TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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A PRELIMINARY MOTION-PICTURE STUDY OF COMBUSTION IN A COMPRESSION-IGNITION ENGINE

By E. C. Buckley and C. D. Waldron
Langley Memorial Aeronautical Laboratory

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SUMMARY

Motion pictures were taken at 1,850 frames per second of the spray penetration and combustion occurring in the N.A.C.A. combustion apparatus arranged to operate as a compression-ignition engine. Indicator cards were taken simultaneously with the motion pictures by means of the N.A.C.A. optical indicator.

The motion pictures showed that when ignition occurred during injection it started in the spray envelope. If ignition occurred after injection cut-off, however, and after considerable mixing had taken place, it was impossible to predict where the ignition would start. The pictures also showed that ignition usually started at several points in the combustion chamber. With this apparatus, as the injection advance angle increased from 0° to 40° before top center, the rate of flame spread increased and the duration of burning decreased.

INTRODUCTION

Many methods have been used to study the combustion process in an internal-combustion engine, including: analysis of indicator cards; observation of the flame by a stroboscope; continuous, or "streak", photography of a narrow band of the flame as shown through a slit; analysis of gas samples taken progressively throughout the cycle by a stroboscopic valve; recording of flame travel by electric devices; and stroboscopic photographing of the spectrum of the gases in the cylinder. Although each of these methods has advantages over the others for studying some particular phase of the combustion process, all of themhave definite limitations. When making a photographic investigation of combustion it is desirable to obtain a progressive picture of the combustion as complete as possible, in respect to both time and included field.

In previous work on the effect of fuel vaporization on combustion with the N.A.C.A. combustion apparatus some continuous photographic records of the flame were obtained through 2-inch round windows fitted in the sides of the combustion chamber (reference 1). These pictures gave the approximate location of the ignition relative to the spray and an idea of the rate of flame spread through the combustion chamber. However, they showed the flame spread only when the progress of the flame was slow and toward the sides of the chamber, giving the speed of flame in only one direction.

This report presents some of the preliminary work done using the N.A.C.A. combustion apparatus in conjunction with a high-speed motion-picture camera capable of taking pictures at rates up to 2,250 frames per second. Motion pictures taken at this rate through 2-1/2-inch-diameter glass windows in the combustion chamber give a fairly complete and progressive picture of normal combustion. Under knocking conditions, however, the combustion process is so speeded up that, even with the present camera speed, the flame fills almost the entire chamber in the interval between successive frames.

DESCRIPTION OF APPARATUS

A sketch of the N.A.C.A. combustion apparatus, as used in these tests, is shown in figure 1. This apparatus as first built is described in references 2 and 3. Several alterations have been made since these descriptions were written. The hydraulically operated compression-release valve has been changed so that full compression pressure exists only for the single cycle in which the injection of fuel occurs, the cylinder being scavenged for all preceding and succeeding cycles.

The common-rail injection system on the engine, as first used, has been replaced by a pump injection system. The operation of the pump is as follows (see fig. 1): Valve B allows the fuel displaced by the pump plunger to by-pass back to the fuel tank except when the clutch is engaged for an explosion cycle. When valve B is closed during the single revolution of the camshaft, the pump plunger compresses the fuel in the pump reservoir until the plunger approaches the upper limit of its travel, when it opens the poppet valve A. The opening of valve A releases a pressure wave into the injection tube, causing injection of the fuel. This new injection system allows continuous circulation of fuel through the injection valve so that, by controlling the temperature of the fuel in the fuel tank, any desired fuel temperature can be maintained at the injection valve.

In all tests the fuel was injected from the top of the combustion chamber, which is at the right side of all flame pictures shown. A 6-orifice nozzle was used except where otherwise noted. The fuel used in the present tests was diesel oil and the quantity injected per cycle was 0.00025 pound, giving an air factor of about 1.3. The compression ratio was 14.6.

An indicator has been designed to use in conjunction with the engine. This indicator is of the optical type, the deflection of a diaphragm causing a corresponding deflection of a light beam. The usual disadvantages of this type of instrument have been minimized by a refinement of design made possible by the particular conditions under which the instrument is used. The large opening in the combustion chamber permits the use of a diaphragm with a 1-3/8-inch diameter. The natural frequency of the diaphragm and mirror is approximately 9,000 per second. The pivot mechanism is of a type designed to minimize the friction and preclude looseness. The effect of temperature on the diaphragm is not an important consideration with this indicator because of the large mass of the diaphragm and the fact that it is exposed to high temperature for only one cycle.

A spark coil and timer record on the indicator card the phasing with respect to the engine by photographing two sparks that occur 90 crankshaft degrees apart. Since the film drum of the indicator is driven by a synchronous motor, the use of these two sparks enables an allowance to be made for any momentary acceleration of the engine caused by the explosion. A switch on the camshaft causes the sparks to jump the spark gap in the indicator only in the single cycle in which injection occurs.

The motion-picture camera used in these tests is a commercial product, a description of which may be found in reference 4. It differs from the usual motion-picture camera in that instead of the intermittent film movement usually employed in such cameras, a continuous movement of the film is used. This continuous movement is made possible by using, in the optical system, a rotating flat prism that causes the image to follow the moving film. With this camera, motion pictures have been taken in some instances at 2,250 frames per second. The particular illustrations in this paper were taken at approximately 1,850 frames per second; that is, a picture approximately every two crankshaft degrees. The exposure time is one third of the time interval from picture to picture. The width of the film is 16 mm and the type of film used in these tests was supersensitive panchromatic.

Included on the edge of each picture, as seen in figure 2, is a simultaneous photograph of the dials of the clock which is included in the base of the camera. Figure 2 shows also an enlargement of one of these clock photographs. This time record can be read to 0.001 second on the original films with the aid of a magnifying glass.

During the majority of the tests the apparatus was arranged as in figure 1 with the optical indicator fitted to one side of the combustion chamber. With this arrangement, flame pictures and optical indicator cards were taken simultaneously. In order to photograph the fuel sprays in the combustion chamber the indicator was replaced by a second pair of glass windows with a piece of ground glass between them. This ground glass was given even, intense illumination by an arc light. Against this ground glass as a neutral background, the fuel spray photographed as a dark silhouette and the combustion, because of its extreme brightness, stood out in excellent contrast.

TEST RESULTS AND DISCUSSION

The first series of pictures with the high-speed motion-picture camera was taken to find the effect of injection advance angle on flame spread. Figure 2 shows indicator cards and motion pictures of the combustion with injection advance angles of 0, 20, and 40 crank degrees before top center. The exact position of the timing lines as given on these records was 3° before top center and 87° after top center. The phasing of the moving-picture film was determined by assuming that the start of flame corresponded with the start of pressure rise on the indicator cards. Measurements on several sets of indicator cards and flame records that were later obtained with the supplementary spark records showed that this method of phasing could be used with an error of not more than ±2°. (See also reference 5.)

The motion pictures of the combustion for the condition in which injection started at top center show that ignition occurred about 5° or 6° after top center and started at several different places near the center of the combustion chamber. The next frame, two crank degrees later, shows that the isolated areas of burning had become connected and the flame had spread through about two thirds of the combustion chamber. The flame appeared to be intense and had irregular edges which were no doubt caused by the unevenness of the mixture. By the time the third frame was taken the flame had filled the combustion chamber and appeared to be very intense. The indicator card shows that the maximum pressure was not reached in the combustion chamber until about 13° after top center. Beyond 15° after top center the indicator card shows that the pressure dropped rapidly, indicating that the rate at which heat was liberated by the burning fuel decreased decidedly after this point; however, the flame pictures show that the flame filled the chamber until more than 20° after top center. Beyond 25° after top center the flame steadily became smaller but lasted about 70° longer. At 90° after top center a few tiny isolated flames still existed.

The photographs of the flame for the condition in which injection started 20° before top center show that the first flame appeared in the chamber about 12° before top center. The ignition lag was slightly greater than when injection started at top center but the flame spread was more rapid. Again the flame started in more than one place. Only two of these tiny isolated flames appear in the picture taken 12° before top center. Examination of similar records indicates that, as a rule, more of these nuclei of burning appeared before the flames spread through the chamber. At 10° before top center the flame had spread almost to the edge of the combustion chamber - a slightly greater rate of flame travel than was obtained when injection started at top center. When the third frame was taken the flame had spread to the edge of the chamber in all directions except one isolated region. In succeeding pictures this dark region moved around the chamber slightly and, although flame reached all parts of the chamber, it never existed in all parts of the chamber simultaneously. The indicator card shows that the start of pressure rise was gradual and smooth and that maximum pressure occurred in the chamber at top center. Although the rate of pressure rise was rapid it was not rapid enough to cause knock. The flame pictures show that at top center the flame was beginning to die out in the combustion chamber. Flame continued until 60° after top center. The flame in this afterburning period had a different appearance from the afterburning that occurred when injection started at top center in that, with an injection start of 20° before top center, the late burning appeared to be masses of burning gas instead of more or less isolated nuclei.

When the injection advance angle was increased to 40° the ignition lag was greater than the lag obtained with the 0° and 20° advance angles. The first sign of combustion was two small flames that appeared 15° before top center. By 2° later the flames had spread to the edges of the chamber in almost all directions. The indicator card shows that the rate of pressure rise was so rapid that it set the indicator to vibrating; however, this particular explosion was not accompanied by a knock. The card shows that the rate of heat input had decreased decidedly and the flame pictures show that the flame was dying out rapidly at top center. At 10° after top center the flame had died out completely. Since the flame continued in the top of the chamber for some time after it had disappeared in the bottom, the injected fuel evidently did not form a homogeneous mixture with the air even when injected 40° before top center and 25° before ignition started.

Figure 3 shows some enlargements, to slightly less than full size, of the flame pictures obtained when fuel was injected from a single 0.060-inch nozzle, injection starting at top center. It may be noted that ignition started in the envelope of the spray at more than one position. The second frame shows how the flames had spread and how burning had started in several new isolated areas. In the lower right-hand section of the flame the spray can still be seen. The third frame also shows the fuel spray and shows that the flames had spread to the bottom of the windows and about half-way to the side of the combustion chamber. The tenth frame shows the flame continuing to spread but never completely filling the chamber. The other two frames show the flame dying out at the top of the chamber, but continuing to burn at the bottom. The last frame shows the small isolated nuclei of incandescence.

Figure 4 shows some enlargements of photographs of the spray and the flame, to slightly less than full size, when injection started at top center. Three frames of the film, of which the third is reproduced in figure 4, show silhouettes of the spray in the chamber. The fourth frame still shows the spray silhouette and also shows the start of the flame in the envelope of one of the sprays. This small flame has a very irregular outline and its brightness varies. The fifth frame shows the flames spread to the edge of the chamber in one direction and to the center of the chamber in the other direction, but still presenting a very uneven appearance. This frame also shows a nucleus of burning in the spray envelope on the opposite side of the chamber. The succeeding pictures show the appearance of the flame as it spread through the rest of the chamber.

A study of the original film with a magnifying glass gives a better idea of the details of the combustion than can be obtained from the contact prints shown in figure 2. However, a full appreciation of the motion and continuity of the combustion can be obtained only from the projection of the film as a motion picture.

CONCLUSIONS

From a study of the high-speed motion pictures presented the following conclusions can be drawn:

1. When ignition occurs during fuel injection in a compression-ignition engine it starts in the spray envelope but when ignition occurs after injection and after considerable mixing has taken place it is impossible to predict where the start will occur.

2. Combustion in a compression-ignition engine usually has many ignition nuclei.

3. With the N.A.C.A. combustion apparatus, as the in-

jection advance angle increases from 0 to 40 crank degrees before top center, the rate of flame spread increases and the duration of burning decreases.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 4, 1934.

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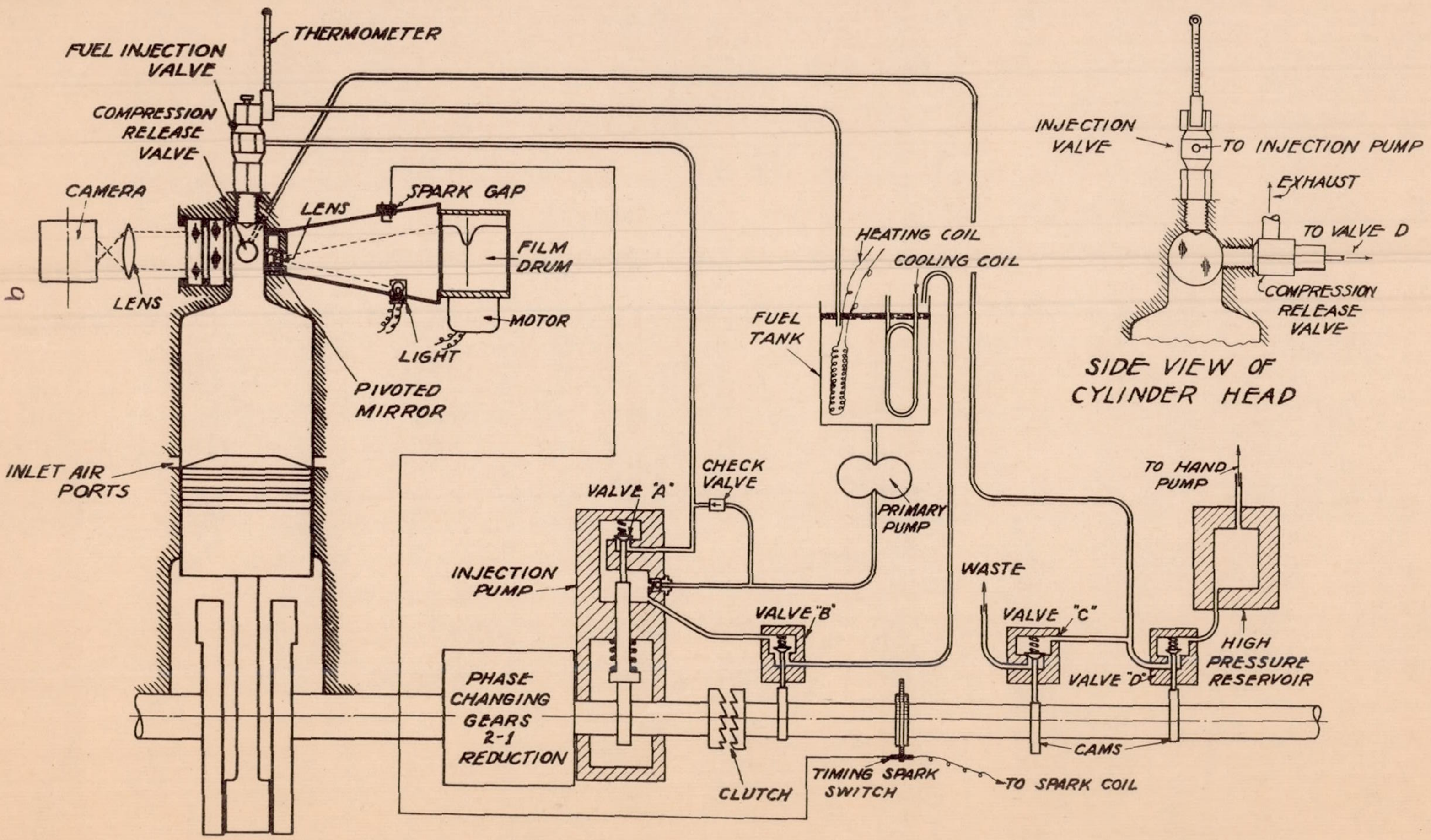
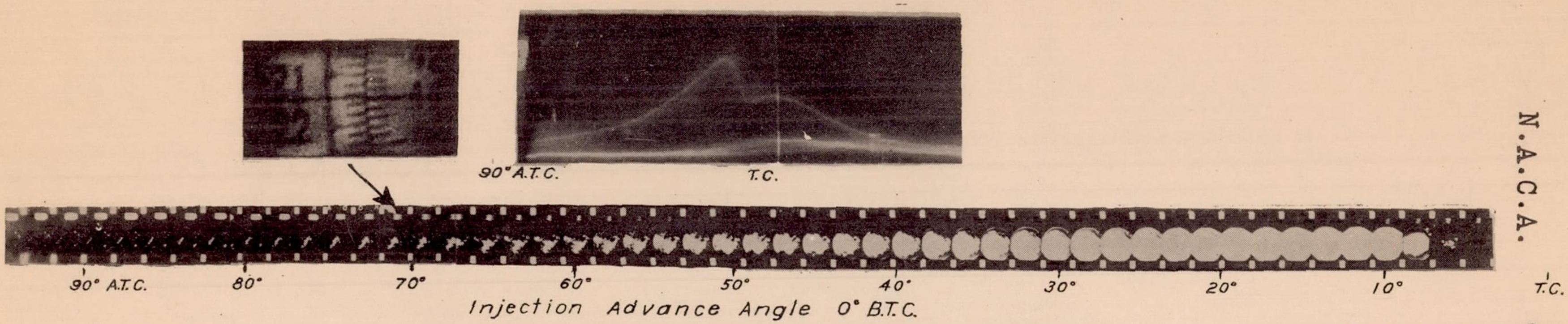
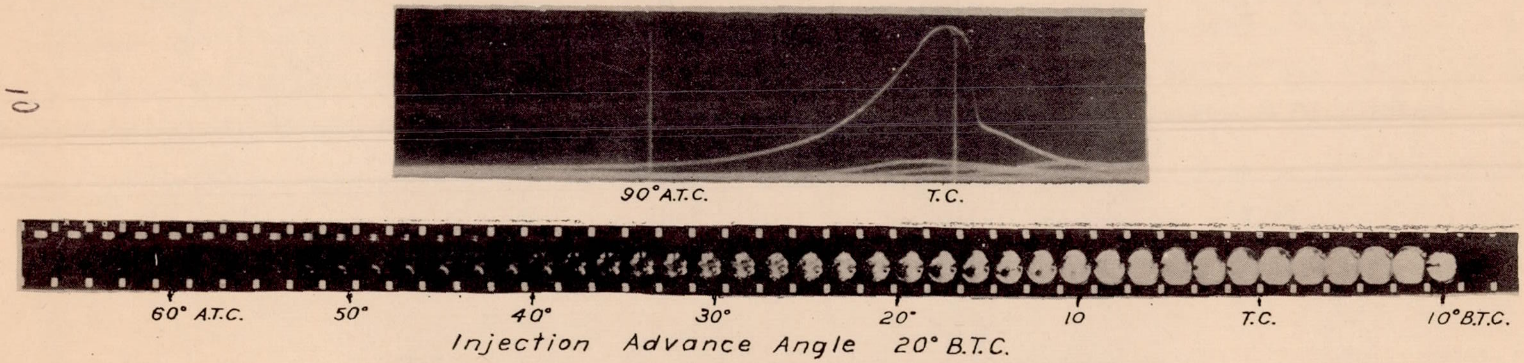
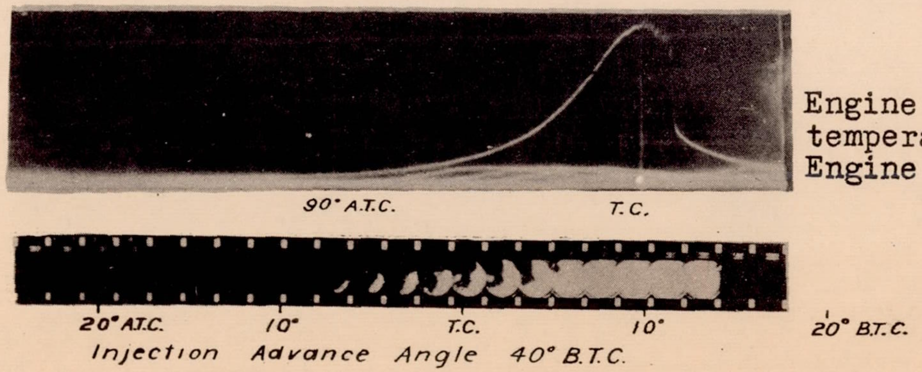


Figure 1.- Diagrammatic sketch of N.A.C.A. combustion apparatus.







Engine coolant temperature, 150 °F.
Engine speed, 570 r.p.m.

Figure 2.- Effect of injection advance angle on flame spread and on pressure rise.

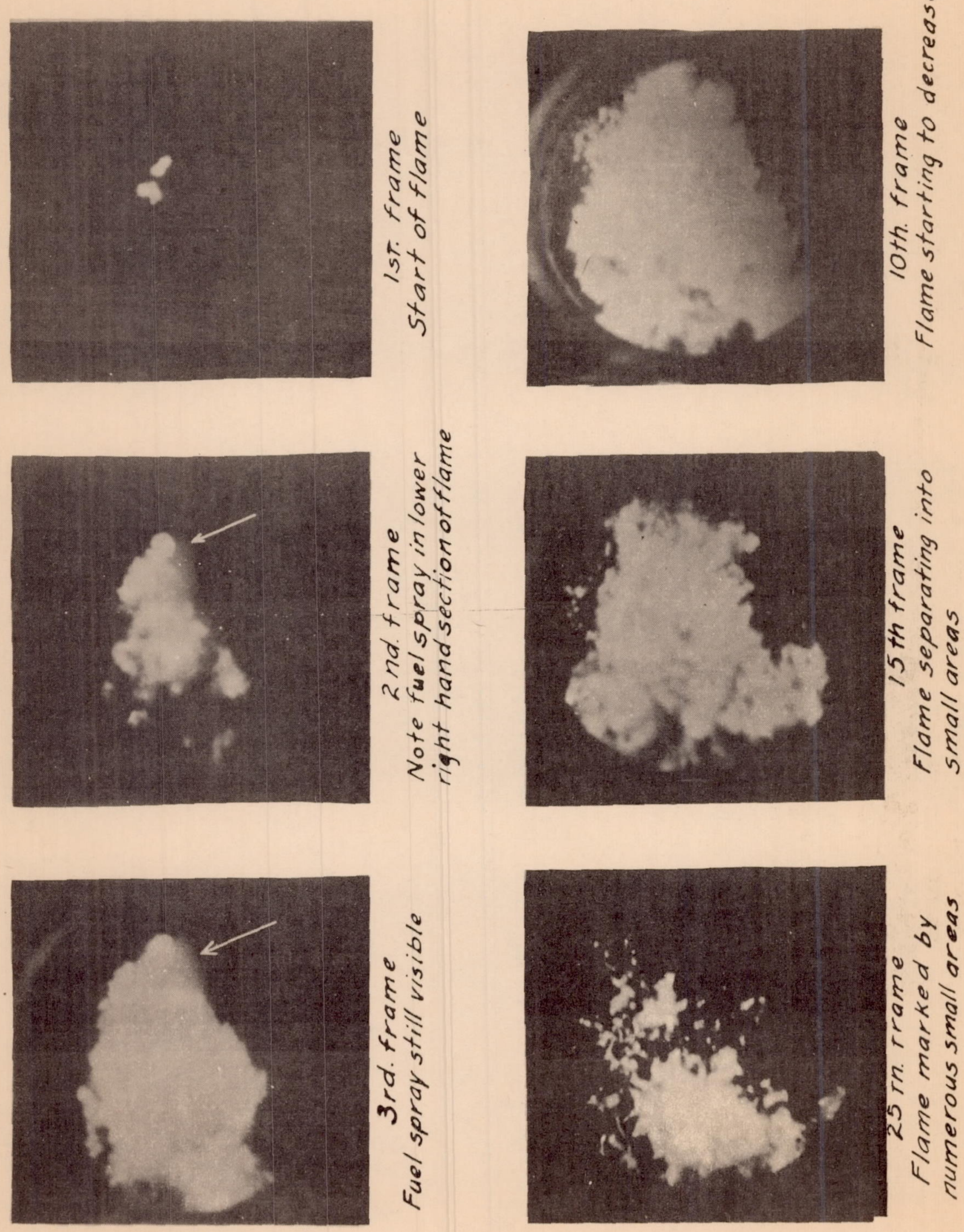


Figure 3.- Flame spread with injection from a single 0.060-inch orifice. Injection starts at top center. Engine speed, 570 r.p.m.

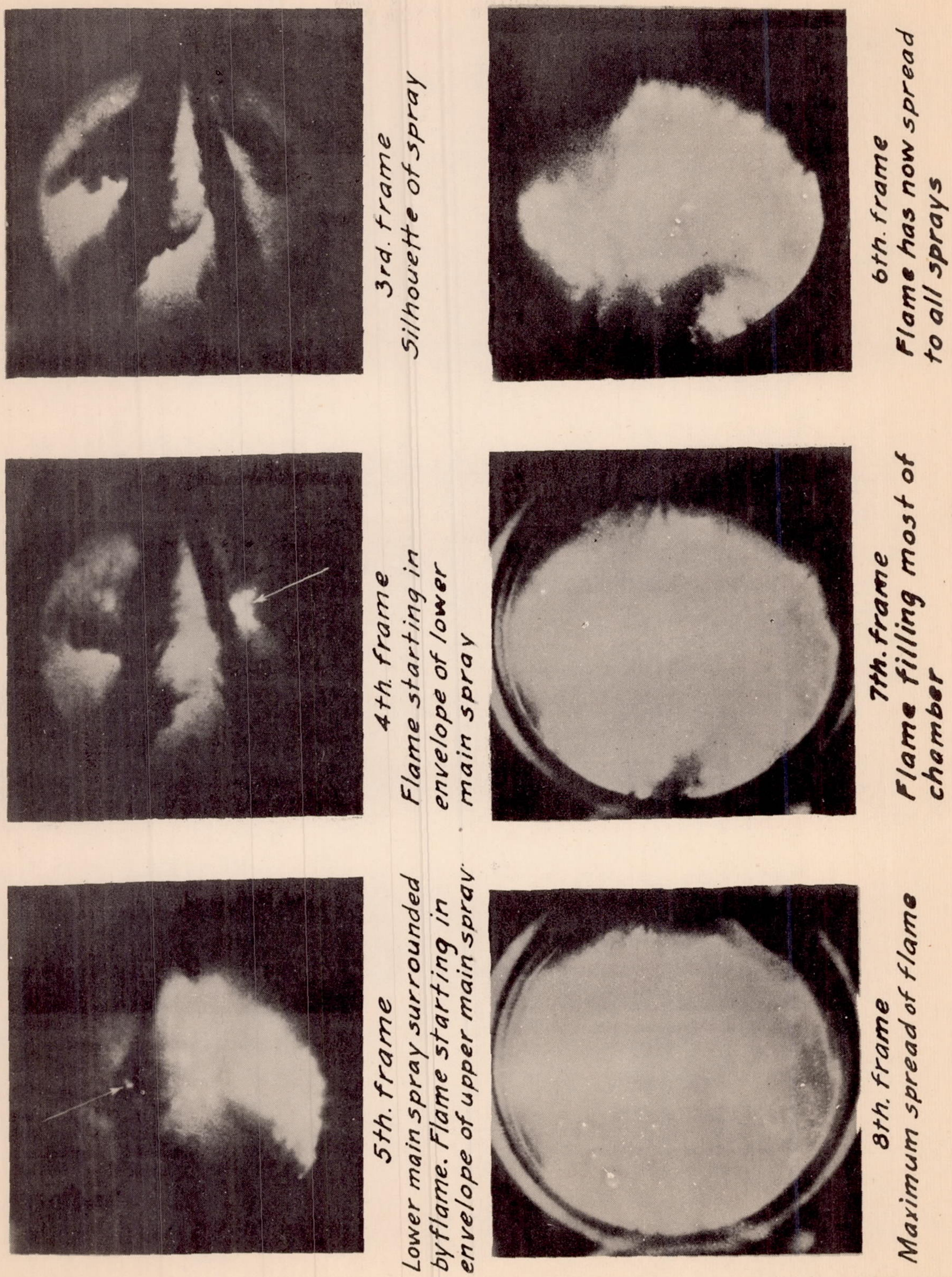


Figure 4.- Fuel spray and flame spread with a multiorifice nozzle. Injection starts at top center. Engine speed, 570 r.p.m.