NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

REPORT No. 483

EFFECT OF MODERATE AIR FLOW ON THE DISTRIBUTION OF FUEL SPRAYS AFTER INJECTION CUT-OFF

By A. M. ROTHROCK and R. C. SPENCER

1934

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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	k.p.h.	miles per hour	m.p.h.
		{meters per second	m.p.s.	feet per second	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.)

μ, Coefficient of viscosity

ν, Kinematic viscosity

ρ, 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

Ω, 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)

α, Angle of attack

ϵ, Angle of downwash

α_o, Angle of attack, infinite aspect ratio

α_i, Angle of attack, induced

α_a, Angle of attack, absolute (measured from zero-lift position)

γ, Flight-path angle

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SUMMARY

High-speed motion pictures were taken of fuel sprays with the N.A.C.A. spray-photographic apparatus to study the distribution of the liquid fuel from the instant of injection cut-off until about 0.05 second later. The fuel was injected into a glass-walled chamber in which the air density was varied from 1 to 13 times atmospheric air density (0.0765 to 0.99 pound per cubic foot) and in which the air was at room temperature. The air in the chamber was set in motion by means of a fan, and was directed counter to the spray at velocities up to 27 feet per second. The injection pressure was varied from 2,000 to 6,000 pounds per square inch. A 0.020-inch single-orifice nozzle, an 0.008-inch single-orifice nozzle, a multiorifice nozzle, and an impinging-jets nozzle were used. The results show that in still air the dispersion of the fuel particles following injection cut-off was extremely slow and that the fuel tended to travel across the chamber from the injection nozzle. At all the air densities used, air velocities as low as 15 to 20 feet per second had an appreciable effect on the distribution of the liquid fuel after injection cut-off. The best distribution was obtained by the use of air flow and a high-dispersion nozzle.

INTRODUCTION

In an internal-combustion engine employing either spark ignition or compression ignition the distribution of the fuel in the combustion chamber at the time combustion is started is of primary importance. The distribution of the fuel is controlled by: the manner in which the fuel is forced into the combustion air, the relative movement between the fuel and the air, the rate of vaporization of the fuel, and the rate of diffusion of the fuel vapors. The relative importance of each of these factors is dependent on the temperature and density of the air, during the admission of the fuel, and on the time between the admission of the fuel and the start of combustion. When injection occurs early in the cycle, as in fuel-injection spark-ignition engines, the time for completing the distribution is long enough to permit the rate of vaporization of a volatile fuel to become the most important factor in forming a uniform mixture. If injection is timed later in the cycle and less volatile fuels are used, as in compression-ignition engines, then more care must be taken in distributing the fuel to the combustion air. Two general methods are available for accomplishing distribution—the directed-spray method, and the use of air flow.

The N.A.C.A. has published the results of several tests on the effect of air flow (references 1 to 4) on fuel sprays. The velocities investigated varied from 60 to 800 feet per second. The purpose of these former tests was primarily to determine the effect of air flow on the distribution during the injection process. The present tests have extended this work to the effects of air flow on the distribution of the liquid fuel following the cut-off of injection. In addition, tests have been made on the distribution of the liquid fuel following injections into still air. In order to make the test results applicable to both spark-ignition and compression-ignition engine development the time interval investigated was from 0 to 0.05 second after injection cut-off and the air densities were varied from 1 to 13 atmospheres (0.0765 to 0.99 pound per cubic foot). Throughout this report, the density of the air in the spray chamber will be expressed in atmospheres; that is, an air density of 13 atmospheres corresponds to the density of the air at room temperature and a pressure of 13 atmospheres. While not strictly conventional, this usage has been adopted for convenience. The tests were conducted during 1933 in the N.A.C.A. power plants laboratory at Langley Field, Va.

APPARATUS AND METHODS

The high-speed photographic apparatus and injection system of the N.A.C.A. spray-photographic equipment (references 5 and 6) were used for this investigation. The apparatus was altered to permit photographs to be taken at the rate of 300 to 500 per second. This change permitted a study of the distribution of the spray during the period from cut-off to about 0.05 second after cut-off.

Because the distance a fuel spray is required to penetrate in a high-speed spark-ignition engine may be greater than the 5 inches permitted in the spray chamber of the apparatus, a 3-inch-diameter tube 3¼ inches long, was added to one end of the chamber so as to permit a maximum penetration of 8 inches. A 4-bladed fan 3 inches in diameter was mounted at the end of the chamber opposite the extension and a honeycomb of ¼-inch openings was mounted ahead of

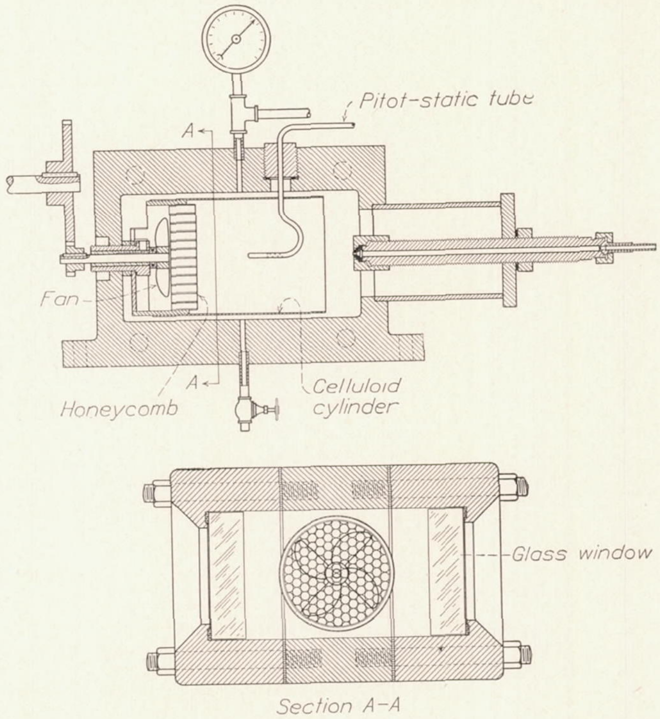

FIGURE 1.—Spray chamber equipped with fan for circulating the air.

the fan to provide reasonably smooth air flow. The fan was mounted in a ring, and a celluloid cylinder was placed around the ring, extending to within 1 inch of the opposite end of the chamber proper. Thus the air was driven through the celluloid cylinder at relatively high velocity and returned to the fan through the space between the cylinder and the walls. The fan was driven by an electric motor at speeds up to 18,000 revolutions per minute. The injection nozzles were mounted on a long threaded open-nozzle holder (see reference 7), which could be adjusted to hold the nozzle at various distances from the fan. A ball check valve was placed in the fuel tube back of the nozzle holder. This arrangement left a length of tube still open to the chamber air, but a better arrangement could not be made conveniently, because of the long nozzle holder that was used. Figure 1 shows the modified spray chamber with the fan in place and with the nozzle mounted in the inner position, 3.5 inches from the honeycomb.

Air velocities were measured with a pitot-static tube ⅛ inch in diameter inserted through the chamber wall; an alcohol manometer was used to indicate the pressure head. The impact opening of the pitot-static tube was placed 1.5 inches from the front of the honeycomb, and velocity readings were taken at four different positions across the cylinder. The curves in figure 2 show the results of the velocity survey. The maximum velocity was reached at a point 1 inch from the cylinder axis; in the data presented, all velocities listed are those measured at this position.

In one series of tests the shape of the spray chamber was altered by means of a wooden frame, to simulate the vertical-disk form of the quiescent combustion chamber shown in reference 8. The frame was provided with thin glass plates to give the same combustion-chamber depth. Tests were made both with and without the glass plates in place.

Most of the tests were conducted with a 0.020-inch orifice nozzle, shaped as shown in figure 1. Tests were also made with an 0.008-inch orifice nozzle, a multiorifice nozzle, and an impinging-jets nozzle containing four orifices. The air density in the chamber was varied from 1 to 13 atmospheres and the injection pressure from 2,000 to 6,000 pounds per square inch.

Previous investigations (references 9 and 10) having shown only slight differences between spray photographs for various fuels, all the tests were made with a diesel fuel oil having a specific gravity of 0.86 and a viscosity of 0.102 poise at room temperature.

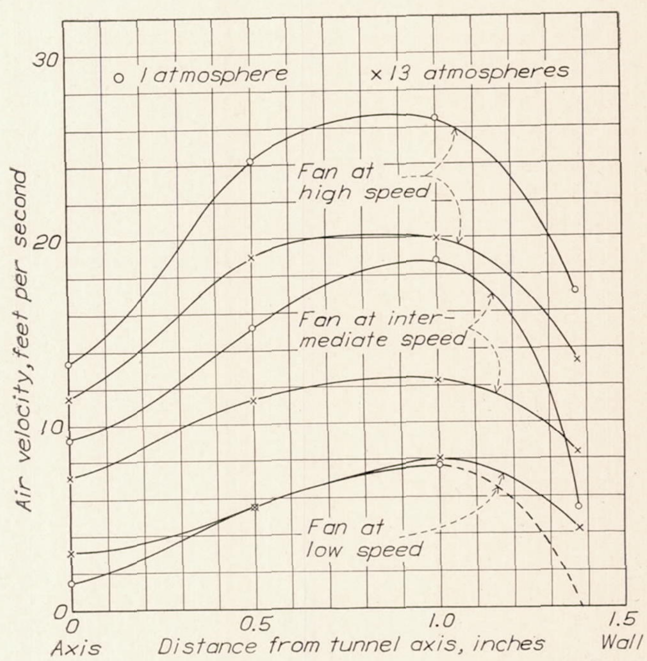

FIGURE 2.—Velocity survey of spray chamber, for various fan speeds.

In all cases the air in the spray chamber was at room temperature, so that no appreciable vaporization of the fuel occurred during the time the photographs were being taken.

ANALYSIS

As early as 1925 Kuehn (reference 11) showed that the penetration obtained with hydraulic injection in internal-combustion engines was the result of the action of the fuel spray as a whole and not as separate drops. The more recent experiments of Lee and Spencer (reference 12) and the analytical work of Castleman (reference 13) have shown that the disintegration of a fuel jet is a gradual process, and that the jet is sometimes continuous for an inch or more from the nozzle. Continuity of the jet is particularly persistent at low air densities. The individual drops lose most of their kinetic energy during formation; thus, after cut-off, further distribution is a slow process unless some auxiliary means is employed to assist the mixing. Tests conducted by DeJuhasz (reference 14), Lee (references 7 and 15), and Rothrock and Waldron (reference 10) indicate that the mixture formation that is attained in a quiescent combustion chamber would be impossible were it not for the vaporization of the fuel drops both before and during combustion.

The effect of air movement on the distribution of the fuel spray can be estimated in the following manner:

Let m, mass of the fuel drop.
- a, acceleration of the drop caused by the moving air.
- ψ, coefficient of resistance of the air to movement of the drop.
- ρ_a, density of the air.
- ρ_f, density of the fuel.
- r, radius of the fuel drop.
- v_a, velocity of the air with respect to the fuel drop.
- v_b, velocity of the air.
- v_f, velocity of the fuel drop.

The resistance offered by the drop to the moving air is at all times equal to the product of the mass of the drop and its acceleration, or

$$ma = \psi \rho_a v_a^2 \pi r^2 \qquad (1)$$

but

$$m = \frac{4}{3} \pi r^3 \rho_f \qquad (2)$$

Substituting and solving for a:

$$\begin{aligned} a &= K v_a^2 \\ &= K(v_b - v_f)^2 \end{aligned} \qquad (3)$$

in which

$$K = \frac{3}{4} \psi \frac{\rho_a}{\rho_f} \frac{1}{r}$$

Substituting for a its equivalent, $\frac{dv_f}{dt}$, in which t is the time measured from the instant at which the velocity of the drop was zero, and integrating:

$$v_f = \frac{v_b^2 K t}{1 + v_b K t} \qquad (4)$$

The velocity v_f is equal to $\frac{ds}{dt}$, in which s is the distance the drop has traveled in the time t. Substituting and again integrating:

$$s = v_b t - \frac{1}{K} \ln(1 + v_b K t) \qquad (5)$$

which expresses the distance traversed by the drop in terms of the velocity of the air and of the time. In the integration the coefficient of resistance has been considered as a constant, although actually the coefficient varies with the velocity. However, the assumption is justified for a first approximation. The values of ψ are determined for the Reynolds Number of the drop under the conditions of air velocity, density, and viscosity, and of the drop size. The Reynolds Number is equal to $\frac{2 v_a r \rho_a}{\mu}$, in which μ is the vicosity of the air.

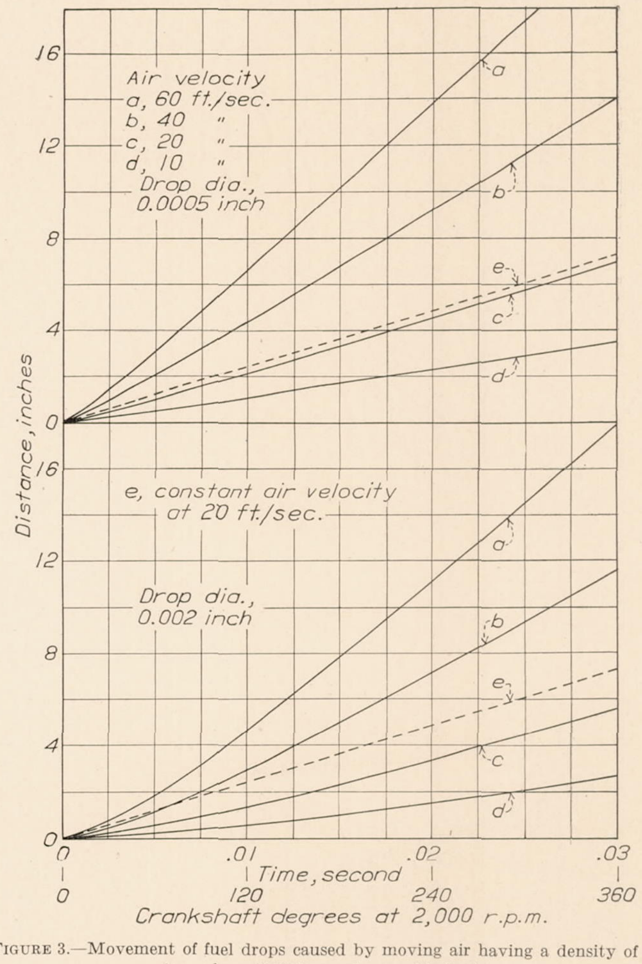

FIGURE 3.—Movement of fuel drops caused by moving air having a density of 1 atmosphere (0.0765 pound per cubic foot).

Curves of Reynolds Number against coefficients of resistance may be found in reference 16.

There are two extreme cases to be considered in the present analysis: First, the conditions in the spark-ignition engine in which the fuel is sprayed into air at a density of approximately one atmosphere; second, the conditions in the compression-ignition engine in which the fuel is sprayed into air at a density of 10 to 17 atmospheres (0.765 to 1.3 pounds per cubic foot). In the spark-ignition engine the fuel is, in general, injected during the intake stroke, starting at approximately 70° after top center (reference 17). The combustion is started approximately 30° before top center, giving a mixing time of approximately 260 crank degrees. With the fuel injected directly into the engine cylinder, the volume through which the fuel is to be distributed consists of the displacement volume plus the clearance volume. It is very difficult to design an injection nozzle that will direct the fuel to all parts of this space; the greater part of the mixing must therefore be accomplished by vaporization and by air flow. Lee has shown in reference 15 that, with hydraulic injection under conditions similar to those in the present tests, by far the greatest number of fuel drops have diameters of 0.0005 inch or less, but that the drops with diameters from 0.0015 to 0.0025 inch contain

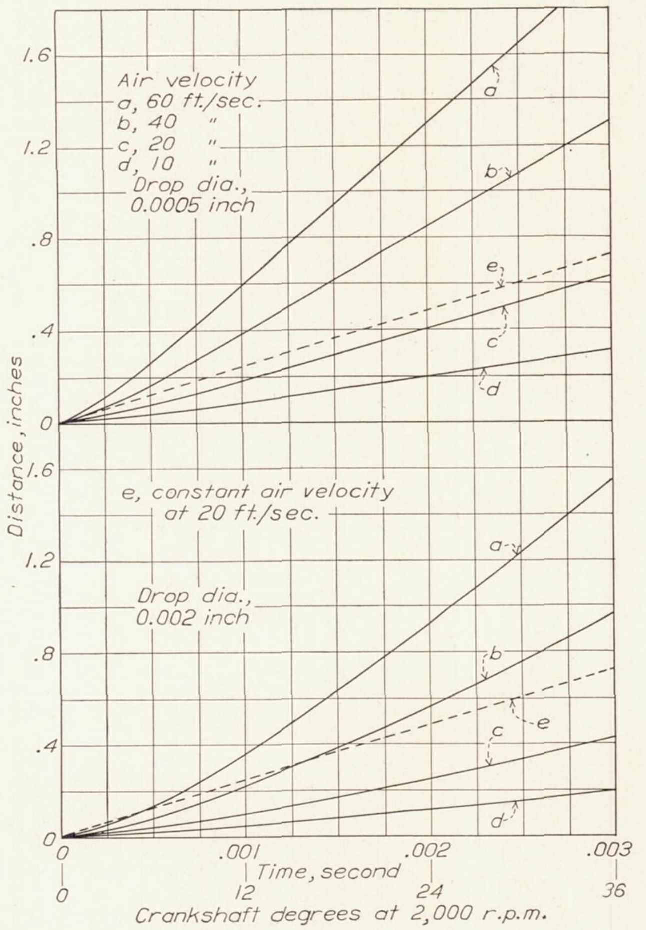

FIGURE 4.—Movement of fuel drops caused by moving air having a density of 13 atmospheres (0.99 pound per cubic foot).

more than half the weight of the fuel charge. Some curves computed from equation (5), showing the displacement of fuel drops caused by moving air, are given in figures 3 and 4. In each figure, curves are given for drop diameters of 0.0005 and 0.002 inch, with air velocities from 10 to 60 feet per second. The two extreme cases were represented by assuming an air density of 1 atmosphere for figure 3, and 13 atmospheres for figure 4 (0.0765 and 0.99 pound per cubic foot, respectively). The computations for figure 4 were made for a time interval of one tenth that for figure 3 because the time available for fuel distribution in the compression-ignition engine is approximately one tenth that in the spark-ignition engine.

The curves show that the total distance a drop is moved by the air in a given time varies approximately as the air velocity and that, after a short accelerating period, the drops attain a velocity very nearly equal to that of the air. The dashed line in each group of curves represents the distance traveled by the air at a constant velocity of 20 feet per second. A comparison between the slopes of the dashed line and the curve for the movement of a drop in air at the same velocity determines the amount of slip between the drop and the air. As would be expected, this slip decreases with decreasing drop size and with increasing air density. In the case of a 0.002-inch drop in air with a velocity of 60 feet per second, the denser air carries the drop 1.7 times as far in 0.003 second as air at atmospheric density. Of course, the chief factor tending to compensate for the shortness of the time available for the distribution of the fuel in the compression-ignition engine is the small size of the chamber into which the fuel is injected. From these curves it may be concluded that with both spark ignition and compression ignition the movement of the fuel drops produced by air having a velocity of 20 feet per second or more should materially aid in mixing the liquid fuel and the air after injection cut-off. It must be remembered that during the injection of the fuel, even high air velocities do not have much effect on the core of the spray, which contains most of the fuel charge, although air movement will deflect the envelop, which is composed of slowly moving drops (references 2, 4, and 14).

TEST RESULTS

Effect of air flow and air density on fuel distribution.—Figure 5 is a series of photographs taken during preliminary experiments, showing the distribution of a spray from a 0.020-inch orifice when the fuel was injected at a pressure of 4,000 pounds per square inch into still air at a density of 13 atmospheres. In the first exposure the spray has struck the opposite end of the spray chamber and has been partly reflected. Following cut-off of injection the spray began to lose its kinetic energy, as shown by its tendency to break up. The successive exposures show that the fuel particles slowly traversed the chamber in the direction of the spray travel and that at the same time the shape of the spray, formed by the drops torn from the core and left suspended in the air, lost its definite outline and took on a wavy appearance. The fuel at the end of the chamber continued to roll back toward the injection nozzle. At 0.038 second after cut-off the spray had traveled back to slightly beyond the middle of the chamber. The photograph shows that any air motion set up by the spray has very little effect in distributing the fuel throughout the chamber, and

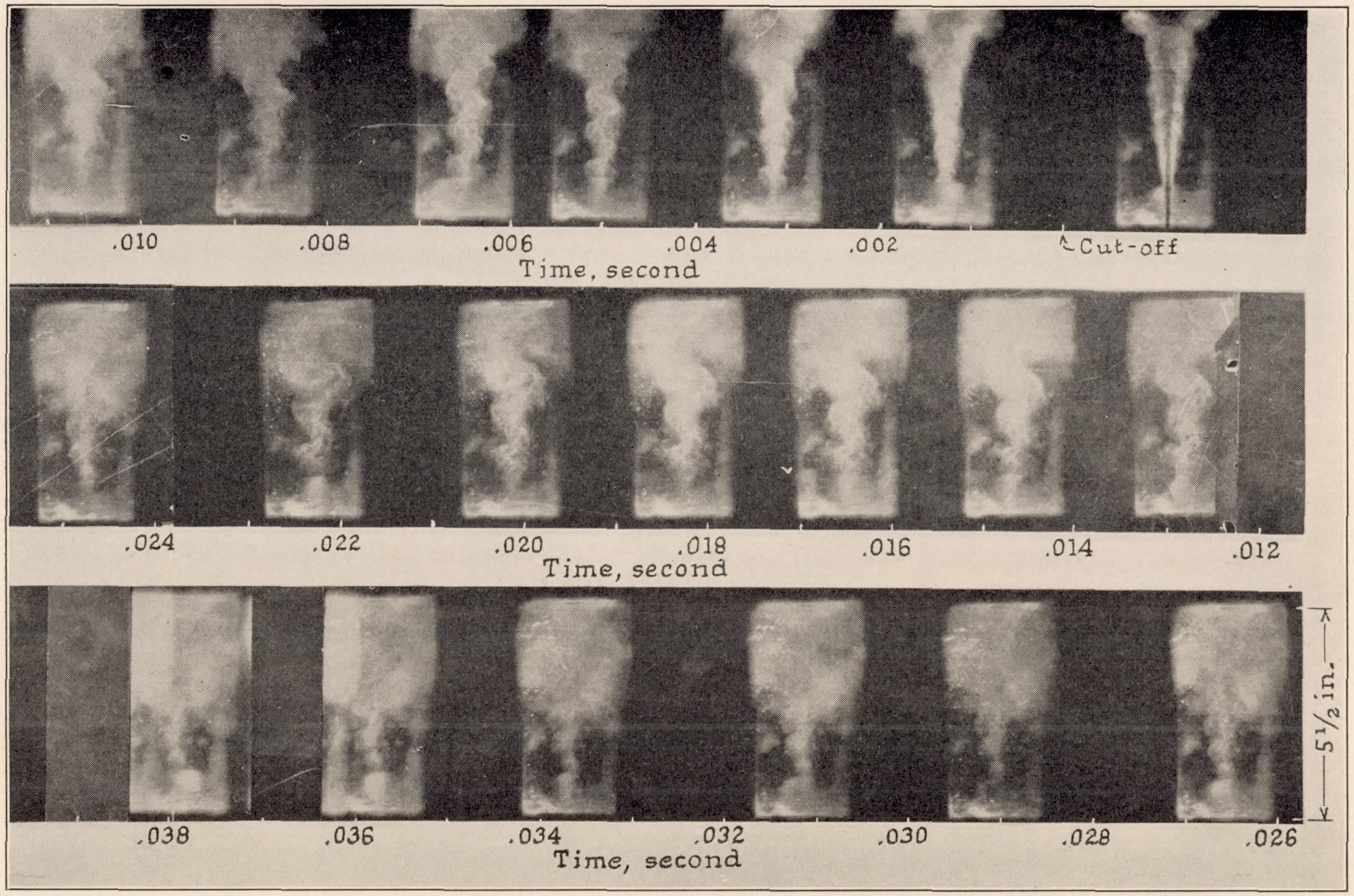

FIGURE 5.—Distribution of fuel in chamber after spray cut-off. Air density, 13 atmospheres (0.99 pound per cubic foot). Still air. Injection pressure, 4,000 pounds per square inch. Orifice diameter, 0.020 inch. No fan or honeycomb in chamber.

that without air flow the distribution of the liquid fuel is very poor. The lack of distribution is further emphasized when it is realized that the interval of 0.038 second represents 456 crankshaft degrees at 2,000 revolutions per minute.

After all the fuel particles have lost most of their velocity relative to the air, there is no longer a distinct core, and the distribution of the fuel within the spray is more uniform. This change in the structure of fuel sprays following injection cut-off is shown by figure 6.

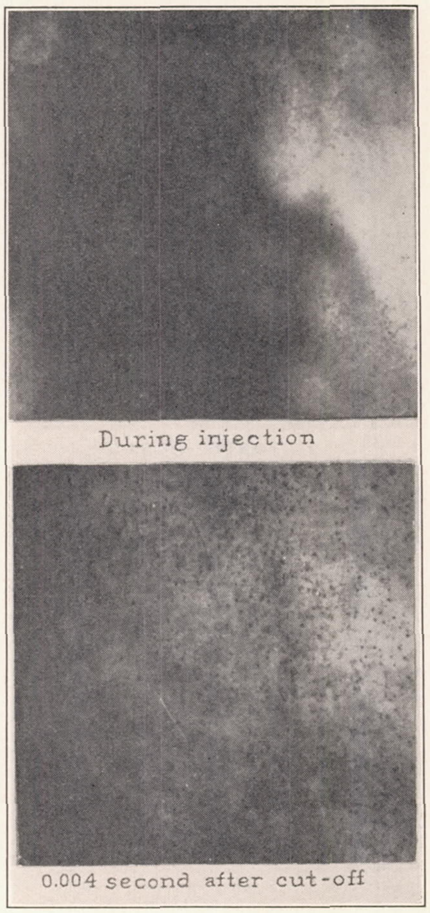

FIGURE 6.—Photomicrographs, 10 diameters, taken at center of spray during injection and at 0.004 second after injection cut-off. Air density, 13 atmospheres (0.99 pound per cubic foot). Still air. Injection pressure, 4,000 pounds per square inch. Orifice diameter, 0.020 inch.

This figure is unlike all other spray photographs shown in this report, for the illuminating spark discharge was directly behind the spray so that the fuel particles appear in silhouette. The upper photomicrograph was taken during the injection period and shows the dense spray core on the left and part of the envelop on the right. In the lower photomicrograph, taken at 0.004 second after injection cut-off, the core has disappeared and the distribution of the fuel has become more uniform.

When the fuel was injected into still air at a density of one atmosphere (fig. 7a) the distribution was even poorer than when the fuel was injected into denser air. The spray traveled the length of the chamber and impinged on the honeycomb in front of the fan with considerable velocity, but less of the spray was reflected. The reflected spray showed little tendency to continue back across the chamber, most of the fuel remaining near the honeycomb.

When an air velocity of 8 feet per second was directed against the spray (fig. 7b) the core again traversed the chamber and impinged on the honeycomb. In this case, however, the moving air blew the spray back toward the discharge orifice, though the motion was comparatively slow and some of the spray always remained around the honeycomb. In the last exposure the spray appears to be fairly well distributed throughout the chamber. The time required for the spray to be blown from the honeycomb to the discharge orifice was about 0.013 second, or approximately 150 crankshaft degrees at 2,000 revolutions per minute. This time interval is within the permissible time for mixing in a 4-stroke spark-ignition engine in which the fuel is injected during the intake stroke. When the velocity was increased to 19 feet per second (fig. 7c) the time required for the fuel to be blown across the chamber decreased slightly and the fuel was blown away from the honeycomb so that there was very little fuel visible in the chamber in the last exposure. When the velocity was further increased to 27 feet per second (fig. 7d) the fuel was blown across the chamber still more rapidly, a time of 0.008 second being sufficient. Figure 7d plainly, and others to a lesser degree, show a stream of large drops issuing from the nozzle long after the cut-off. These drops were a result of dribbling from the open nozzle, and were unavoidable because of the characteristics of the injection system used. Note that the large drops are quite unaffected by the moving air, showing that the fuel must be well broken up before air at low velocity can affect the distribution.

The effect of air flow with an air density of 5 atmospheres is shown in figures 8 and 9. Comparison of figure 8 with figure 7 shows that the moving air at a density of 1 atmosphere apparently had more effect on the spray than the air at a density of 5 atmospheres. The apparent discrepancy is explained by a consideration of the effects of air density on the penetration and rate of disintegration of the spray. As has been shown in the reports previously referred to, increasing the air density decreases both the maximum penetration and the rate of penetration of the spray and increases the rate of spray disintegration. The distance between the discharge nozzle and the honeycomb for the conditions under which these photographs were taken was 3.5 inches, a distance considerably less than that required for complete disintegration of the jet at atmospheric air density. Therefore, with the air at a density of one atmosphere the spray column struck the honeycomb with considerable force and, as the figure shows, the remainder of the column following cut-off also traversed the chamber and impinged on the honey-

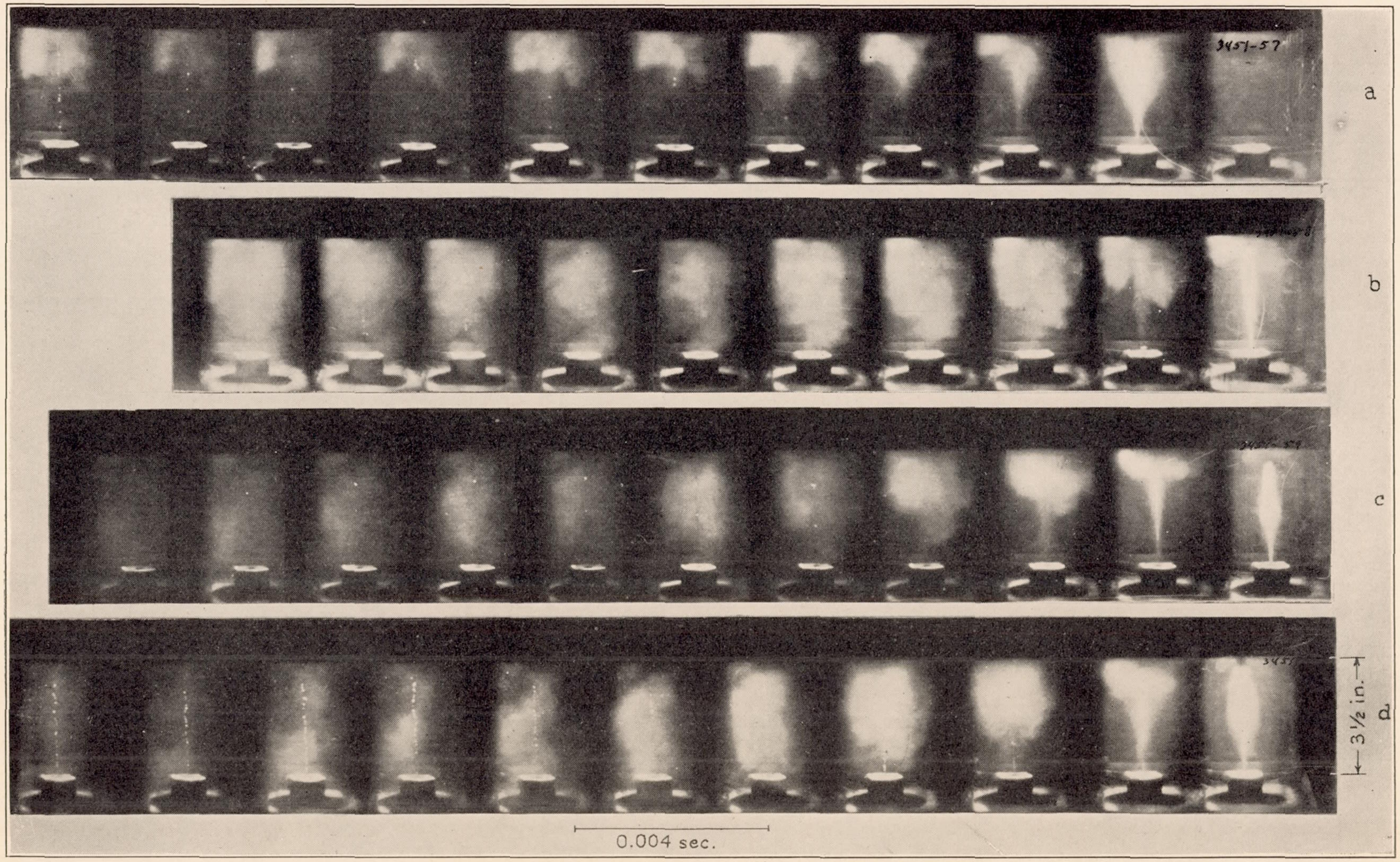

FIGURE 7.—Effect of air flow on fuel distribution. Air density, atmospheric (0.0765 pound per cubic foot). Air velocities: (a) no air flow, (b) 8 feet per second, (c) 19 feet per second, (d) 27 feet per second. Injection pressure, 4,000 pounds per square inch. Orifice diameter, 0.020 inch.

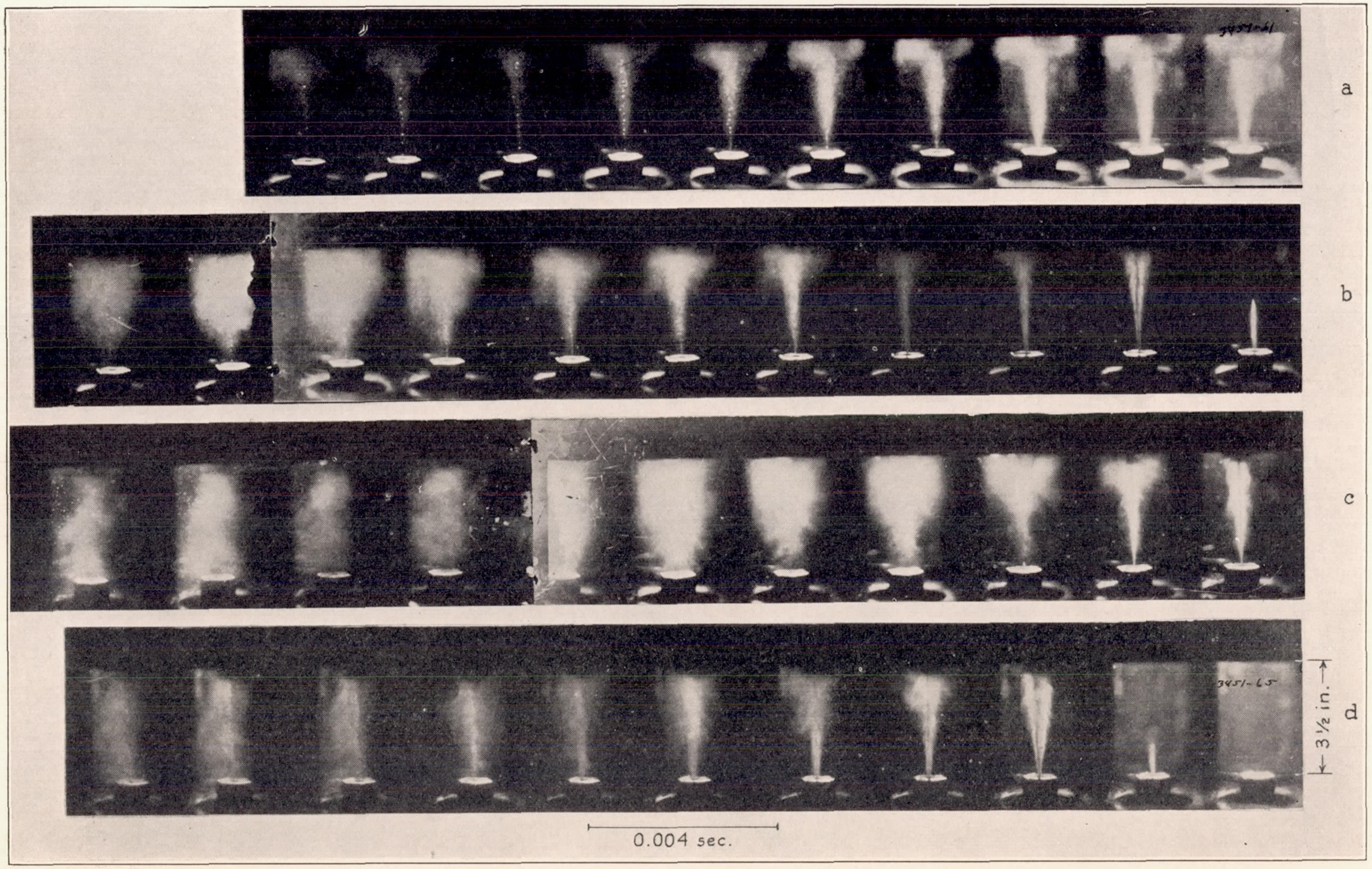

FIGURE 8.—Effect of air flow on fuel distribution at chamber air density of 5 atmospheres (0.38 pound per cubic foot). Air velocities: (a) no air flow, (b) 8 feet per second, (c) 19 feet per second, (d) 25 feet per second. Injection pressure, 4,000 pounds per square inch. Orifice diameter, 0.020 inch.

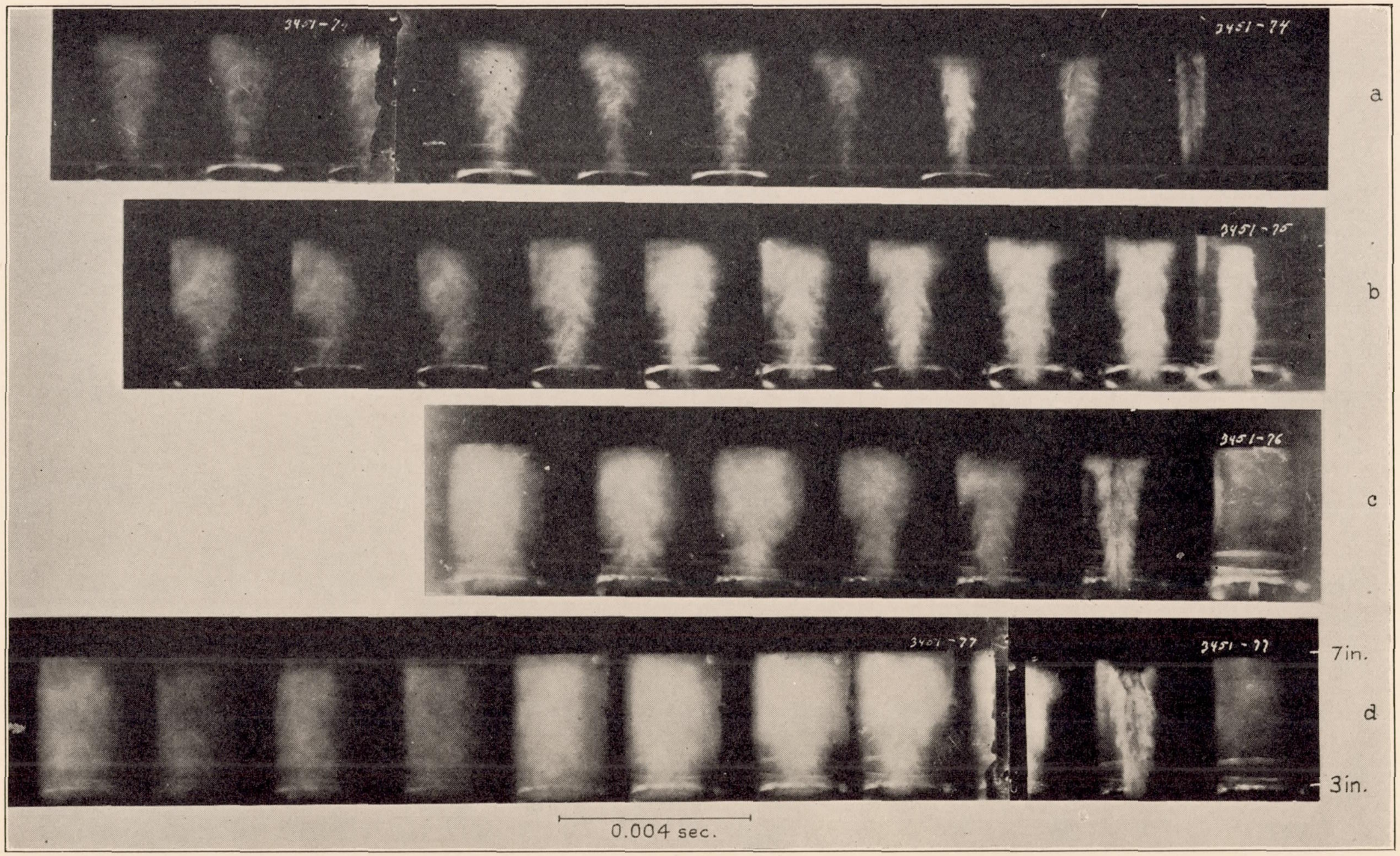

FIGURE 9.—Effect of air flow on fuel distribution at chamber air density of 5 atmospheres (0.38 pound per cubic foot). Air velocities: (a) no air flow, (b) 8 feet per second, (c) 19 feet per second, (d) 25 feet per second. Injection pressure, 4,000 pounds per square inch. Orifice diameter, 0.020 inch. Nozzle at outer end of chamber.

comb. Consequently, the fuel caught up by the moving air was either what had been torn from the spray previous to impingement or that caught up at the time of impingement. As a result, both the number and size of the fuel drops shown in the air stream in figure 7 were probably smaller than those shown in figure 8 and, consequently, the air at the lower density appears to provide better distribution than that at the higher density. In general, the figures show that the fuel drops are blown back across the chamber at increasingly shorter time intervals as the air velocity is increased. Because of poor lighting, figure 8d does not show the fine cloud of mist as well as the other photographs.

In the test for which the results are shown in figure 9 the injection nozzle was placed in the tubular section of the spray chamber 7 inches from the honeycomb. As before, the spray impinged on the honeycomb but with considerably less intensity than with the nozzle 3.5 inches from the honeycomb. In still air the spray retains its shape for the duration of the exposures and is seen to diffuse slowly, but the final distribution is rather poor. With an air velocity of 8 feet per second the spray is considerably widened but the velocity is not sufficient to blow the fuel back through the chamber within the time shown. With a velocity of 19 feet per second the spray is blown back so that the fuel is fairly well distributed in the last exposure. With the highest velocity, good distribution is obtained in about 0.008 second; from then on the fuel is apparently blown out of the cylindrical portion of the spray chamber. A comparison of this figure with the preceding one shows that the increased distance permits more nearly complete disintegration of the fuel spray and that as a result the moving air comes in contact with more of the fuel and consequently provides better mixing. A test was made with the air at atmospheric density and with the nozzle 7 inches from the honeycomb. Unfortunately, sufficient detail could not be obtained for reproduction. The photographs showed that the spray struck the honeycomb with considerable velocity so that, in general, the results were similar to those shown in figure 7.

With still air (fig. 10a) at a density of 9 atmospheres and the nozzle 3.5 inches from the honeycomb the spray did not rebound from the honeycomb to any great extent; also, its outline is clearly visible in all the exposures. At an air velocity of 7 feet per second the moving air blew some of the fuel partly back across the chamber, although not to the extent that was apparent with an air density of 5 atmospheres. When the air velocity was increased to 18 feet per second the fuel was blown completely back across the chamber and the spray outline was destroyed. With an air velocity of 23 feet per second the distribution was still further improved. The photograph shows a certain unevenness in the air flow, so that more fuel is visible to the left of the core than to the right. This unevenness shows in all the photographs in which the moving air picked up the fuel before it impinged on the honeycomb.

With the injection nozzle mounted 7 inches from the honeycomb (fig. 11) the spray again penetrated the length of the chamber and impinged on the honeycomb. As the air velocity was increased the distribution was improved until at a velocity of 25 feet per second the spray was blown back to the opposite end of the chamber in about 0.008 second. In general, the photographs show that once the spray has disintegrated it will be distributed fairly rapidly with moderate air velocities.

The effect of air flow on the distribution of the spray at an air density of 13 atmospheres is shown in figures 12 and 13. The first photograph in figure 12 is similar to figure 5, which has already been discussed. When the spray was directed counter to an air velocity of 8 feet per second there was little mixing of the fuel and air except as shown in the last 2 exposures. An air velocity of 12 feet per second considerably improved the distribution and with a velocity of 20 feet per second the fuel was blown completely away from the end of the chamber opposite the injection nozzle. The air density used in this test is comparable with that used in compression-ignition engines. The photographs of figure 12 show that although moderate air velocities will assist in the distribution, they should not be depended upon entirely, but should be used to supplement distribution as obtained through correct design of the injection nozzle.

With the injection nozzle 7 inches from the honeycomb (fig. 13) the spray in the still air struck the honeycomb but was moving at a low velocity at the time of impingement. With the air in motion, considerable distribution of the fuel resulted and the distribution was improved as the air velocity was increased up to the maximum of 20 feet per second. The photographs show that if the permissible penetration of the fuel spray is such that the disintegration of the core can be completed before the start of combustion, moderate air velocities will result in considerable distribution of the liquid fuel spray. Of course, in small high-speed compression-ignition engines, a distance of 7 inches is greater than is usually employed for the maximum distance of spray penetration. In this case, smaller discharge-orifice diameters can be used to obtain a more rapid disintegration of the spray core.

In some cases it was possible to determine the velocity of the spray movement toward the nozzle after injection cut-off by selecting parts of the spray having distinctive appearances, and measuring the distances they moved between photographic exposures. In a majority of cases the part of the spray selected for measurement was that part which was first reflected from the farther end of the chamber. In still air the

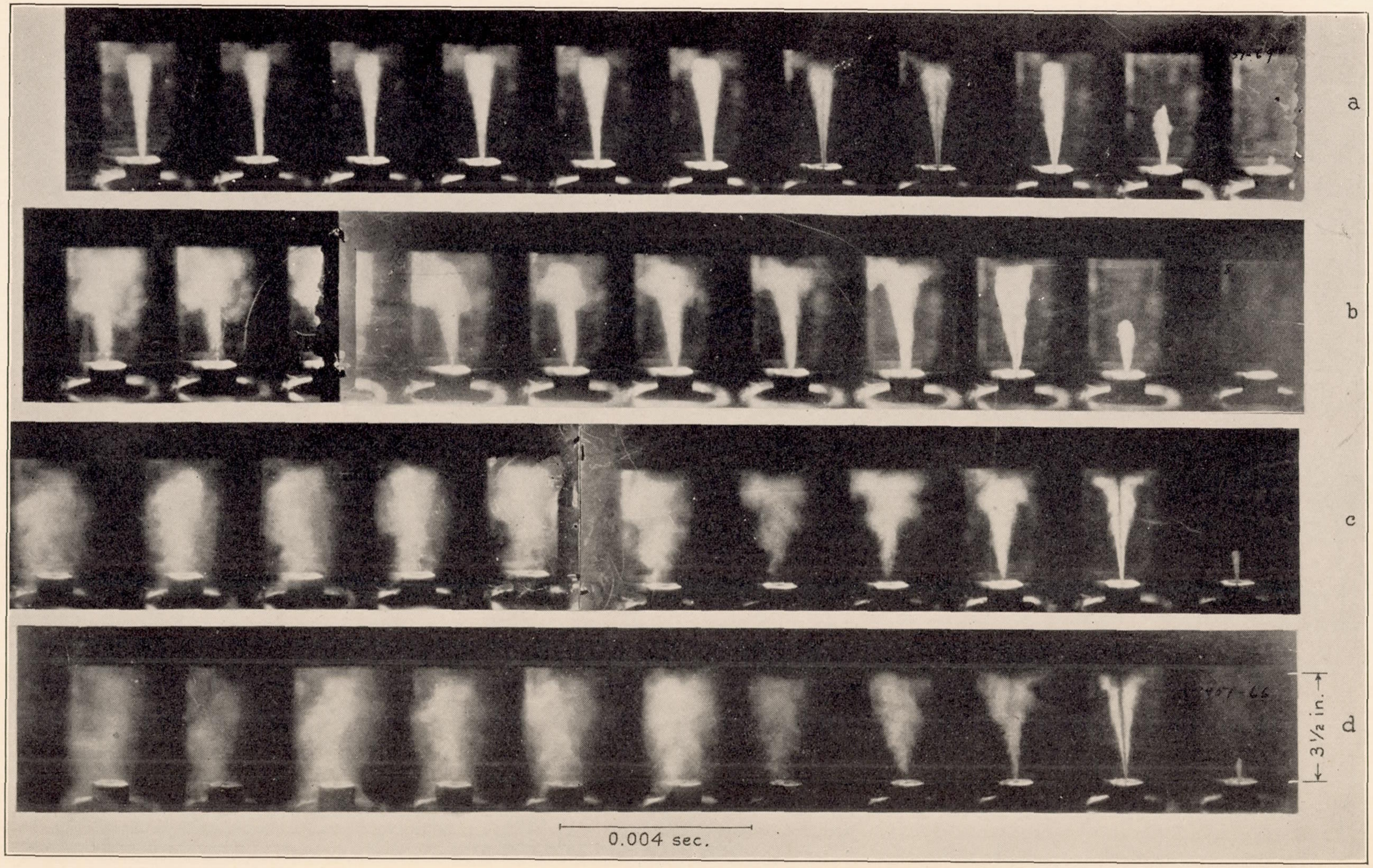

FIGURE 10.—Effect of air flow on fuel distribution at chamber air density of 9 atmospheres (0.69 pound per cubic foot). Air velocities: (a) no air flow, (b) 7 feet per second, (c) 18 feet per second, (d) 23 feet per second. Injection pressure, 4,000 pounds per square inch. Orifice diameter, 0.020 inch.

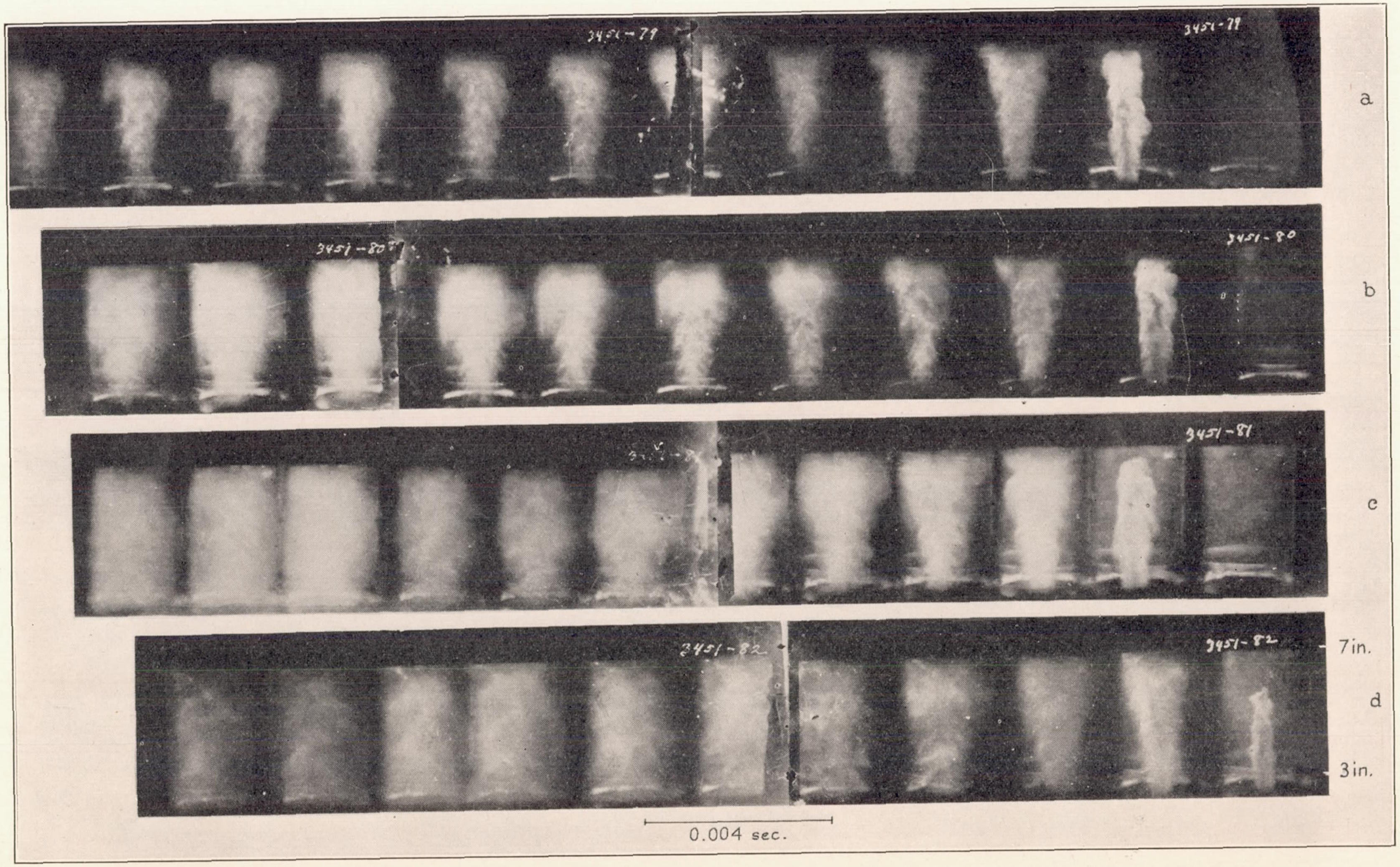

FIGURE 11.—Effect of air flow on fuel distribution at chamber air density of 9 atmospheres (0.69 pound per cubic foot). Air velocities: (a) no air flow, (b) 7 feet per second, (c) 18 feet per second, (d) 23 feet per second. Injection pressure, 4,000 pounds per square inch. Orifice diameter, 0.020 inch. Nozzle at outer end of chamber.

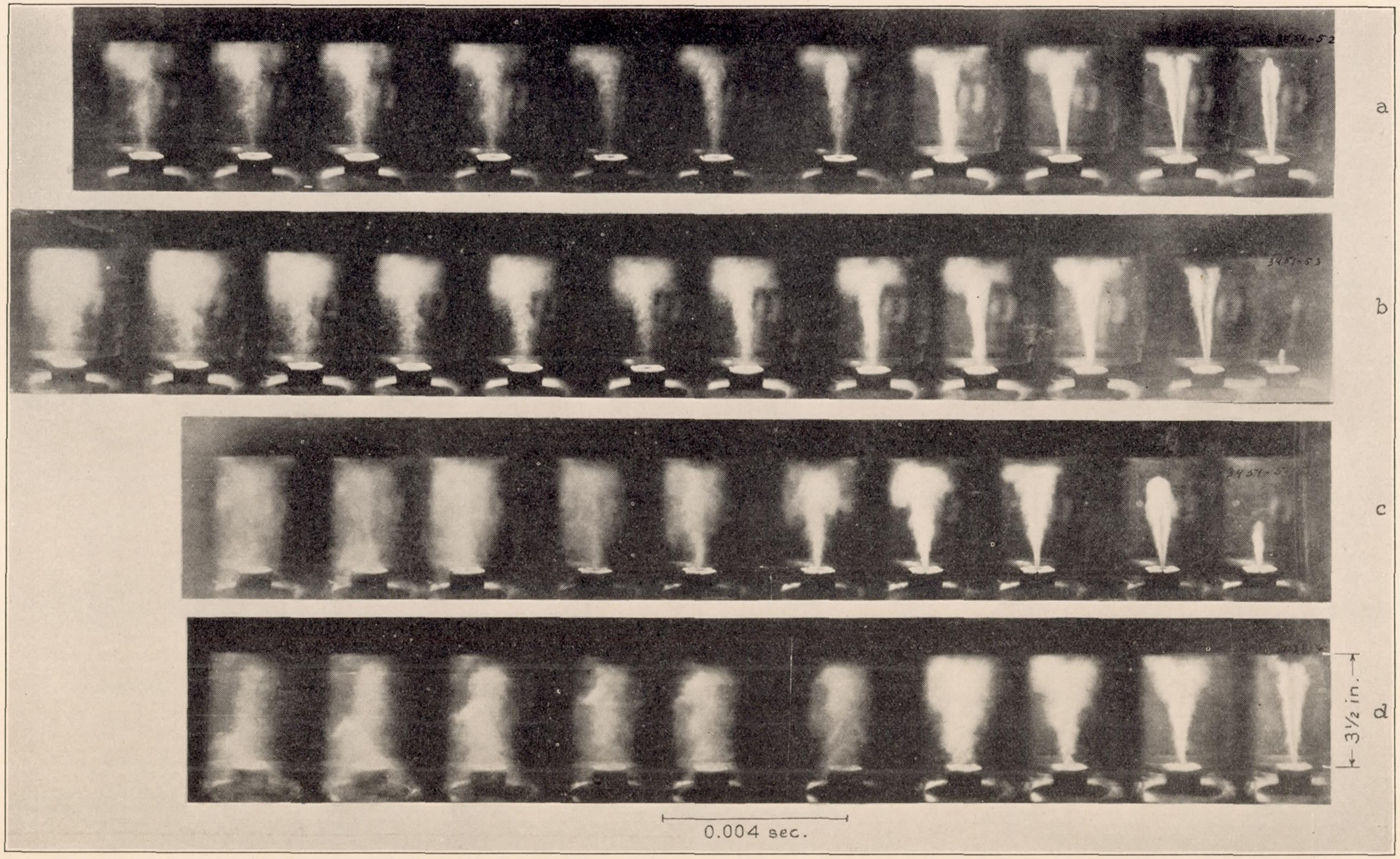

FIGURE 12.—Effect of air flow on fuel distribution at chamber air density of 13 atmospheres (0.99 pound per cubic foot). Air velocities: (a) no air flow, (b) 8 feet per second, (c) 12 feet per second, (d) 20 feet per second. Injection pressure, 4,000 pounds per square inch. Orifice diameter, 0.020 inch.

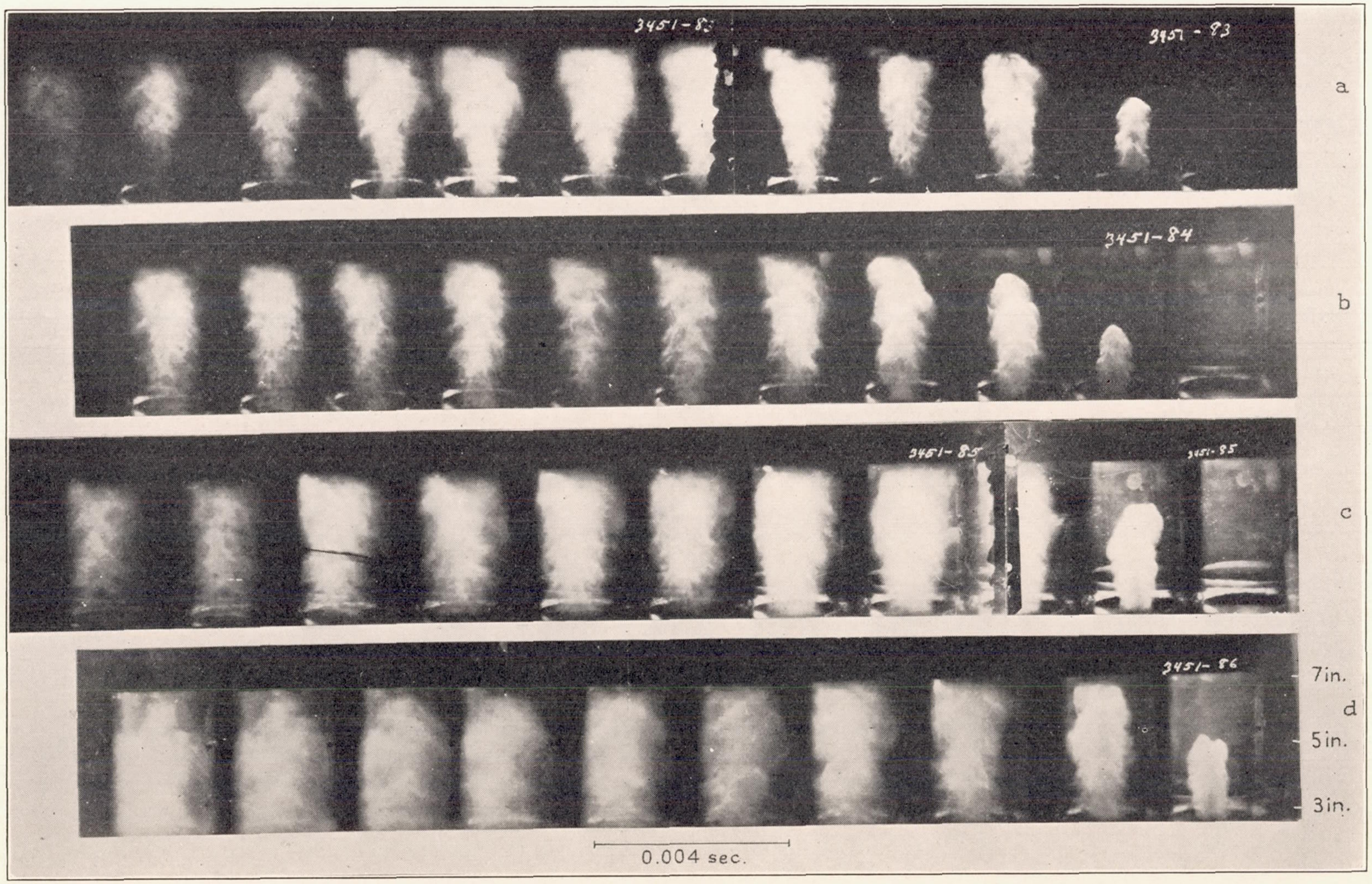

FIGURE 13.—Effect of air flow on fuel distribution at chamber air density of 13 atmospheres (0.99 pound per cubic foot). Air velocities: (a) no air flow, (b) 8 feet per second, (c) 12 feet per second, (d) 20 feet per second. Injection pressure, 4,000 pounds per square inch. Orifice diameter, 0.020 inch. Nozzle at outer end of chamber.

velocity of these reflected spray tips was found to be about 3.5 feet per second for an injection pressure of 4,000 pounds per square inch and at densities of either 1 or 13 atmospheres. In moving air the reflected spray tips often had velocities greater than the air velocities as measured with the pitot-static tube, and sometimes even exceeded the sum of the air velocity and the velocity of reflection as measured in still air. These latter cases were probably caused by local air velocities near the fan which were greater than the average air velocity. In cases where it was possible to measure parts of the spray which had not been reflected from the end of the chamber, the spray velocities were found to be less than the measured air velocities by amounts approximating those shown by the estimated curves of figures 3 and 4 for drops of 0.002-inch diameter.

Effects of injection pressure on fuel distribution.—The effects of injection pressure on the distribution are shown in figures 14 to 17, inclusive. Figure 14 shows that an increase in the injection pressure made little change in the distribution. In each case the spray impinged against the honeycomb and such variations as might have occurred because of differences in the rates of penetration or maximum penetration were consequently lessened. However, the lowest injection pressure does show that because of its lower velocity more of the fuel was left in the path of the core following injection cut-off and that as a result the air picked the spray up more rapidly than was the case with the two higher pressures. With the injection nozzle mounted 7 inches from the honeycomb (fig. 15), the spray at each injection pressure had lost most of its velocity by the time it had reached the honeycomb, so that the effects of the spray disintegration during injection caused by increasing the injection pressure are shown.

The use of an 0.008-inch orifice (fig. 16) caused a more rapid disintegration of the spray and the formation of smaller drops of the liquid fuel (references 12 and 15). The fuel was picked up more rapidly than was the case with the 0.020-inch orifice. The higher injection pressures caused more rapid mixing of the fuel and air, probably because of more rapid jet disintegration. With the nozzle mounted 7 inches from the honeycomb (fig. 17), the differences in the maximum penetrations at the different injection pressures become apparent.

Effect of chamber depth on fuel distribution.—In the tests on the effect of chamber depth, a dummy chamber similar to that employed by Spanogle, Hicks, and Foster (reference 8) was placed in the spray chamber. The open space in the model was 3.5 inches long, 2.5 inches wide, and 3.0 inches deep. Two glass plates could be inserted, one on each side of the nozzle, to reduce the open space to a depth of 1 inch. Figure 18 shows photographs of sprays injected into this chamber, with and without the glass inserts. With the shallow chamber the spray did not rebound more than 2 inches from the end of the chamber within the time investigated. However, when the glass inserts were removed, the fuel rebounded and filled the entire space. No provisions for air flow were made with this set-up, the fan and honeycomb having been removed from the chamber. The most probable explanation of the different action of the sprays in the two above-mentioned cases is that the glass inserts interfered with the normal expansion of the spray and with its reflection from the end of the chamber. With the glass inserts in place, the chamber depth was reduced to less than the normal diameter of the spray at a distance of 3.5 inches from the nozzle, so that the spray could be reflected only into the narrow spaces between the plates on either side of the main spray.

Fuel distribution with high-dispersion nozzles.—It is evident from the foregoing data that to secure reasonably good distribution after cut-off of the fuel in the liquid phase with low air velocities, the nozzle must be of a type to give high dispersion. Such nozzles produce sprays that have a large amount of surface exposed to the air and have a high rate of spray disintegration. This combination affords the best opportunity for uniform distribution. Figure 19 shows sprays from two such nozzles. The multiorifice nozzle has a 0.020-inch orifice in the center, two 0.012-inch orifices at 18° from the center, and two 0.006-inch orifices at 38° from the center. The impinging-jets nozzle has four 0.030-inch orifices in two planes at right angles to each other. Each orifice is at 37° to the nozzle axis. The center lines of the orifices intersect at a point 0.040-inch from the orifices. As a result of this arrangement of orifices the spray had a core of large diameter, but disintegration of the core started at the point of impingement of the sprays. When the sprays from either nozzle were injected into still air the fuel proceeded slowly across the chamber after injection cut-off. When air moving at a velocity of 20 feet per second was directed counter to the sprays the fuel was rapidly distributed throughout the chamber. This rapid distribution was particularly true of the spray from the multiorifice nozzle. The results show that if care is used in designing the discharge nozzle to distribute the fuel to the air, the distribution can be materially assisted by air flow at moderate velocities.

CONCLUSIONS

The following conclusions are drawn from the test data and the analysis presented:

1. In fuel-injection engines that have quiescent combustion chambers and in which ignition takes place a considerable time interval after the end of injection, most of the fuel charge will tend to penetrate to the side of the chamber opposite the injection nozzle and will thus be concentrated in one part of the combustion

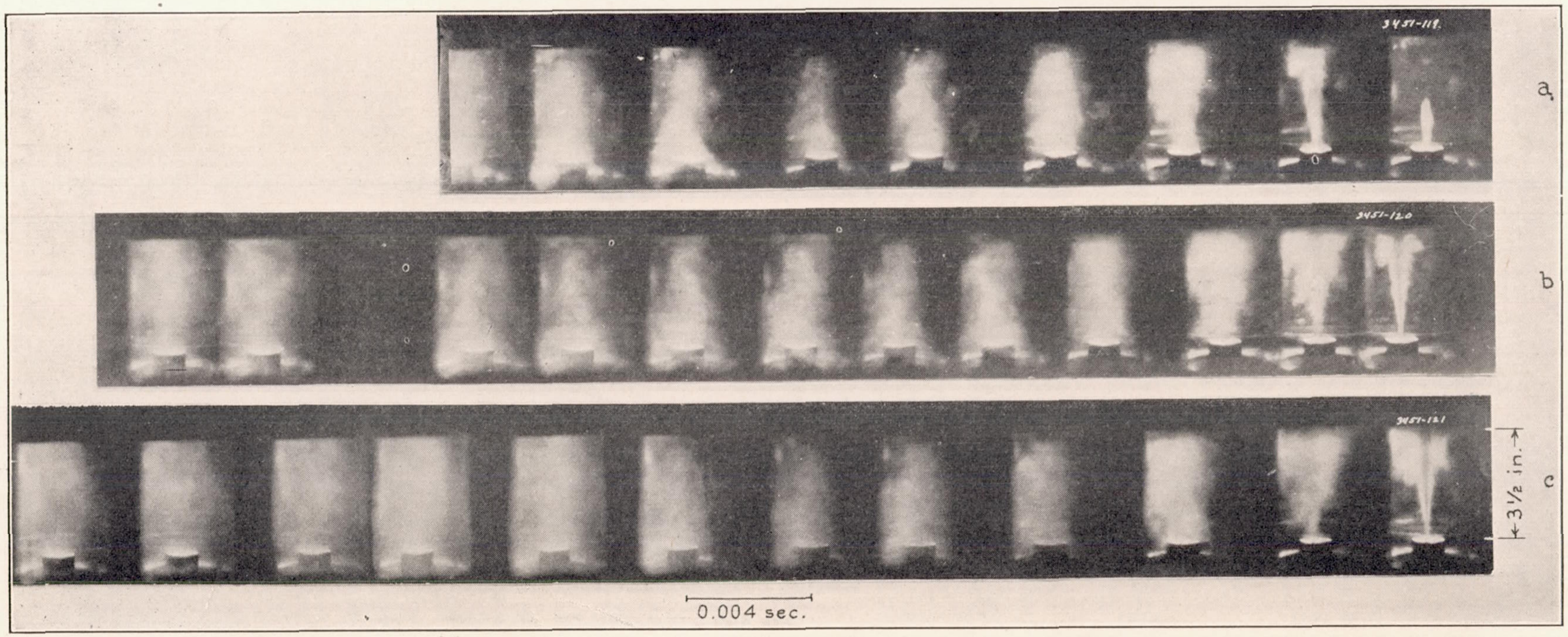

FIGURE 14.—Effect of injection pressure on fuel distribution, with air flow. Air density, 13 atmospheres (0.99 pound per cubic foot). Air velocity, 20 feet per second. Injection pressures: (a) 2,000 pounds per square inch, (b) 4,000 pounds per square inch, (c) 6,000 pounds per square inch. Orifice diameter, 0.020 inch.

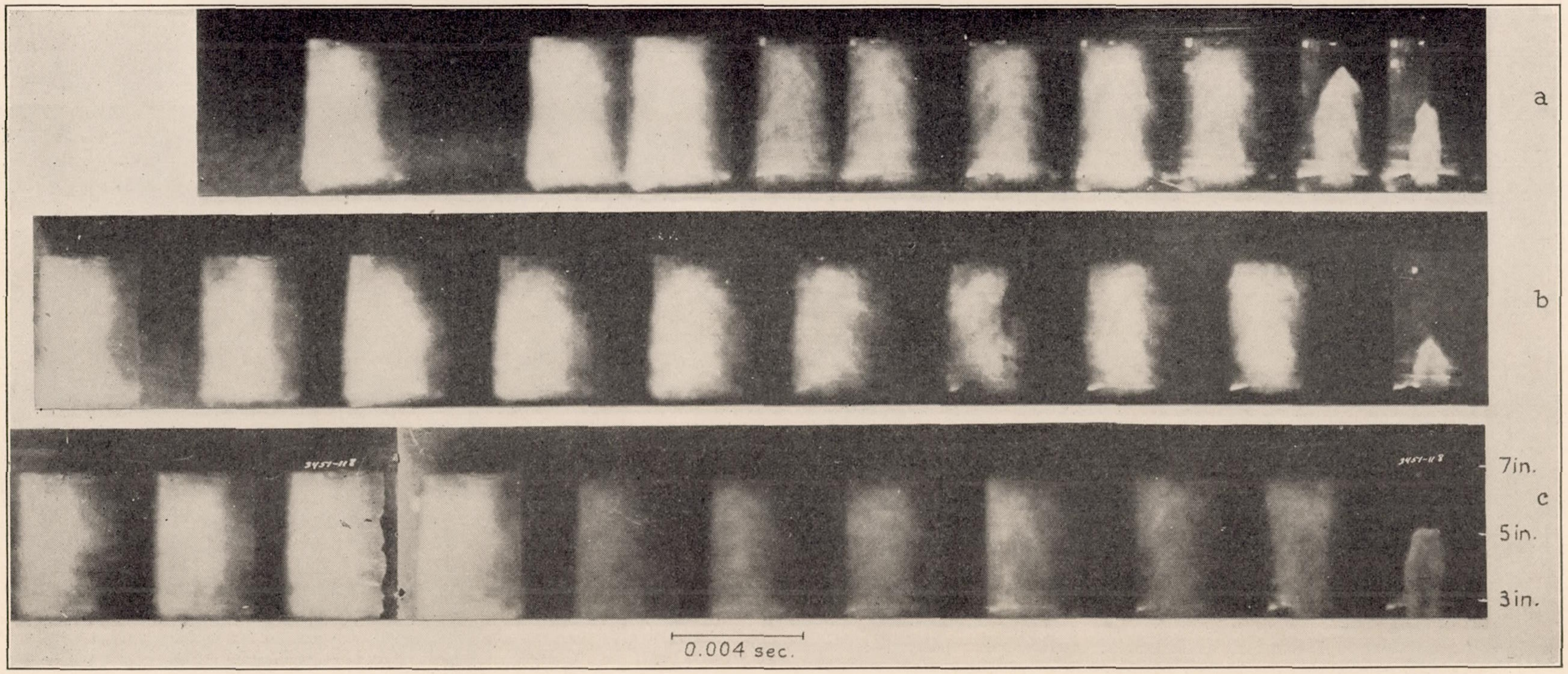

FIGURE 15.—Effect of injection pressure on fuel distribution, with air flow. Air density, 13 atmospheres (0.99 pound per cubic foot). Air velocity, 20 feet per second. Injection pressures: (a) 2,000 pounds per square inch, (b) 4,000 pounds per square inch, (c) 6,000 pounds per square inch. Orifice diameter, 0.020 inch. Nozzle at outer end of chamber.

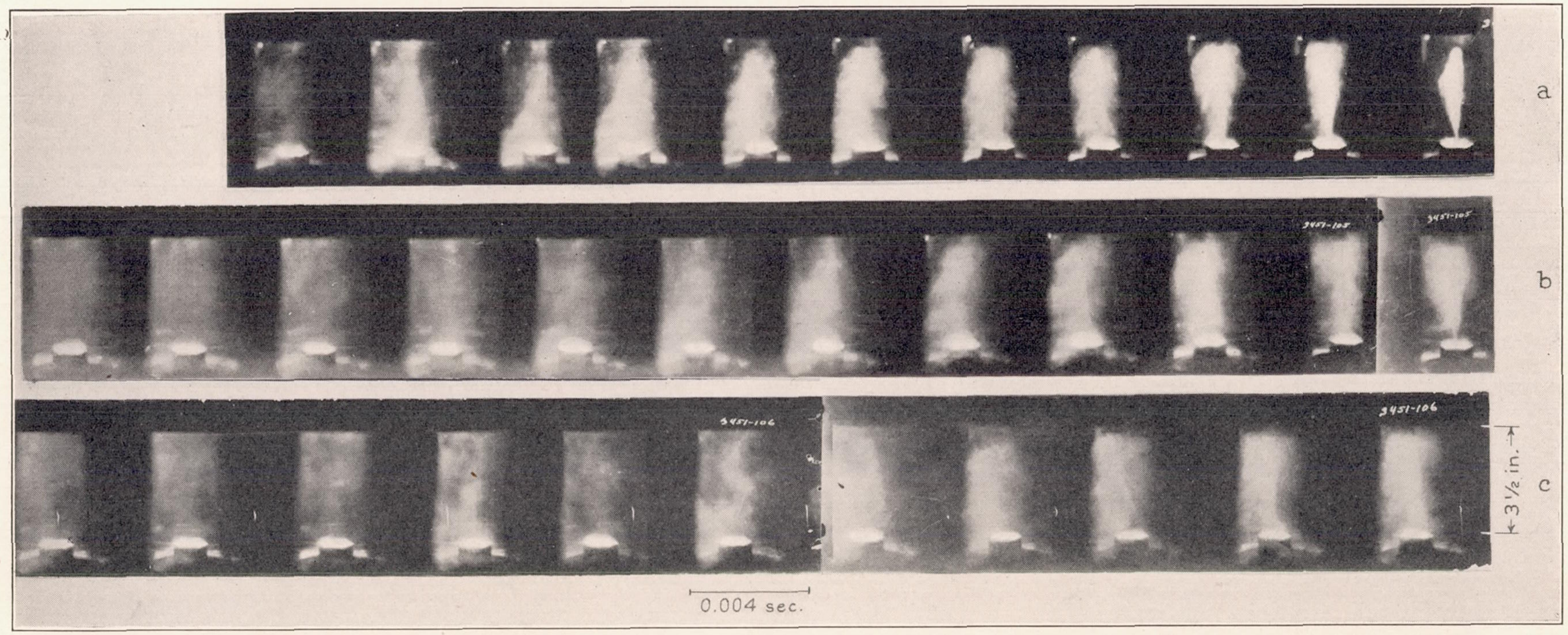

FIGURE 16.—Effect of injection pressure on fuel distribution, with air flow. Air density, 13 atmospheres (0.99 pound per cubic foot). Air velocity, 20 feet per second. Injection pressures: (a) 2,000 pounds per square inch, (b) 4,000 pounds per square inch, (c) 6,000 pounds per square inch. Orifice diameter, 0.008 inch.

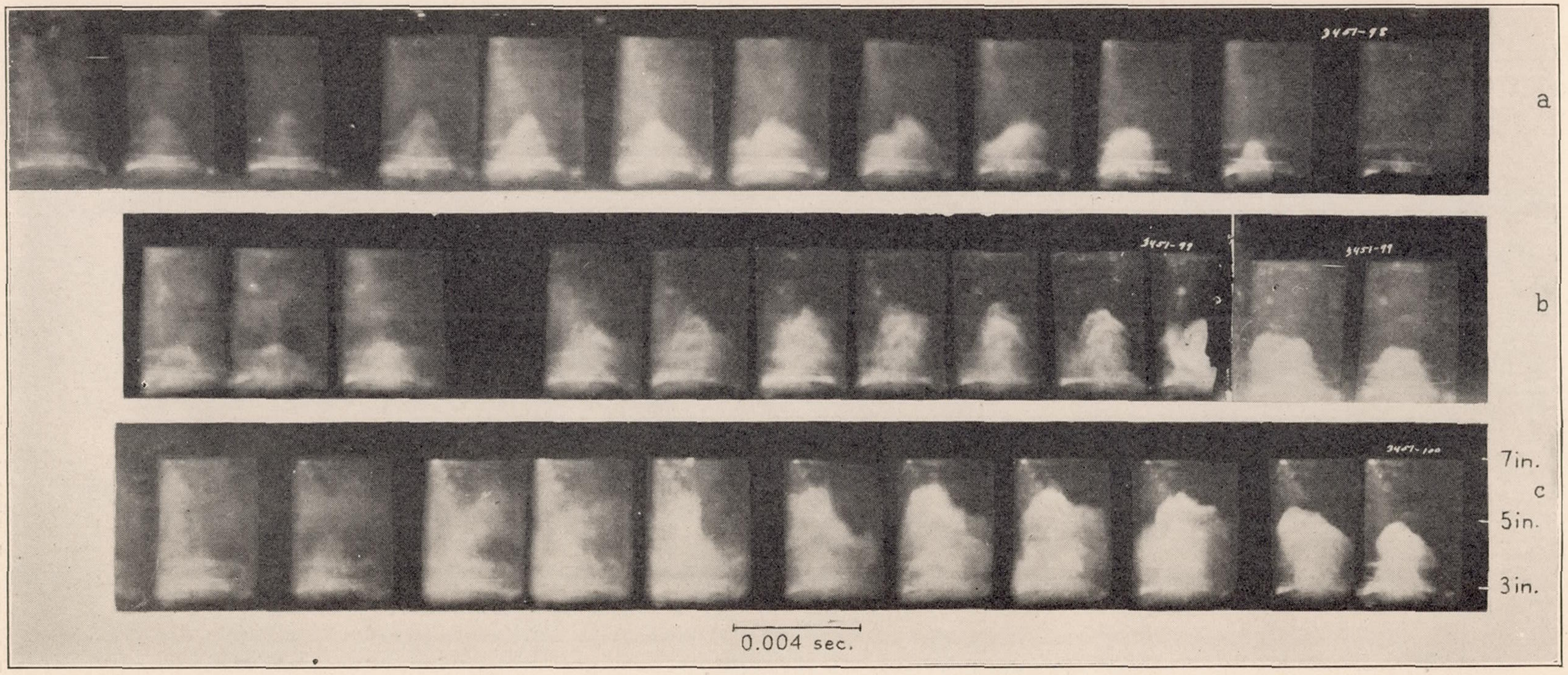

FIGURE 17.—Effect of injection pressure on fuel distribution, with air flow. Air density, 13 atmospheres (0.99 pound per cubic foot). Air velocity, 20 feet per second. Injection pressures: (a) 2,000 pounds per square inch, (b) 4,000 pounds per square inch, (c) 6,000 pounds per square inch. Orifice diameter, 0.008 inch. Nozzle at outer end of chamber.

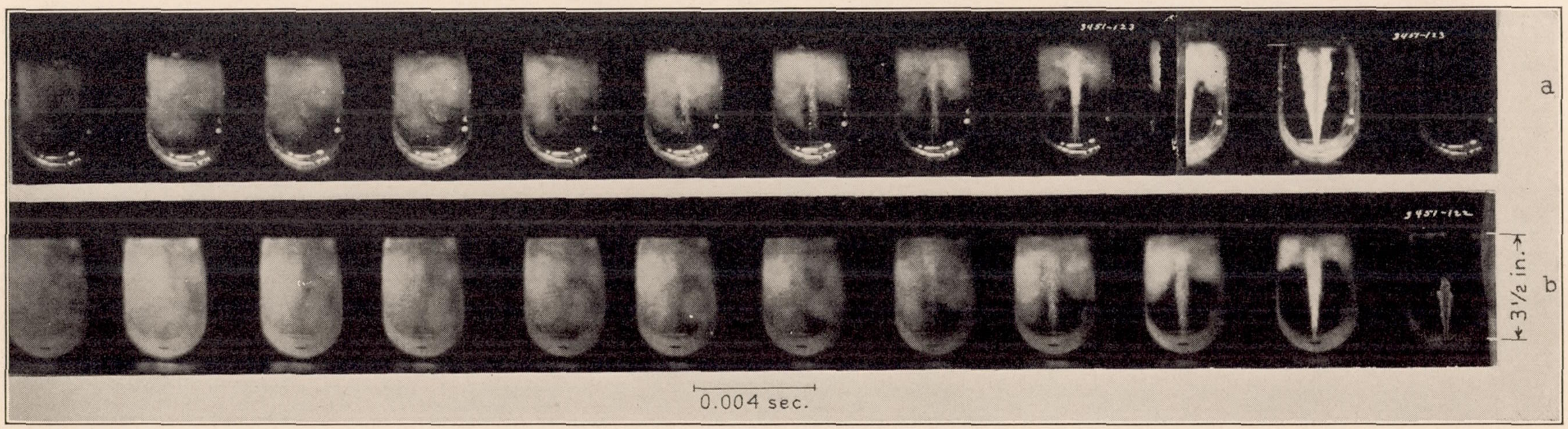

FIGURE 18.—Fuel distribution in model of combustion chamber. Thickness of chamber: (a) 1 inch, (b) 3 inches. Injection pressure, 4,000 pounds per square inch. Air density, 13 atmospheres (0.99 pound per cubic foot). Orifice diameter, 0.020 inch. No air flow.

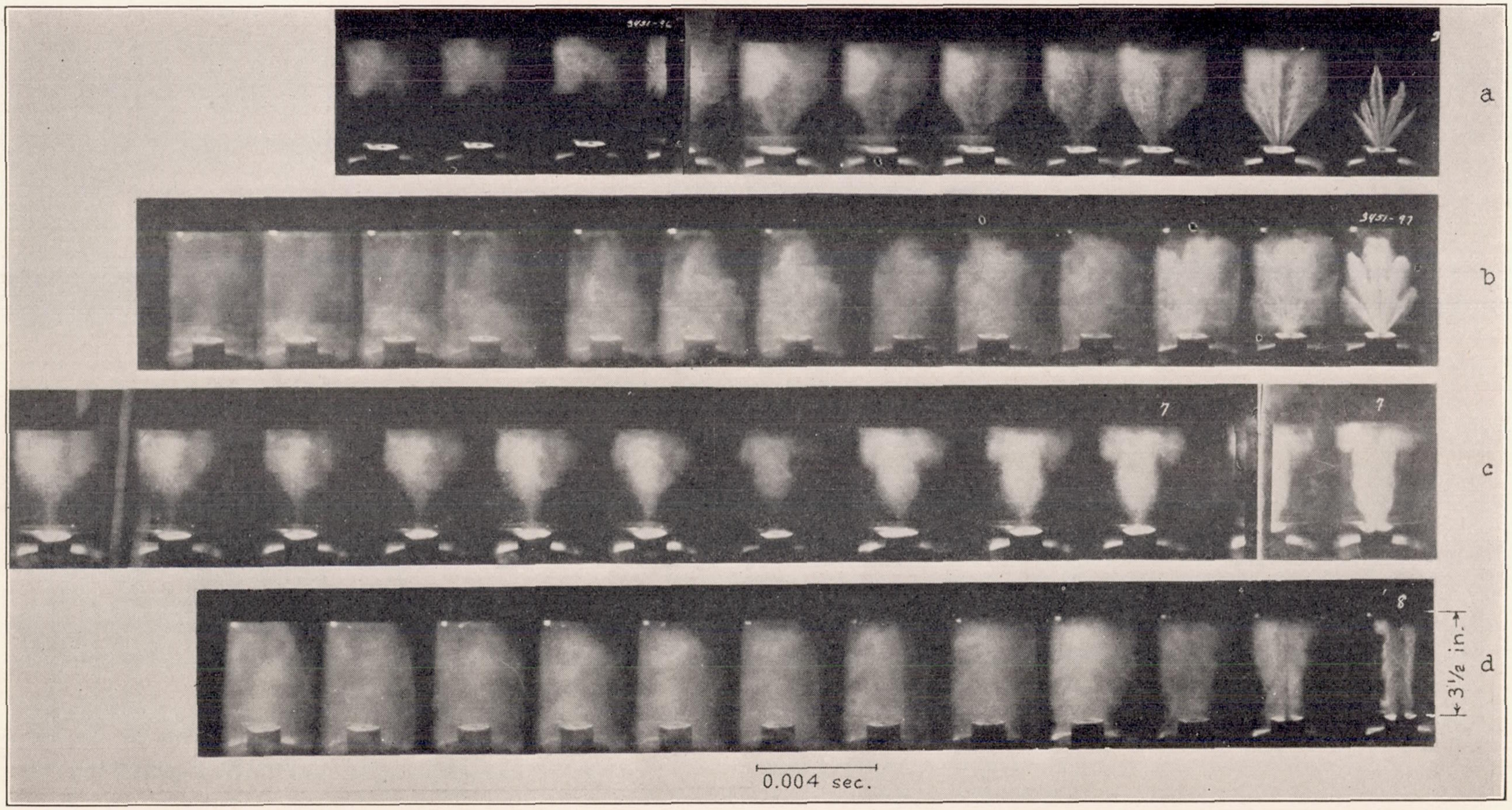

FIGURE 19.—Effect of air flow on sprays from two high-dispersion nozzles. Air density, 13 atmospheres (0.99 pound per cubic foot). Injection pressure, 4,000 pounds per square inch. Nozzles: (a) and (b), multiorifice nozzle; (c) and (d), impinging-jets nozzle. Air velocities: (a) and (c), no air flow, (b) and (d), 20 feet per second.

space. Consequently, the final mixing of the air and fuel must be accomplished through the vaporization and diffusion of the fuel vapors, through the use of air flow, or both.

2. After spray cut-off, air flow at velocities as low as 15 or 20 feet per second is effective in promoting good distribution of the fuel in the liquid phase.

3. If low-velocity air flow is used and if the fuel is to be distributed in the liquid phase, it is very important that the fuel be well broken up during the injection process. Therefore, nozzles of some high-dispersion type are to be preferred in both spark-ignition and compression-ignition engines.

4. Increasing the air density, the injection pressure, or the distance which the spray travels before meeting the moving air increases the initial fuel-jet disintegration produced by the nozzle and aids distribution by air flow.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *February 14, 1934.*

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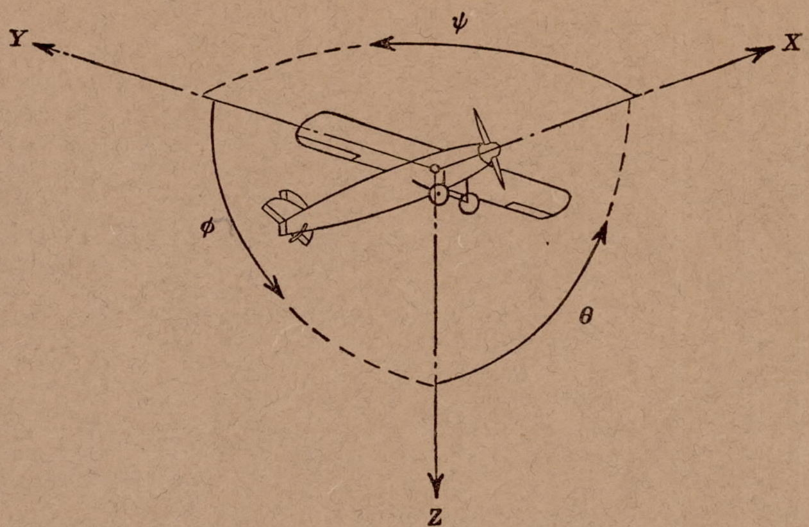

Positive directions of axes and angles (forces and moments) are shown by arrows

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	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	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), δ. (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 $=\sqrt[5]{\frac{\rho V^5}{Pn^2}}$
η, Efficiency
n, Revolutions per second, r.p.s.
Φ, Effective helix angle $=\tan^{-1}\left(\frac{V}{2\pi rn}\right)$

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.