REPORT No. 545

EFFECTS OF AIR-FUEL RATIO ON FUEL SPRAY AND FLAME FORMATION IN A COMPRESSION-IGNITION ENGINE

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

SUMMARY

High-speed motion pictures were taken at the rate of 2,500 frames per second of the fuel spray and flame formation in the combustion chamber of the N. A. C. A. combustion apparatus. The compression ratio was 13.2 and the speed 1,500 revolutions per minute. An optical indicator was used to record the time-pressure relationship in the combustion chamber. The air-fuel ratio was varied from 10.4 to 365. The results showed that as the air-fuel ratio was increased definite stratification of the charge occurred in the combustion chamber even though moderate air flow existed. The results also showed the rate of vapor diffusion to be relatively slow.

INTRODUCTION

One of the advantages of the compression-ignition engine is that as the fuel quantity injected into the combustion chamber is decreased the air quantity inducted can remain constant so that the fuel is burned with a large excess of air. As a result, the combustion efficiency of the engine increases as the air-fuel ratio is increased. As the combustion efficiency increases the mechanical efficiency decreases; therefore the overall efficiency tends to remain constant. It is this fact that causes the fuel-consumption curve of the compression-ignition engine to show so little change for a wide range of load conditions.

Tests on compression-ignition engines have shown the fuel to auto-ignite with an estimated air-fuel ratio of about 1,000 (reference 1). In practice, an engine will use ratios as high as 70 to 80. Although the fuel is undoubtedly stratified at the high ratios so that the actual ratio in the combustible mixture is considerably lower, no information has been obtained on the extent of the stratification. Data on the stratification of the fuel may be obtained by exploring the combustion chamber with a gas-sampling valve such as that developed by Spanogle and Buckley (reference 2). High-speed motion pictures, such as those presented in reference 3, may be taken of the fuel spray and flame formation under conditions of varying air-fuel ratio. The present report discusses the results of tests made during the latter part of 1934 in which the motion-picture method was used. These tests are part of a general program of research on combustion in a compression-ignition engine being conducted with the N. A. C. A. combustion apparatus. Reports describing other parts of this program are given in references 3, 4, 5, and 6.

APPARATUS AND METHOD

The data were obtained with the N. A. C. A. combustion apparatus (references 3 and 4) in conjunction with a special high-speed motion-picture camera described in reference 7. The combustion apparatus consists essentially of a single-cylinder test engine in which the sides of the combustion chamber are two 2.5-inch diameter glass windows. The engine has a bore of 5 inches, a stroke of 7 inches, and an intake-port height of one-half inch. After the apparatus has been brought to the desired speed by an electric motor, a single charge of fuel is injected into the combustion chamber. The engine is consequently operated under power for a single cycle. Figure 1 of reference 3 shows the apparatus with the indicator installed in one side of the combustion chamber. Figure 1 of the present report shows the apparatus with the windows in both sides of the chamber so that high-speed motion pictures may be taken of both the fuel sprays and the flame.

Since the tests presented in reference 3, the injection system has been altered by replacing the engine-operated pump with a reservoir in which the pressure is regulated with a hand pump. This change was made to increase the accuracy of the amount of fuel injected. The fuel quantity is varied by changing the pressure in the reservoir. The timing spark has been placed between the prismatic shutter on the camera and the film. With this arrangement the timing sparks at top center and 90° after top center are recorded on the film for each engine cycle.

A calibration curve of injection pressure against fuel quantity injected (fig. 2) was first obtained. Five separate discharges of fuel were weighed at each injection pressure. From this curve the injection pressure for the desired fuel quantity was chosen. The indicator was installed and two indicator cards were taken at the

given fuel quantity. The fuel-quantity weight was then checked and two series of high-speed motion pictures of the sprays and combustion were taken. The indicator was again installed and two more indicator cards taken.

The injection nozzle (fig. 3) has a smaller total area than that used in the tests described in reference 3 and, as a result, fuel was discharged from all six orifices.

The diesel fuel used in the tests was designated fuel 2 in reference 3. The fuel temperature was measured as the fuel left the injection valve through the hollow injection-valve stem.

indicator cards taken before and after the photographing of the fuel and the spray agreed very well, generally within the width of the recorded line. Originals of similar cards have been reproduced in reference 3. The flame pictures showed variation in both the positions of flame start and in the flame spread. Nevertheless, all the general characteristics were reproduced in both runs for any one condition. In each case the photographs reproduced in this report appeared to be representative.

The air quantity was estimated from the air temperature and pressure in the cylinder at the start of the

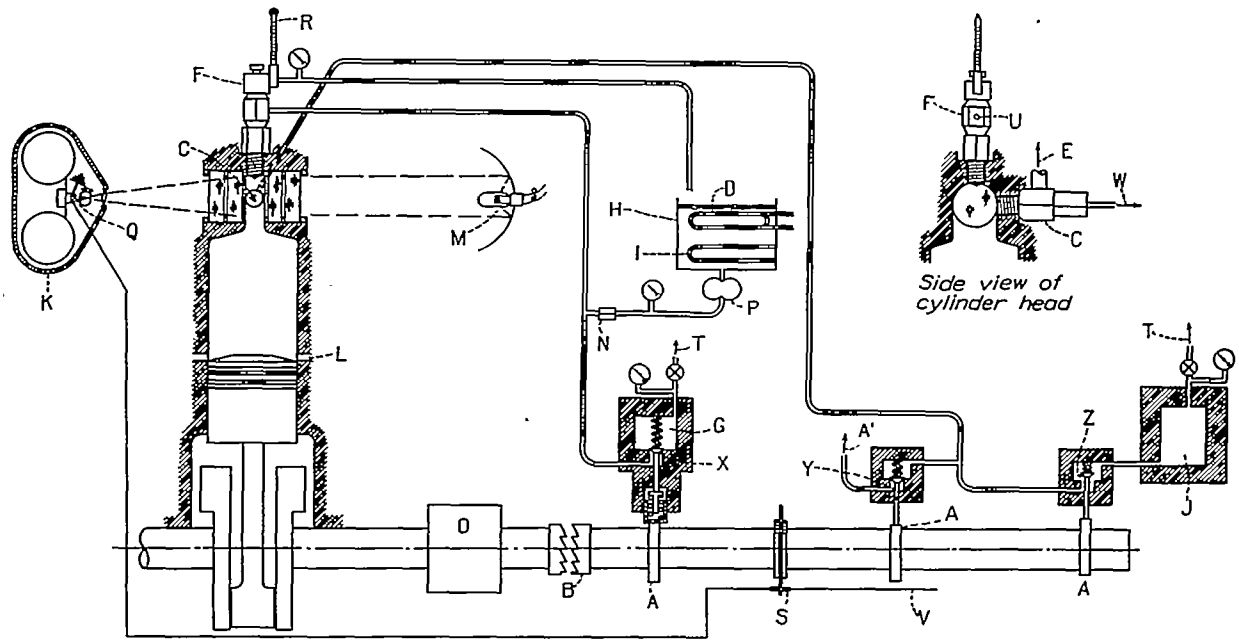

FIGURE 1.—Diagrammatic sketch of the N. A. C. A. combustion apparatus.

A, cam	H, fuel tank	O, phase-changing gears, 2:1 reduction	V, to spark coil
B, clutch	I, heating coil	P, primary pump	W, to valve Z
C, compression-release valve	J, high-pressure reservoir	Q, spark gap	X, valve
D, cooling coil	K, high-speed camera	R, thermometer	Y, valve
E, exhaust	L, inlet-air ports	S, timing-spark switch	Z, valve
F, fuel-injection valve	M, lamp and reflector	T, to hand pump	A', waste
G, fuel reservoir	N, 0.020-inch orifice	U, to injection pump	

The following test conditions were maintained constant:

Engine speed	1,500 r. p. m.
Engine-jacket temperature	150° F.±5°.
Fuel temperature at injection valve	110° F.±2°.
Compression ratio (based on 6.5-inch stroke):	
With indicator installed	13.9.
With glass windows in each side	13.2.

The value of 150° F. for the engine-jacket temperature was that of the outgoing temperature of the glycerin used to heat the jacket; this temperature was measured both at the cylinder and at the combustion chamber. The incoming temperature of the glycerin was about 10° higher than the outgoing.

The curve of figure 2 shows that the fuel quantities did not vary more than ±3 percent. The weighing of the fuel just before each run served as a check. The

compression stroke and from the displacement of the engine. The temperature of the air was assumed to be between that of the room, approximately 85° F., and that of the engine jacket. The air pressure at the time the intake ports were closed was assumed to be 750 millimeters of mercury.

The start of the injection was determined by injecting against a paper mounted on the flywheel of the engine. When the injection valve was mounted in the engine, however, the injection-valve opening pressure was decreased somewhat because of the force exerted by the air pressure on the end of the injection-valve stem. As a result the timing at the small fuel quantities was advanced. The injection start therefore increased from about 9° before top center at the lowest air-fuel ratio to about 15° before top center at the highest air-fuel ratio. This decrease in the injection-valve opening pressure also increased by an unknown

amount the fuel quantity injected. Comparison of the indicator cards with cards from an engine indicates that the increase was insufficient to affect the precision of the results.

RESULTS AND DISCUSSION

The reproductions of the indicator cards are shown in figure 4. When the air-fuel ratio was increased from 10.4 to 13.0, the maximum cylinder pressure showed a slight increase, possibly because less heat was given to the unburned fuel. As the ratio was

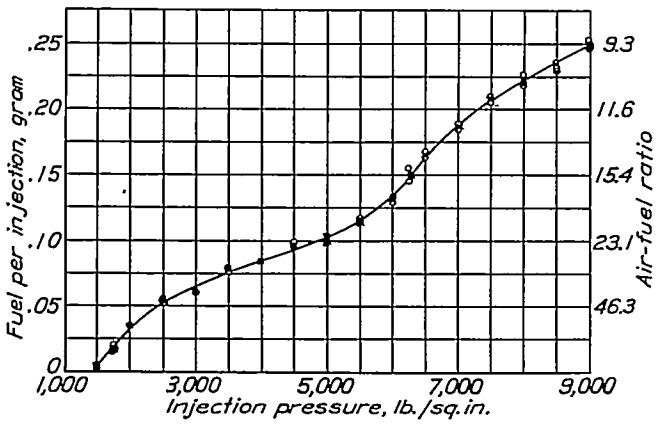

FIGURE 2.—Calibration of the fuel-injection system of the combustion apparatus.

further increased, the maximum cylinder pressure and the power output decreased. When considering the effect of air-fuel ratio on the thermal efficiency of the engine, two factors must be considered: the combustion efficiency and the cycle efficiency. It must also be remembered that there are two fluids entering into the chemical reaction, the fuel and the air. In order to obtain the maximum and most efficient heat input both fluids must be completely utilized. With the present knowledge of methods of distributing the fuel in the combustion chamber, either fluid can be completely utilized only at the expense of an excess of the other. Of course, in practice the air is present in excess because a low specific fuel consumption is more important than a low specific air consumption.

The photographs of the fuel sprays and of the combustion (figs. 5 to 9) indicate the extent to which both fuel and air are utilized and also indicate the distribution of the fuel in the air. Figure 5 is a composite from prints of the original 16-millimeter film[1] taken with the high-speed motion-picture camera. Figures 6 to 9 are enlargements of the photographs of the fuel sprays and the initial flame formation. In the assembly of figure 5 the top center may vary by half a frame width because the strips of film were alined so that the photographs are directly under each other. In the enlargements the true top centers are used.

When an excess of fuel was injected into the combustion chamber (figs. 5 and 6), the sprays penetrated across the visible portion of the chamber. The two outside sprays from the smallest orifices are difficult to

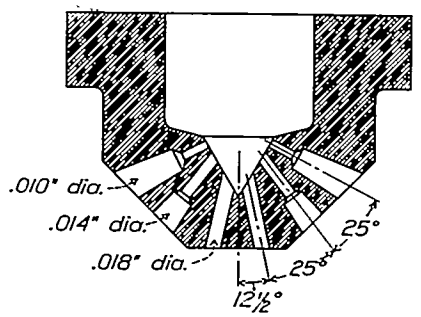

FIGURE 3.—The 6-orifice injection nozzle.

distinguish because they are very close to the edge of the chamber. The flame fills most of the chamber for 6 or 7 photographs, 22 to 25 crankshaft degrees. The chamber then starts to become fogged and the flame is either slowly obscured by the smoke or dies out; the flame finally disappears at 90° after top center or later. From a fuel-air ratio of 17.2 to one of 25.7, the duration of the maximum flame spread seems to increase, reaching a value of about 30 crankshaft degrees. These data compare favorably with the data shown in figure 14 of reference 9 in which the rate of burning is shown to start to decrease rapidly about 40 crankshaft degrees after the maximum has been reached. A comparison of the afterburning periods in figure 5 shows that as the air-fuel ratio passed through the chemically correct mixture ratio, an air-fuel ratio of 14.5, the chamber showed less smoke after the disappearance of the flame. From an air-fuel ratio of 25.7 to one of 365, the chamber remained clear of any

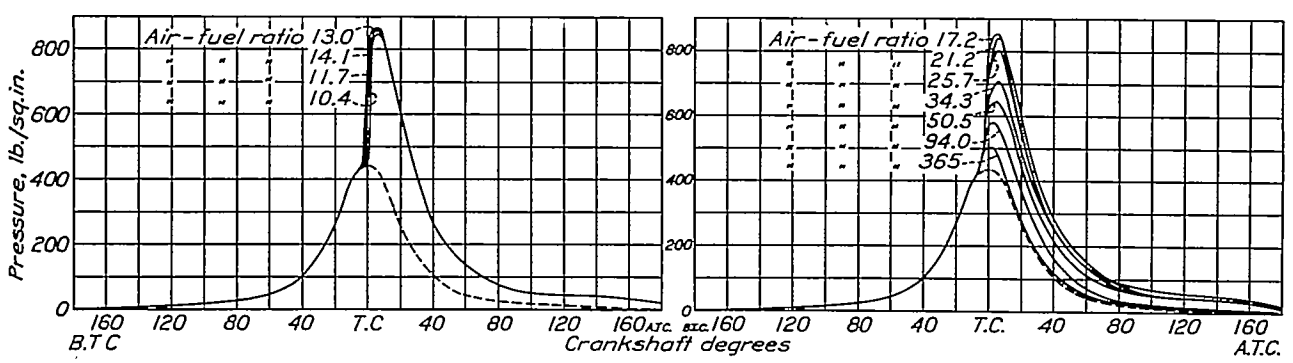

FIGURE 4.—Effect of air-fuel ratio on instantaneous pressures in the combustion chamber.

[1] The motion-picture film is available on loan. (See reference 8.)

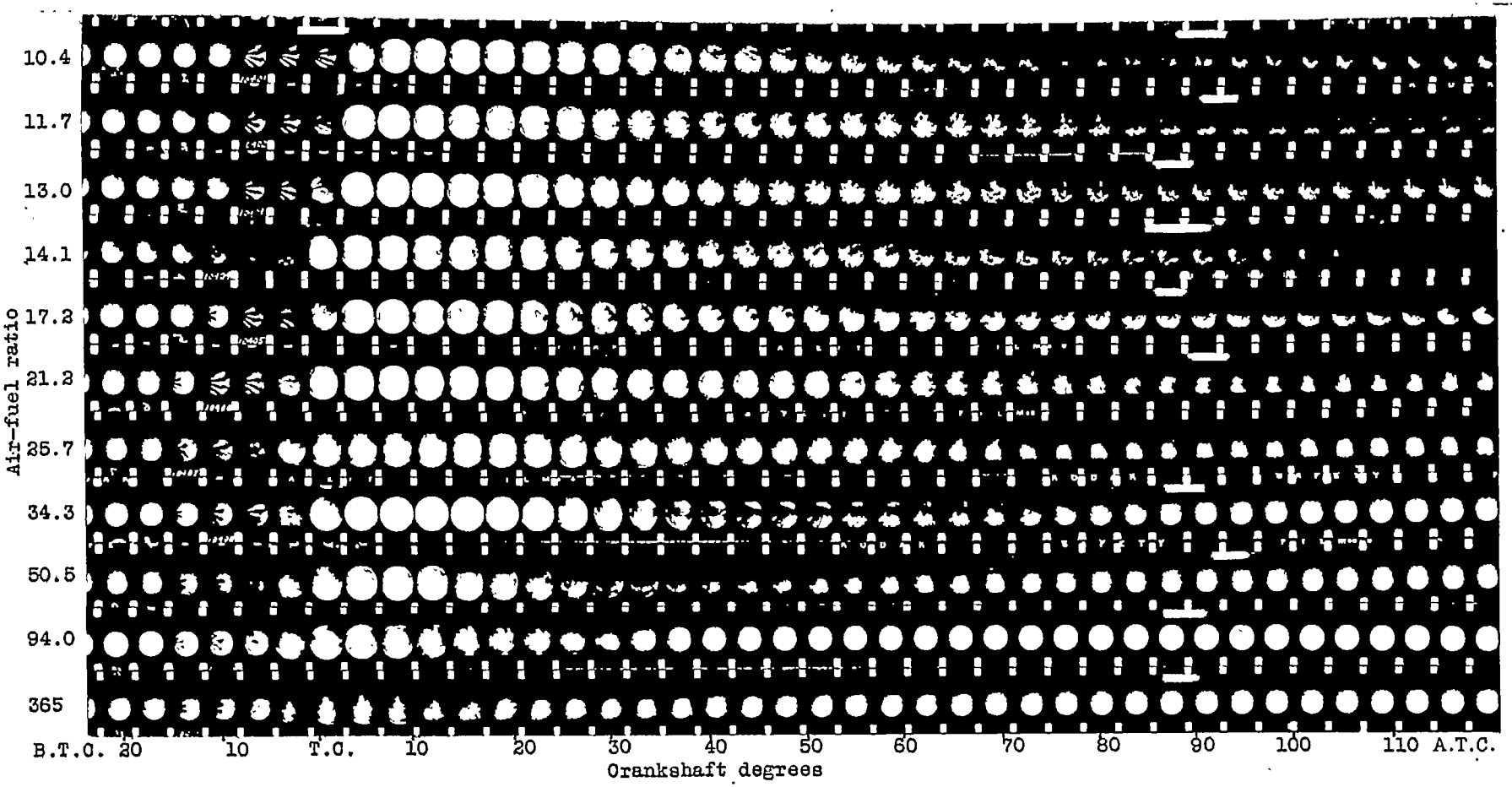

FIGURE 5.—Effect of air-fuel ratio on fuel spray and flame formation.

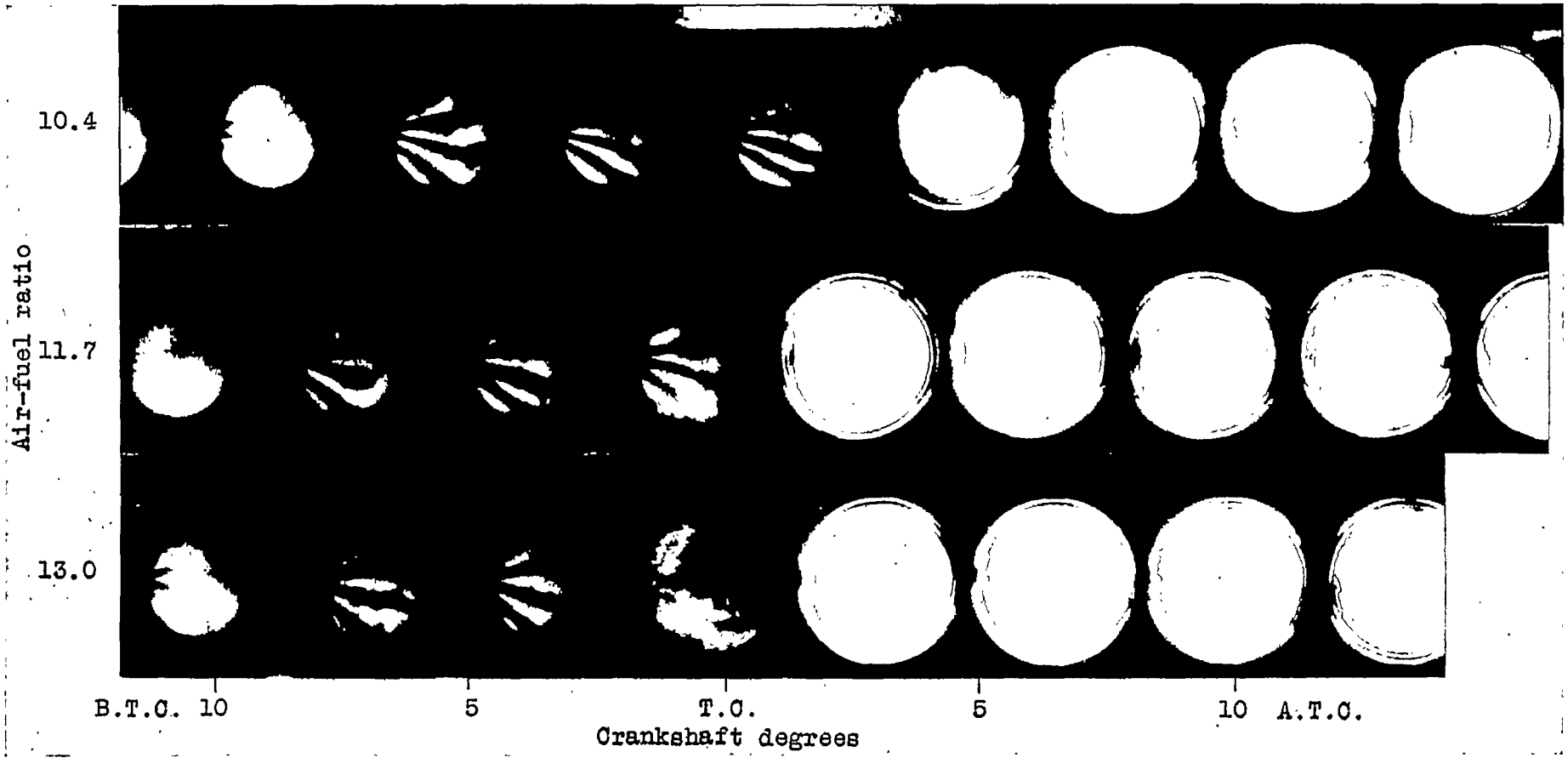

FIGURE 6.—Enlargements of photographs of fuel sprays and first part of flame for air-fuel ratios from 10.4 to 13.0.

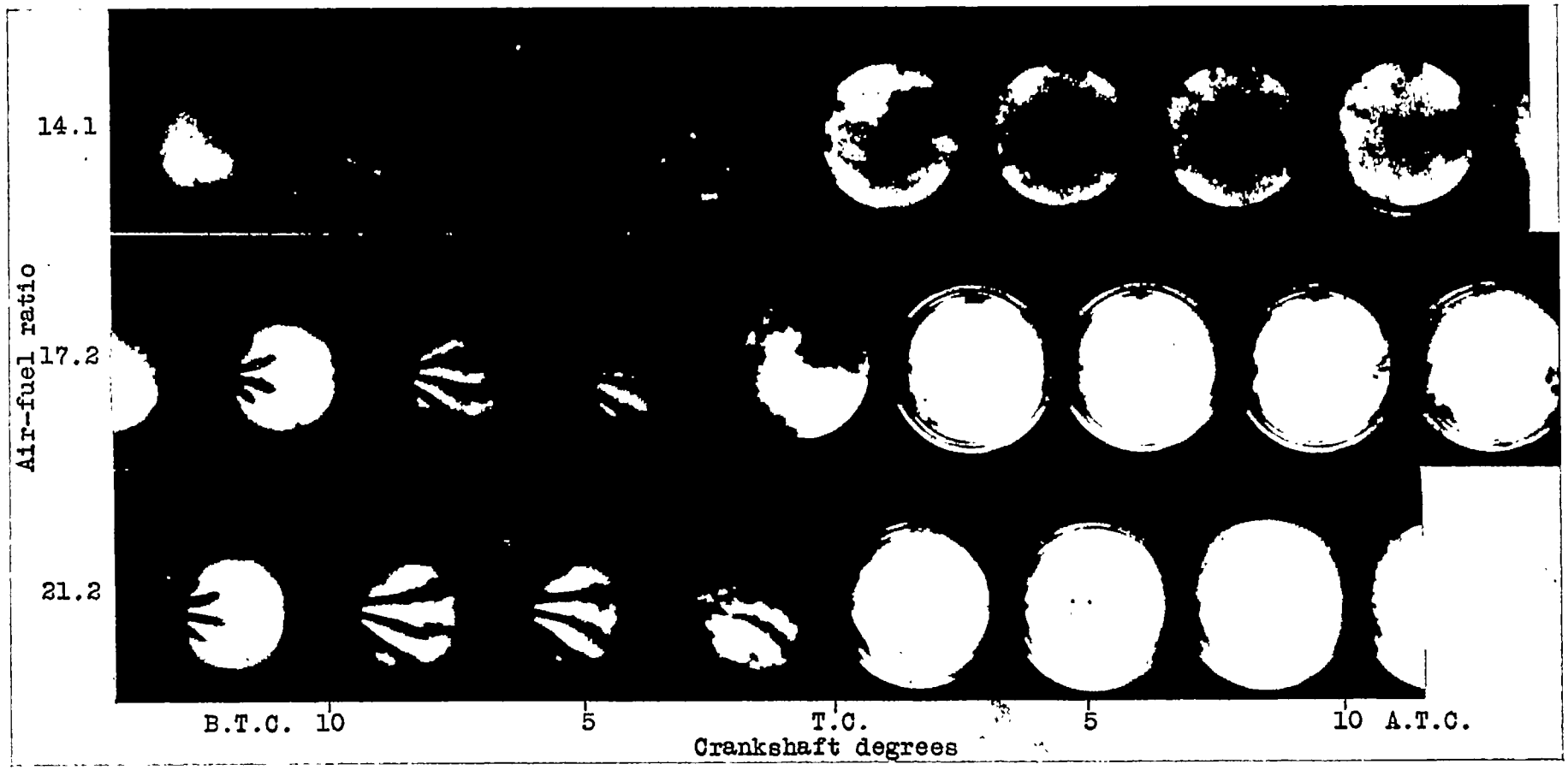

FIGURE 7.—Enlargements of photographs of fuel sprays and first part of flame for air-fuel ratios from 14.1 to 21.2.

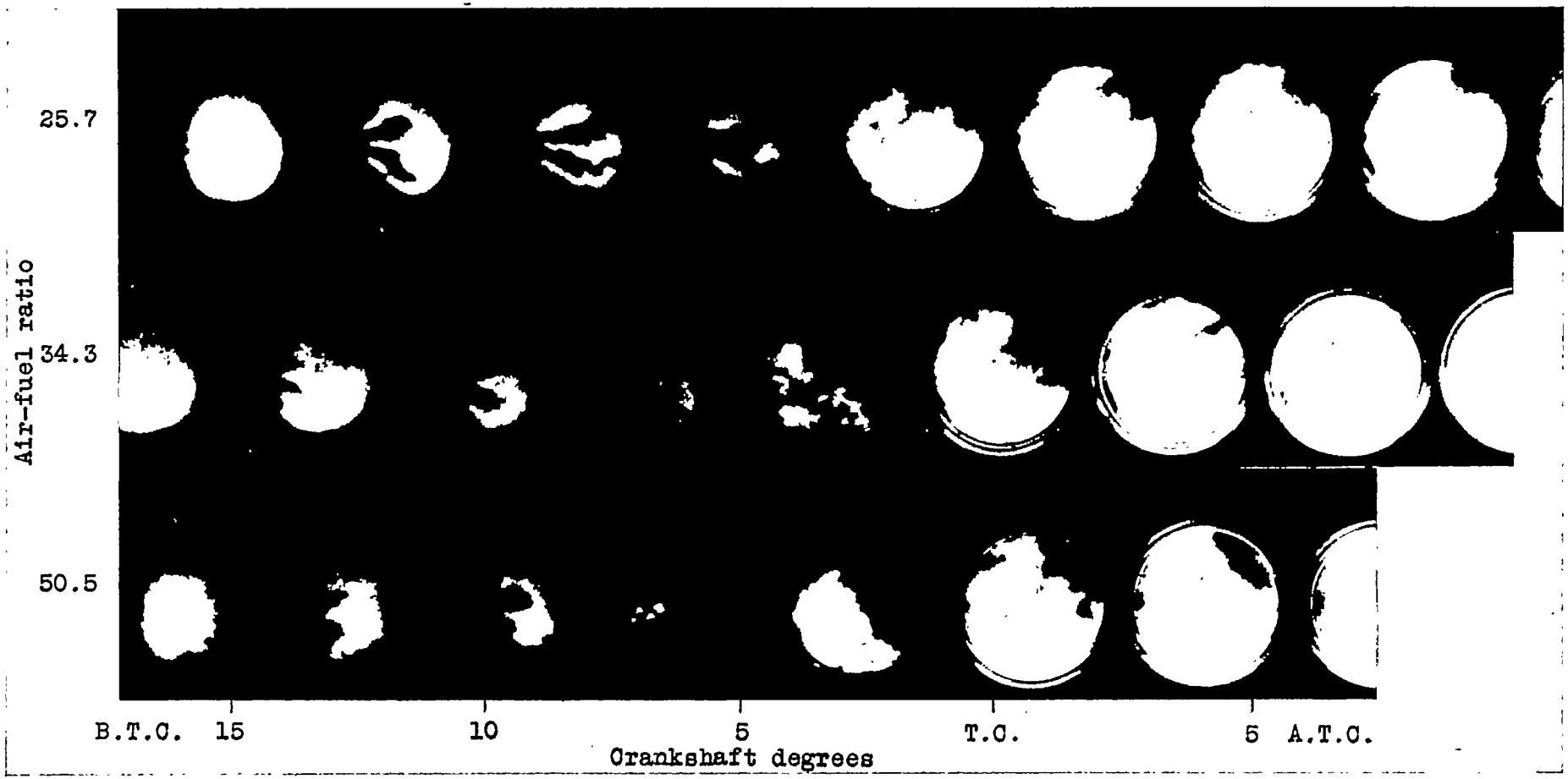

FIGURE 8.—Enlargements of photographs of fuel sprays and first part of flame for air-fuel ratios from 25.7 to 50.5.

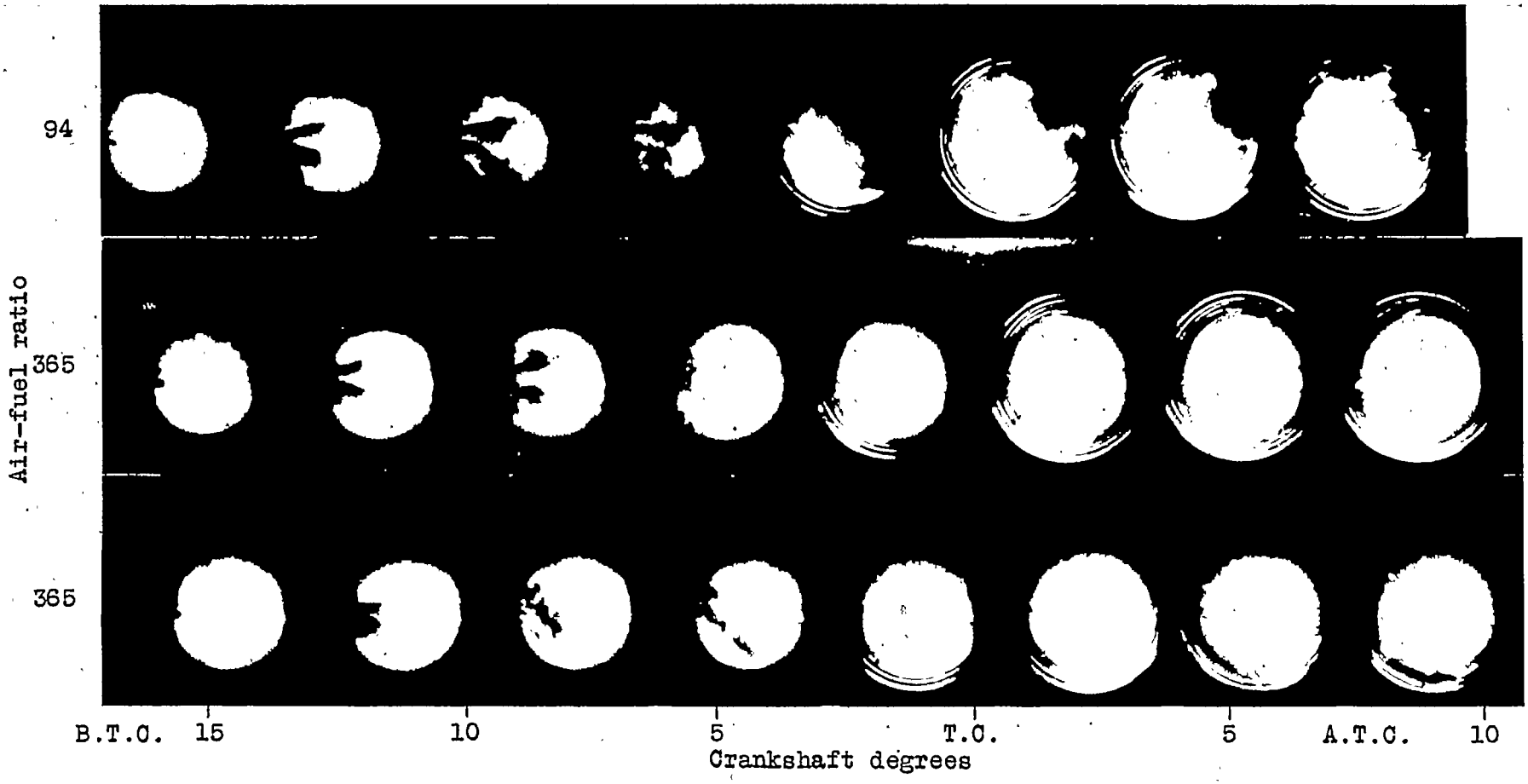

FIGURE 9.—Enlargements of photographs of fuel sprays and first part of flame for air-fuel ratios from 94 to 365.

smoke. The end of the appearance of the flame also occurred earlier in the cycle. These results indicate that both the combustion efficiency and the cycle efficiency are increased as the fuel quantity is decreased. Computations made of data obtained on a test engine at the same time that the data presented in reference 9 were obtained showed that as the air-fuel ratio was increased from 15.4 to 31.8 the combustion and cycle efficiencies were increased, respectively, from 70 and 44 percent to 84 and 49 percent, causing an increase in the indicated thermal efficiency of from 31 to 41 percent.

The enlargements (figs. 6 and 7) show that there was little change in either the spray or the initial-flame formation as the air-fuel ratio was increased from 10.4 to 21.2. It is interesting to note that the burning is always recorded as starting in more than one place. Also, in those series of photographs in which the start of burning is not recorded, the fuel sprays at the injection nozzle are still visible after the flame has filled most of the portion of the chamber between the glass windows. There is a tendency for a small portion of the chamber to remain free of flame, but otherwise the chamber is surprisingly well filled. The sprays show no appreciable effect of any air flow persisting in the chamber although there is some air movement, probably caused by the air entering through the intake ports.

At an air-fuel ratio of 21.2, a slight decrease in spray penetration is noticed. This decrease becomes more marked until at a ratio of 365 the sprays penetrate to a distance of only about 1 inch. The stratification of the charge becomes noticeable at a ratio of 25.7 and is very marked at the ratios of 94 and 365 (figs. 8 and 9). The sprays at the three highest ratios show marked effects of air movement, being blown to the left side of the chamber (the bottom in the figures). Comparing the two series of photographs for a ratio of 365 shows that this effect is not constant. The second series at this ratio shows clearly how the flame appears in that part of the chamber in which the spray last appeared and that the flame spreads to a slightly larger area than that covered by the spray just before it disappeared because of its vaporization.

CONCLUSIONS

The results presented show that definite stratification of the fuel charge does occur in the combustion chamber of the compression-ignition engine even though moderate air flow exists. The start of burning relative to the fuel sprays is not affected by the air-fuel ratio, nor is the rate of flame spread greatly affected by the ratio.

The results at the higher ratios showed that the rate of diffusion of the gases in the combustion chamber, as indicated by the flame spread after the maximum pressure has been reached, was relatively slow. This result in itself indicates why it is difficult to obtain a good mixture of the air and fuel in the combustion chamber of a compression-ignition engine.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *August 26, 1935.*

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