D.: Effects of Air-Fuel Ratio on Fuel Spray and Flame Formation in a Compression-Ignition Engine. T. R. No. 545, N. A. C. A., 1935.
3. Rothrock, A. M., and Waldron, C. D.: Effect of Nozzle Design on Fuel Spray and Flame Formation in a High-Speed Compression-Ignition Engine. T. R. No. 561, N. A. C. A., 1936.
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.
5. Moore, C. S., and Collins, J. H., Jr.: Prechamber Compression-Ignition Engine Performance. T. R. No. 577, N. A. C. A., 1936.
6. Foster, H. H.: The Quiescent-Chamber Type Compression-Ignition Engine. T. R. No. 568, N. A. C. A., 1936.
7. Moore, C. S., and Foster, H. H.: Performance Tests of a Single-Cylinder Compression-Ignition Engine with a Displacer Piston. T. N. No. 518, N. A. C. A., 1935.
8. Moore, C. S., and Foster, H. H.: Boosted Performance of a Compression-Ignition Engine with a Displacer Piston. T. N. No. 569, N. A. C. A., 1936.
9. Gawthrop, D. B.: Applications of the Schlieren Method of Photography. Rev. Sci. Instruments, vol. 2, no. 9, Sept. 1931, pp. 522-531.
10. Lee, Dana W.: Measurements of Fuel Distribution within Sprays for Fuel-Injection Engines. T. R. No. 565, N. A. C. A., 1936.
11. Selden, Robert F., and Spencer, Robert C.: Heat Transfer to Fuel Sprays Injected into Heated Gases. T. R. No. 580, N. A. C. A., 1936.
12. Alcock, J. F.: Air Swirl in Oil Engines. Auto. Eng., vol. XXV, no. 329, Feb. 1935, pp. 49–54.
13. Gerrish, Harold C., and Ayer, Bruce E.: Influence of Fuel-Oil Temperature on the Combustion in a Prechamber Compression-Ignition Engine. T. N. No. 565, N. A. C. A., 1936.
14. National Advisory Committee for Aeronautics: Nineteenth Annual Report, 1933, p. 17.

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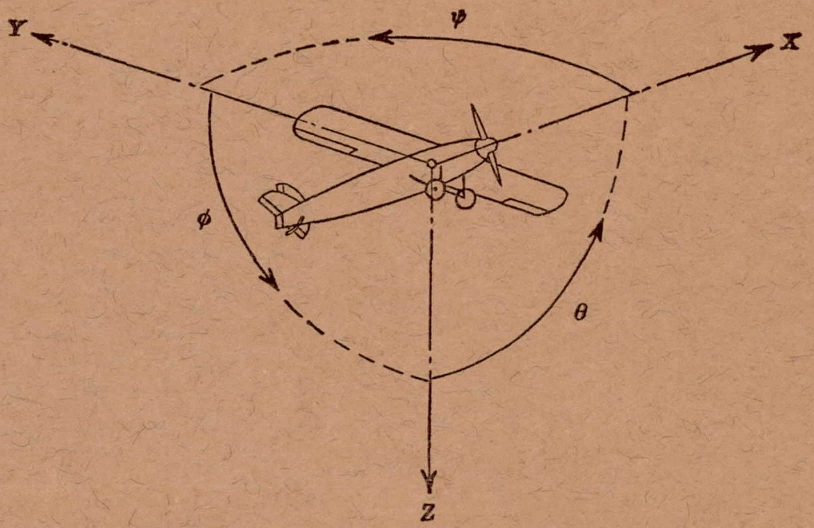

Positive directions of axes and angles (forces and moments) are shown by arrows

| Axis | | Force (parallel to axis) symbol | Moment about axis | | | Angle | | Velocities | |
|---|---|---|---|---|---|---|---|---|---|
| Designation | Symbol | | Designation | Symbol | Positive direction | Designation | Symbol | Linear (component along axis) | Angular |
| Longitudinal | $X$ | $X$ | Rolling | $L$ | $Y \longrightarrow Z$ | Roll | $\phi$ | $u$ | $p$ |
| Lateral | $Y$ | $Y$ | Pitching | $M$ | $Z \longrightarrow X$ | Pitch | $\theta$ | $v$ | $q$ |
| Normal | $Z$ | $Z$ | Yawing | $N$ | $X \longrightarrow Y$ | Yaw | $\psi$ | $w$ | $r$ |

Absolute coefficients of moment

$C_l = \frac{L}{qbS}$ (rolling)  $C_m = \frac{M}{qcS}$ (pitching)  $C_n = \frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), $\delta$. (Indicate surface by proper subscript.)

### 4. PROPELLER SYMBOLS

| | |
|---|---|
| $D$, | Diameter |
| $p$, | Geometric pitch |
| $p/D$, | Pitch ratio |
| $V'$, | Inflow velocity |
| $V_s$, | Slipstream velocity |
| $T$, | Thrust, absolute coefficient $C_T = \frac{T}{\rho n^2 D^4}$ |
| $Q$, | Torque, absolute coefficient $C_Q = \frac{Q}{\rho n^2 D^5}$ |
| $P$, | Power, absolute coefficient $C_P = \frac{P}{\rho n^3 D^5}$ |
| $C_s$, | Speed-power coefficient $= \sqrt[5]{\frac{\rho V^5}{P n^2}}$ |
| $\eta$, | Efficiency |
| $n$, | Revolutions per second, r.p.s. |
| $\Phi$, | Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi r n}\right)$ |

### 5. NUMERICAL RELATIONS

1 hp. = 76.04 kg-m/s = 550 ft-lb./sec.
1 metric horsepower = 1.0132 hp.
1 m.p.h. = 0.4470 m.p.s.
1 m.p.s. = 2.2369 m.p.h

1 lb. = 0.4536 kg.
1 kg = 2.2046 lb.
1 mi. = 1,609.35 m = 5,280 ft.
1 m = 3.2808 ft.