NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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THE EFFECT OF NOZZLE DESIGN AND OPERATING CONDITIONS ON THE ATOMIZATION AND DISTRIBUTION OF FUEL SPRAYS

By DANA W. LEE

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AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Symbol	Unit	Symbol
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of one kilogram	kg	weight of one pound	lb.
Power	P	kg/m/s		horsepower	hp
Speed		km/h	k. p. h.	mi./hr.	m. p. h.
		m/s	m. p. s.	ft./sec.	f. p. s.

2. GENERAL SYMBOLS, ETC.

W, Weight $= mg$

g, Standard acceleration of gravity $= 9.80665$ m/s^2 $= 32.1740$ ft./sec.^{2}

m, Mass $= \frac{W}{g}$

ρ, Density (mass per unit volume).

Standard density of dry air, 0.12497 (kg-m^{-4} s^2) at 15° C. and 760 mm $= 0.002378$ (lb.-ft.$^{-4}$ sec.^{2}).

Specific weight of "standard" air, 1.2255 kg/m^3 $= 0.07651$ lb./ft.^{3}.

mk^2, Moment of inertia (indicate axis of the radius of gyration k, by proper subscript).

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord.

$\frac{b^2}{S}$, Aspect ratio.

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed.

q, Dynamic (or impact) 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 mi./hr. normal pressure, at 15° C., the corresponding number is 234,000;

or for a model of 10 cm chord 40 m/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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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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By Dana W. Lee

SUMMARY

The atomization and distribution characteristics of fuel sprays from automatic injection valves for compression-ignition engines were determined by catching the fuel drops on smoked-glass plates, and then measuring and counting the impressions made in the lampblack. The experiments were made in an air-tight chamber in which the air density was raised to values corresponding to engine conditions.

The effects of the jet velocity, chamber-air density, orifice diameter, and the orifice length-diameter ratio on the fineness and uniformity of the atomization and on the distribution of the fuel in sprays from plain cylindrical nozzles were determined. The atomization and distribution characteristics of sprays from valves having spirally grooved stems, of sprays produced by the impinging of two fuel jets, and of sprays produced by a fuel jet striking a metal lip were also measured and compared with those of sprays from the plain nozzles.

It was found that each spray is composed of several million drops whose diameters range from less than 0.00025 inch to 0.005 inch, and sometimes to 0.010 inch. The experiments indicated that with a given fuel the fineness and uniformity of the atomization increase with an increase in the jet velocity, and with a decrease in the orifice diameter. Orifice length-diameter ratio and chamber-air density had no decided effect on the spray atomization. Centrifugal-type sprays, impinging-jets sprays, and sprays formed by a jet striking a metal lip were found to have no better atomization than sprays from plain nozzles, provided that the jet velocity was the same, but the distribution of the fuel within these sprays was found to be much better than for plain sprays.

INTRODUCTION

One of the most difficult problems encountered in the development of high-speed compression-ignition engines has been the proper atomization and distribution of the fuel in the combustion chamber during the extremely short time available. Rapid combustion of the fuel does not take place as soon as it enters the combustion chamber, but a certain time, known as the ignition lag, elapses during which the temperature of the fuel is raised to its auto-ignition point by the absorption of heat from the compressed air. The rate of heat absorption by a fuel drop is directly proportional to its surface area; the rate of its temperature rise is inversely proportional to its volume. Because the surface area varies as the square of the diameter, whereas the volume varies as its cube, a small drop will have a shorter ignition lag than a large one. The time required for the complete combustion of small drops is also less than that for large ones; therefore the smallest drops are the most desirable if they can be obtained without sacrificing good distribution.

Engine-performance tests made in connection with measurements of the atomization of the fuel (reference 1) showed that a decrease in the mean drop size was not always accompanied by a better engine performance. The smaller drops probably did not penetrate to all parts of the combustion chamber, and some of them failed to burn because of lack of oxygen. Conversely, a change in nozzle design which improves the distribution may also change the atomization. In the experiments described herein, these two spray characteristics have been studied together.

A survey of most of the previously published work on the atomization and distribution of fuel sprays (see bibliography appended) showed that these problems have usually been studied separately. Kuehn in 1924 published an account of an experimental investigation of the atomization of fuel sprays produced at relatively low pressures and injected into air at atmospheric pressure and temperature. He caught the sprays on smoked-glass plates, counted the number of impressions made in the lampblack by the fuel drops, and very carefully determined the weight of the fuel caught on the plates. From these data he computed the mean drop size for each experimental condition.

Wöltjen in 1925 studied the atomizations of fuel sprays by injecting them into a gelatinous substance, which caught and held the drops. He then took photomicrographs of the drops, from which he determined the relative fineness and uniformity of the atomizations. He used injection pressures and chamber-air densities corresponding to those used in engines.

Sass in 1930 published the results of some atomization experiments made by himself while using a variation of Wöltjen's method. He caught the drops on the surface of a pool of glycerin which was placed about 8 inches directly below the spray nozzle, and then took photomicrographs of them.

The most direct method employed to study fuel atomization has been the spark photography of the drops while they are still in the spray. Scheubel has thus photographed the sprays from carburetor jets, and Sass has been able to photograph the drops in a high-velocity spray at a magnifying power of 10. Photomicrographs of fuel sprays have also been taken at this laboratory using the same magnification, and the results will be published at a later date. (See Bibliography.)

The best known tests on the distribution of fuel in sprays are those made at the Pennsylvania State College using a "spiral staircase" of collecting pads. (References 2 and 3.) The results of these tests showed that the fuel concentration was greatest along the axes of the sprays, and that it decreased rapidly toward the edges.

The present report presents the results of a series of measurements of the atomizations and distributions of fuel sprays made in 1931 by the National Advisory Committee for Aeronautics, at Langley Field, Va. Four different types of sprays were investigated, using different injection pressures, chamber-air densities, and nozzle dimensions. Wherever possible, the results have been compared with those obtained by other investigators.

APPARATUS AND TEST METHOD

FUEL-INJECTION SYSTEM

The fuel-injection system used for an investigation of spray characteristics should be as nearly like those used on engines as possible. At the same time, there must be only a single injection, the duration and velocity of which can be controlled and measured. The common-rail fuel-injection system which is used with the N. A. C. A. spray photography equipment fulfills these requirements, and was used for these tests.

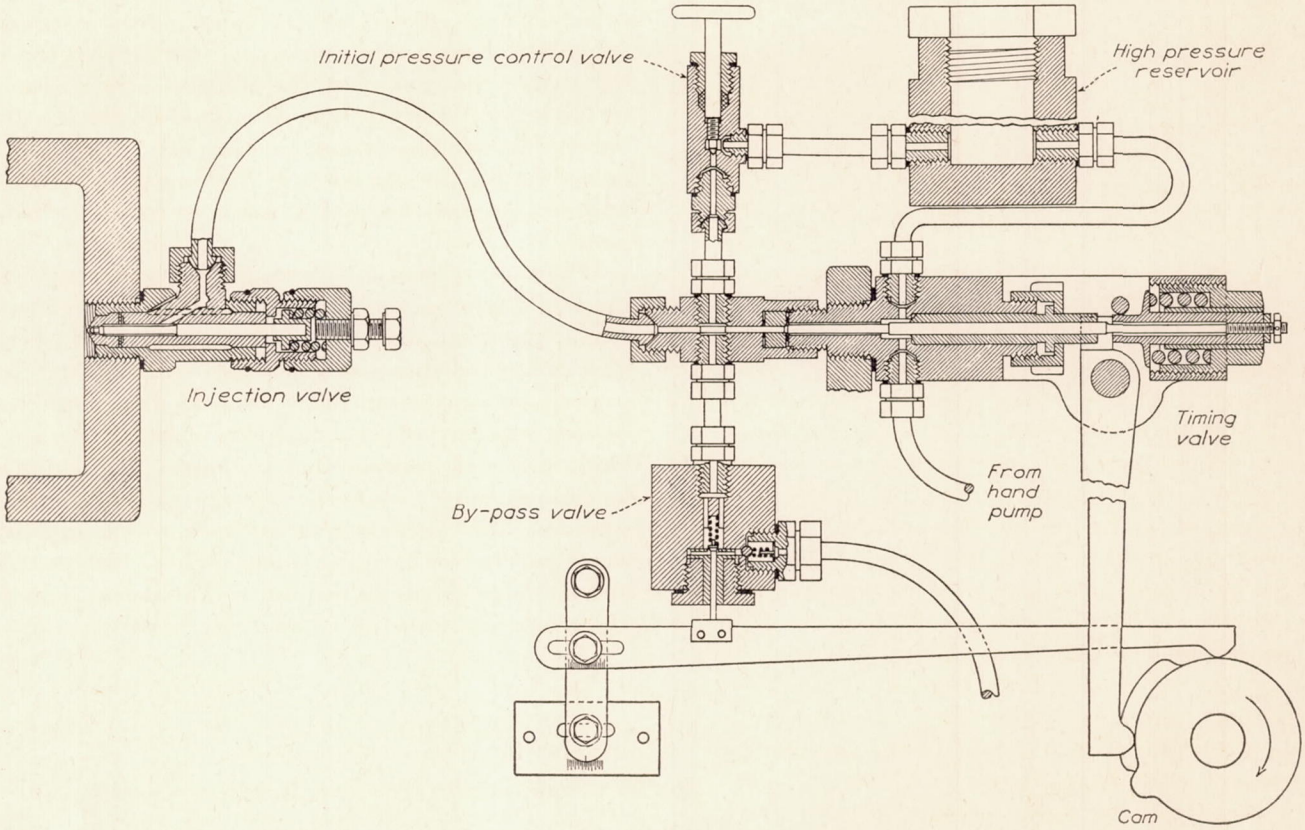


FIGURE 1.—Fuel-spray injection system

It is shown diagrammatically in Figure 1, and its action is fully described in reference 4.

The steel injection tube that was used had an external diameter of 0.25 inch, an internal diameter of 0.125 inch, and a length of 100 inches. Previous experiments (reference 4) had shown that the fuel pressure at the nozzle was steadier when long tubes were used.

The different types of nozzles used are shown in Figure 2. Figure 2 (a) shows a plain nozzle assembled in the end of the injection valve shown in Figure 1. The same type of nozzle in the same valve, assembled with an adapter and a valve stem having four helical grooves which gave the fuel a whirling motion as it was injected, is shown in Figure 2 (b). The orifice diameter

was 0.020 inch, the total area of the grooves and clearance space was 0.00052 square inch, and the rectified length of each groove was 0.204 inch. Figure 2 (c) shows a nozzle which directed the fuel jet against a flat

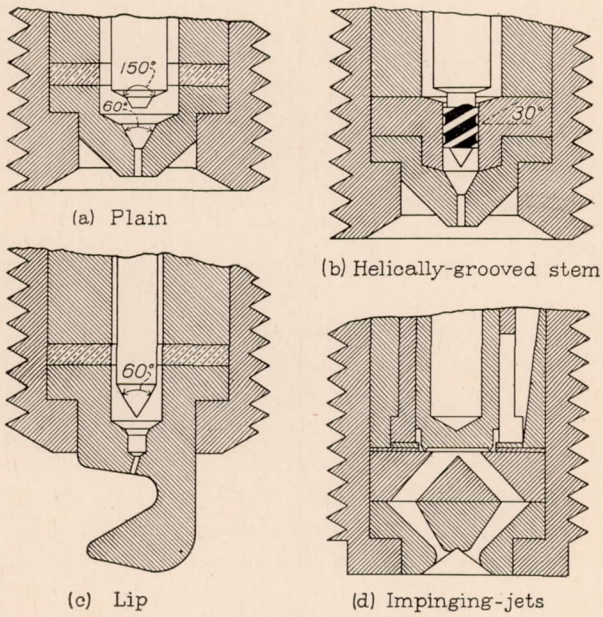


FIGURE 2.—Assemblies of the four types of nozzles tested

lip set at an angle of about 45° to the jet. The fuel did not rebound after striking the lip, but continued in nearly the same direction as the lip surface. The injection valve used with this nozzle was very much like that used with the plain nozzles, the principal difference being in the size of the stem and in the seat angle. Figure 2 (d) shows a nozzle in which two fuel jets impinged upon each other just after leaving their orifices. The angle between the jets was 74° and the diameter of each orifice was 0.028 inch. A complete description of this valve and nozzle is given in reference 5. Except where otherwise noted, all tests were made with the plain type of nozzle in the injection valve shown in Figure 1.

In each case the valve opening pressure was 500 pounds per square inch less than the reservoir pressure.

MEASUREMENT OF INJECTION PRESSURE

Because of pressure-wave phenomena in injection systems, the pressure of the fuel at the nozzle is never constant during injection. The instantaneous variations in pressure were obtained for all the conditions used in these tests by analyzing the photographically recorded lift-time curves of the valve stem. The method of recording and analyzing the stem-lift curves is fully described in reference 4. Because the flow velocity through a nozzle varies as the square root of the pressure difference, the effective injection pressure for each test was obtained by plotting the square roots of the instantaneous pressures against time, then integrating this curve with a planimeter, determining the mean square root, and squaring that value.

The fuel used for all the tests made at this laboratory was a high-grade diesel fuel, having a specific gravity of 0.86, a viscosity of 38.5 Saybolt Universal seconds, and a surface tension of 0.000160 pound per inch at atmospheric pressure and at a temperature of 73° F.

APPARATUS FOR MEASURING THE ATOMIZATION AND DISTRIBUTION OF SPRAYS

The apparatus used to obtain a record of the atomization and distribution of the injected fuel is shown diagrammatically in Figure 3. A cylindrical steel chamber 18 inches long and 6 inches in diameter had one end closed by a steel plate welded in place. The other end was fitted with a flange and a removable cover bolted to it, with air-tight packing between the flange and the cover. A threaded opening was made in the fixed end of the chamber to insert the injection valve. A similar opening (marked "Hole for lip nozzle" in fig. 3) was made in the wall of the chamber and was used to insert the valve when using the lip nozzle.

When a record was to be made, a glass plate was given a heavy coating of lampblack with a kerosene flame, and then placed in the bottom of the chamber. The end of the chamber was bolted in place, and compressed air was admitted to the chamber until the desired pressure was indicated by a spring gauge. A baffle plate in front of the incoming air stream was found necessary to prevent damage to the lampblack surface. Fuel sprays from all except the lip nozzle were injected with their axes parallel to and $2\frac{5}{16}$ inches above the smoked plate. The spray from the lip nozzle was directed at an angle toward the plate,

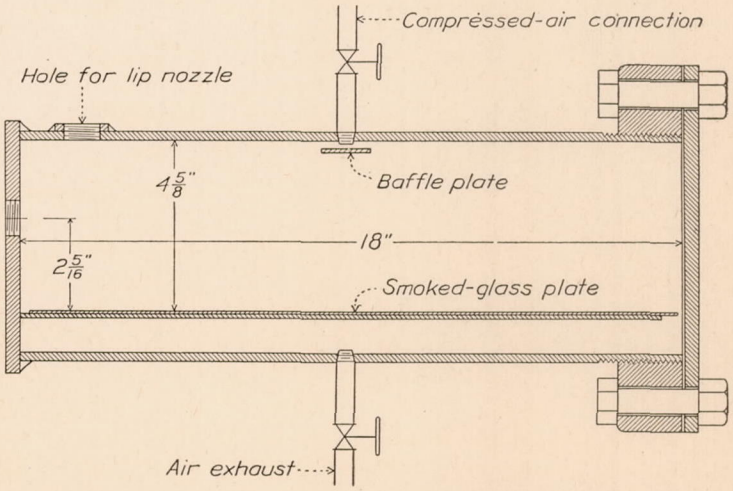


FIGURE 3.—Chamber used to obtain atomization and distribution records on smoked-glass plates

but did not reach it until it had penetrated nearly to the opposite end of the chamber. When the forward velocity of the fuel drops had become nearly zero, they slowly descended toward the smoked plate. As each

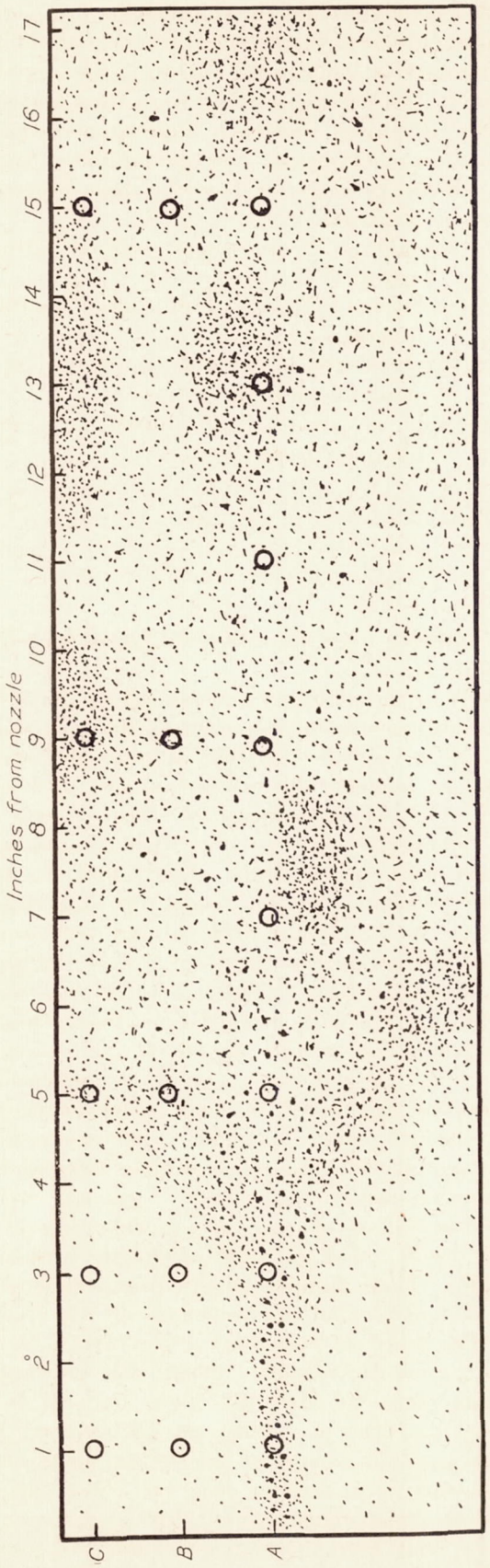


FIGURE 4.—Sketch of smoked-glass plate used to catch fuel drops, showing system used for locating photomicrographs. The dots represent a typical distribution of the larger drops and the circles indicate the positions of a set of photomicrographs

drop touched the surface a hole was made in the lampblack, the diameter of which was a function of the diameter of the drop making it.

These holes were studied with a microscope, and photomicrographs were taken of a number of representative regions, to be analyzed later.

TEST METHOD

In one of the preliminary trials made to find the best method of catching the drops, a tray divided into 1,500 parts by thin partitions and filled with glycerin was placed at the bottom of the chamber. After the drops had settled, samples of the glycerin from different parts of the tray were transferred to microscope slides and examined. This method proved to be less satisfactory than the smoked-plate method, for the transfer of the samples to the slides was difficult, and disturbed the arrangement of the drops.

The smoked-plate method required that the layer of lampblack have a smooth surface, and that its thickness be uniform and of such a magnitude that the fuel would be absorbed by it and not be allowed to reach the surface of the underlying glass, where it might spread. After many experiments it was found that smooth even coatings of lampblack could be applied to the plates by supporting them at the ends and smoking them with a lamp having a wick whose width was greater than the width of the plates. Experiments were made to determine the thickness of lampblack best suited for catching the oil particles. If the coating was less than about 0.001 inch thick, severe spreading of the oil particles took place. However, thicknesses greater than about 0.003 inch showed little evidence of spreading. Two narrow plates smoked to a depth of 0.003 inch and 0.025 inch, respectively, and placed in the atomization chamber side by side showed very nearly the same sizes of drop impressions. Therefore, a thickness of from 0.006 to 0.012 inch was considered sufficient, and in each case the depth of the lampblack was checked by means of a micrometer focusing screw on the microscope.

Some of the records were made with the chamber vertical instead of horizontal. In these tests 6-inch-diameter glass plates were smoked and placed at the bottom of the chamber. Although the fuel was then sprayed directly toward the plate, in only a few cases did it retain sufficient velocity to damage the lampblack coating.

Different powers were tried with the microscope, and a magnification of 50 was found to be most suitable. This magnification easily showed the smallest impressions that the lampblack was capable of recording, the granular structure of the lampblack being of such a magnitude that no impressions less than about 0.00025 inch in diameter were discernible.

Stokes's formula for the terminal velocity of freely falling spheres was used to determine the time required for the drops to fall the height of the chamber; in each case the compressed air was not released and the plates removed until the smallest measurable drops had had time to settle to the lampblack.

A preliminary test was made to determine whether the size of the drop impressions varied with time. The record was removed from the chamber as soon as possible, and a series of photomicrographs of the same area was made, the first one taken 2 minutes after the injection and the last one 16 hours later. No difference in the size of the impressions could be observed.

Figure 4 shows the system used to designate the positions on the plates at which photomicrographs were taken. The position A–0 is directly under the fuel nozzle, and the various positions are all 1 inch apart. Before taking each photomicrograph the region within about 0.5 inch of the indicated position was examined carefully and a group of impressions selected which were most representative of the region.

It was found that the best way to illuminate the surface of the lampblack for photographing was to throw two strong beams of light along the surface inclined slightly downward, the two beams being diametrically opposite each other. When this was done the surface appeared nearly white, but the holes were in dense shadow. Some typical examples of the photomicrographs are shown in Figure 5. The lines across the photographs were made by wires stretched in the camera, and were placed there as an aid to counting the drop impressions.

COMPUTATION OF RESULTS

All of the data on the atomization and distribution of fuel sprays that are presented in this report are based on the measurement and classification of the impressions made by the fuel drops in the lampblack coating of the receiving plates. Tests and computations made especially for the purpose showed that no great error is introduced if the diameters of the impressions are assumed to be equal to the diameters of the drops that made them. The justification of this assumption will be discussed in greater detail later.

To facilitate the work of classifying the drop sizes, a series of small circles were drawn on a piece of celluloid, each one representing an impression of a certain diameter, magnified the same amount as the photomicrographs. The smallest of these represented an impression 0.0005 inch in diameter, the next 0.0010 inch, then 0.0015 inch, etc. By placing this celluloid sheet over prints of the photomicrograph negatives and moving it about by hand, the circle which most nearly fitted each impression was quickly found. This method divided all the impressions into a series of groups, the mean diameters in each group differing from the next by 0.0005 inch. During this investigation about 180,000 impressions were thus measured.

It was recognized that each impression except the very smallest must obscure a certain number of smaller ones. All results were corrected for these superposed impressions as follows:

Let n—number of impressions counted with diameter d.

N—corrected number of impressions with diameter d.

A—surface area of lampblack included in the photomicrograph.

A'—sum of areas of all impressions with a diameter greater than d.

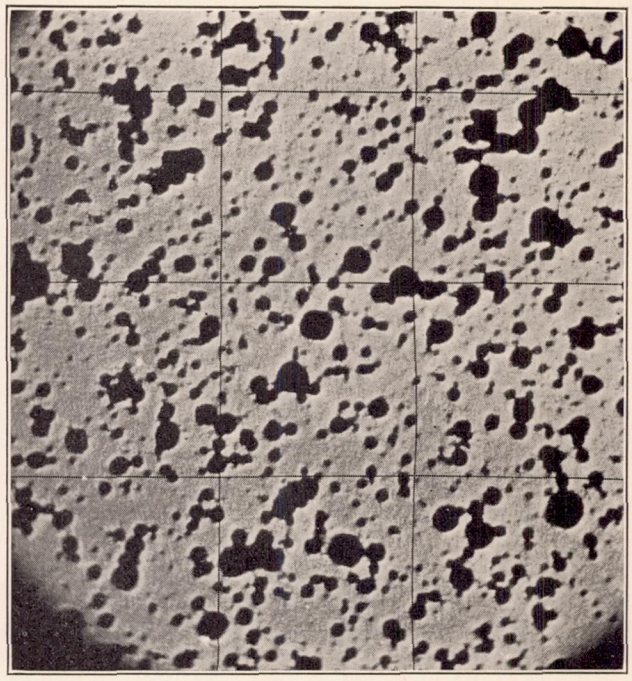
Then
$$\frac{n}{A-A'}=\frac{N}{A}$$

or
$$N=\frac{A\,n}{A-A'}$$

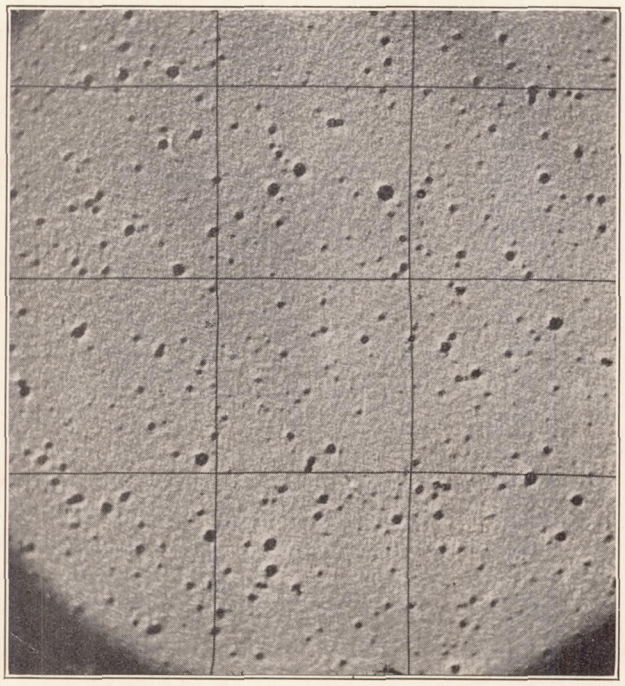
These corrected numbers were used for all subsequent computations.

Both Wöltjen and Sass expressed the results of their atomization experiments by plotting the diameters of the drops as abscissas and the number of drops, or their weight, included within a certain area, such as the field of a microscope, as ordinates. These curves were called "frequency curves," since they expressed the frequency with which drops of any size might be expected to occur. In this report the same type of curves are used, but the ordinates are expressed in terms of percentages of the total number of drops, or of the total volume. Thus all the curves can be directly compared without confusion arising from the different amounts of fuel on which the curves are based. This method gave a series of independent points, rather than points on a curve, but curves were drawn through them to make comparisons easier. The curves given in this report will be referred to as "atomization curves" rather than "frequency curves," both because of the change made in the ordinates and because it is felt that the word "frequency" might be confusing. These atomization curves express both the degree of fineness and the uniformity of the atomization. The closer the curves are to the vertical axis the finer is the atomization, and the smaller the range of drop diameters included the more uniform is the atomization. Specific values can be obtained from the curves only at points for the "group mean diameters," 0.0005 inch, 0.0010 inch, etc. For example, at a group mean diameter of 0.0010 inch the curves should be read: So many per cent of the total number (or volume) of the drops larger than 0.00025 inch in diameter were found to be between 0.00075 and 0.00125 inch in diameter.

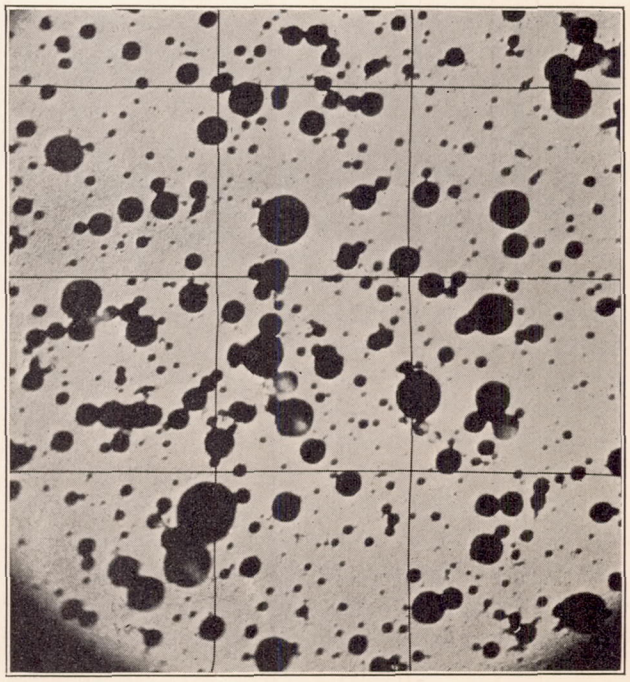
(a) Plain nozzle, 0.020-inch orifice. Effective injection pressure—4,120 lb. per sq. in. Position on record—A-2



(b) Plain nozzle, 0.020-inch orifice. Effective injection pressure—4,120 lb. per sq. in. Position on record—A-14



(c) Plain nozzle, 0.020-inch orifice. Effective injection pressure—4,120 lb. per sq. in. Position on record—C-2



(d) Impinging-jets nozzle. Effective injection pressure—1,730 lb. per sq. in. Position on record—A-15

FIGURE 5.—Photomicrographs of lampblack surface showing impressions made by fuel drops, ×50

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Atomization curves representing the average for the entire spray were obtained by combining the data from the various photomicrographs. The horizontal records were divided into sections by lines perpendicular to the center line and halfway between the photomicrograph locations. For the sections which included three photomicrographs the data for the section were obtained by taking the average of the data for the photomicrographs, counting the center one once and each of the others twice. The data for the entire record were then obtained by adding the data for the various sections. When the test chamber was mounted vertically the distribution of the drops was fairly uniform, so that curves for the entire spray were computed by using the combined data from several photomicrographs taken at even intervals over the record.

In Table I are listed the data concerning the nozzles tested, the injection conditions, and a summary of the results obtained. Column 10, the total number of drops on the record, was computed by multiplying the number of drops classified (column 9) by the ratio of the area of the lampblack record to the area included in the photomicrographs. Column 11, the total weight of the drops on the record, was computed by assuming that every drop in each group had a diameter equal to the group mean diameter. Now if, in each group, the various sizes were evenly distributed, the weights thus obtained would be too low because the volume varies as the cube of the diameter. However, it is known that there was always a greater number of the smaller sizes in any group, which would tend to compensate for this error.

TABLE I

TEST CONDITIONS AND COMPUTED RESULTS OF THE ATOMIZATION EXPERIMENTS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Record No.	Figures which show results from this record	Orifice diameter, inch	Orifice length-diameter ratio	Chamber-air density, lb. per cu. ft.	Injection period, second	Effective injection pressure, lb. per sq. in.	Positon of spray axis	Number of drops classified $=N$ (corrected for overlapping)	Total number of drops on record	Total weight of drops on record, pound	Computed weight of fuel discharged, pound	Arithmetic mean drop diameter $=\frac{\Sigma(nd)}{N}$, inch	Volumetric mean drop diameter $=\sqrt[3]{\frac{\Sigma(nd^3)}{N}}$, inch	Sauter's equivalent drop diameter $=\frac{\Sigma(nd^3)}{\Sigma(nd^2)}$, inch	Volumetric mean drop diameter from number of drops and computed discharge, inch	Variable
1	7, 21	0.020	.6	0.94	0.0041	450	Horizontal	3,240	9,580,000	0.000211	0.000125	0.00112	0.00177	0.00271	0.00043	Injection pressure.
2	7	.020	6	.94	.0049	880	do	6,225	18,400,000	.000331	.000210	.00112	.00170	.00248	.00041	Do.
3	7, 14, 18, 21	.020	6	.94	.0046	2,280	do	4,108	8,090,000	.000441	.000303	.00113	.00158	.00215	.00134	Do.
4	6, 7	.020	6	.94	.0051	4,160	do	16,572	16,568,000	.000631	.000473	.00091	.00128	.00180	.00121	Do.
5	7, 21	.020	6	.94	.0046	5,700	do	8,547	16,800,000	.000574	.000491	.00095	.00127	.00172	.00121	Do.
6	9, 22	.020	.5	.31	.0058	4,100	do	5,328	9,440,000	.000378	.000530	.00100	.00134	.00178	.00152	Chamber-air density.
7	9, 22	.020	.5	.67	.0058	4,100	do	5,601	11,020,000	.000506	.000526	.00104	.00142	.00189	.00143	Do.
8	9, 22	.020	.5	1.30	.0058	4,100	do	6,383	12,570,000	.000555	.000517	.00103	.00150	.00213	.00137	Do.
9	10	.020	2	.31	.0040	4,140	do	2,970	15,300,000	.000337	.000367	.00082	.00111	.00149	.00114	Do.
10	10, 13, 23	.020	2	.94	.0040	4,140	do	2,316	11,900,000	.000355	.000362	.00088	.00123	.00169	.00124	Do.
11	10	.020	2	1.56	.0040	4,140	do	2,388	12,320,000	.000311	.000356	.00083	.00116	.00161	.00122	Do.
12	12	.008	6	.94	.0015	3,920	Vertical	1,049	4,060,000	.000065	.000021	.00077	.00100	.00129	.00069	Orifice diameter.
13	12, 17	.020	6	.94	.0015	3,920	do	5,005	3,590,000	.000084	.000132	.00094	.00115	.00156	.00133	Do.
14	12	.030	6	.94	.0015	3,900	do	4,145	4,520,000	.000178	.000296	.00095	.00134	.00183	.00161	Do.
15	13, 23	.020	.5	.94	.0040	4,140	Horizontal	2,185	11,280,000	.000320	.000362	.00089	.00121	.00162	.00126	Orifice length/diameter.
16	6, 13, 14, 23	.020	6	.94	.0040	4,120	do	2,560	13,200,000	.000351	.000361	.00085	.00118	.00162	.00119	Do.
17	14, 19, 24	.020	6	.94	.0045	4,900	do	4,231	8,330,000	.000391	.000175	.00094	.00143	.00214	.00115	Centrifugal spray.
18	17	.018	4	.94	.0015	3,600	Vertical	3,077	3,770,000	.000078	.000102	.00079	.00109	.00151	.00128	Lip nozzle.
19	15, 20, 25	.028	1	.94	.0046	1,730	Horizontal	5,154	10,140,000	.000647	.001020	.00096	.00158	.00253	.00188	Impinging jets.
20	15	.028	1	.94	.0018	1,730	Vertical	3,742	3,540,000	.000435	.000399	.00108	.00197	.00345	.00190	Do.
21	15	.030	6	.94	.0015	1,730	do	4,609	4,970,000	.000155	.000191	.00086	.00125	.00181	.00132	Comparison with records 19 and 20.

Column 12, the computed weight of the fuel discharged, was obtained by substituting the proper values in the usual flow formula.

$$W = a\ t\ c\ \sqrt{2Pg\rho}$$

where

W—the weight of fuel discharged, in pounds.

a—the area of the discharge orifice, in square inches.

t—the time, in seconds.

c—the coefficient of discharge of the nozzle.

P—the effective injection pressure, in pounds per square inch.

g—the gravitational constant, in inches/second.[2]

ρ—the specific weight of the fuel, 0.0307 pound/cubic inch.

The discharge time was obtained directly from the stem-lift records, and the coefficients of discharge of

the nozzles used in this investigation had been previously determined. (Reference 6.)

In column 13 are given the arithmetical means of the drop diameters, and in column 14 are given the diameters obtained by taking the arithmetical means of the drop volumes.

In column 15 are given the mean drop diameters computed by the method proposed by Sauter. (Reference 7.) After studying the various ways that may be used to compute mean drop diameters, he concluded that for fuel sprays neither the arithmetic nor the volumetric mean value is as important as a value based on the ratio of the total volume of the drops to their total surface area. He therefore proposed that another method be used in which the actual mixture is assumed to be replaced by a uniform mixture in which the total surface area O and volume V of the drops are the same as for the actual mixture, but the number of drops is different. The value of the mean radius under these conditions he showed to be:

$$r_m = \frac{3V}{O}$$

In the computation of columns 13, 14, and 15 the same assumption was made as for column 11—that all drops within a group had the same group mean diameter.

To furnish a comparison between this work and that of Kuehn, the mean drop diameters were computed from the total number of drops, column 10, and the computed weight of discharge, column 12. These values are listed in column 16.

ACCURACY

The test method employed is subject to several possible errors. First, the assumption that the drops falling on the lampblack made impressions of the same diameter as the drops themselves needs justification. By a comparison of the results listed in columns 11 and 12 of Table I, it will be seen that in nearly every case the weight of the discharged fuel as computed from the size and number of the drop impressions does not differ by more than 50 per cent from the weight as computed with the flow formula. When it is considered that only 0.1 per cent or less of the drop impressions were measured, such a check seems surprisingly good. As smoked plates were placed only below the spray, it is likely that some of the fuel drops struck the top and sides of the chamber, and never reached the lampblack. One of the experiments was carried out with the spray surrounded by smoked plates arranged in the form of a hollow triangular prism and placed in the experimental chamber so that the spray was injected along the axis of the prism. The farther end of the prism was closed by fastening another smoked plate to the end of the chamber. Each of the four smoked plates was analyzed and the data combined. The results of this experiment are listed in Table I as Record No. 4. The weight of fuel as computed from the drop impressions is 0.000631 pound, whereas that computed from the orifice diameter and the effective injection pressure is 0.000473 pound, which is about the same degree of variation as found for all other experiments.

The accuracy of the results computed from the orifice area and effective pressure has been reported in reference 4, in which the same equipment was used as for these atomization experiments, except that the discharge was caught in a small receptacle and weighed with an analytical balance. When the computed values were compared with the measured ones, it was found that the former were about 10 per cent too great.

Another chance for error lay in the choice of the drop impressions which were to be photographed. These were selected very carefully after studying each record through the microscope, but with millions of impressions on the plates the ones selected may not always have been truly representative.

Figure 6 contains the results of two experiments made under the same conditions. The results were worked up independently of each other, and they show that the atomization curves can be reproduced fairly consistently. It will be noticed that the two curves for percentage by volume vary mostly in the end regions. This difference at the left of the curves is because the smaller drops are hard to distinguish, and their visibility is considerably affected by the texture of the lampblack surface, which varies with the different records. At the right of the curves the variation is caused by the fact that a difference of one or two large drops makes large changes in the volume. The fuel pressure in the reservoir of the injection system was the same for each case; the difference in the effective injection pressures indicates the degree of error in the method of measuring these pressures.

TEST RESULTS AND DISCUSSION

EFFECT OF DIFFERENT FACTORS ON THE ATOMIZATION OF FUEL SPRAYS FROM PLAIN NOZZLES

Operating conditions—Injection pressure.—The results of the tests on the effect of injection pressure on the atomization are shown in Figure 7. As will be shown later, it is not the pressure that affects the atomization, but the velocity imparted to the fuel by virtue of the pressure drop through the nozzle. However, with plain nozzles, the simplest means of obtaining an increase in the injection velocity is to increase the injection pressure; for the sake of simplicity, the results have been plotted in terms of the injection pressure. This factor has the greatest effect on the atomization of sprays, and is also the one which varies between the widest limits. As Figure 7 shows, an increase in the jet velocity (injection pressure) results in a decrease in

the mean size of the drops and an increase in the uniformity of the atomization.

These results agree in general with those of previous investigators; but as to the magnitude of the effect of jet velocity on atomization and the sizes of the drops found, the agreement between the investigators is not as good. A close agreement could hardly be expected in view of the different injection valves, injection systems, nozzles, and fuels used, as well as the different methods of measuring the injection pressure and determining the drop sizes.

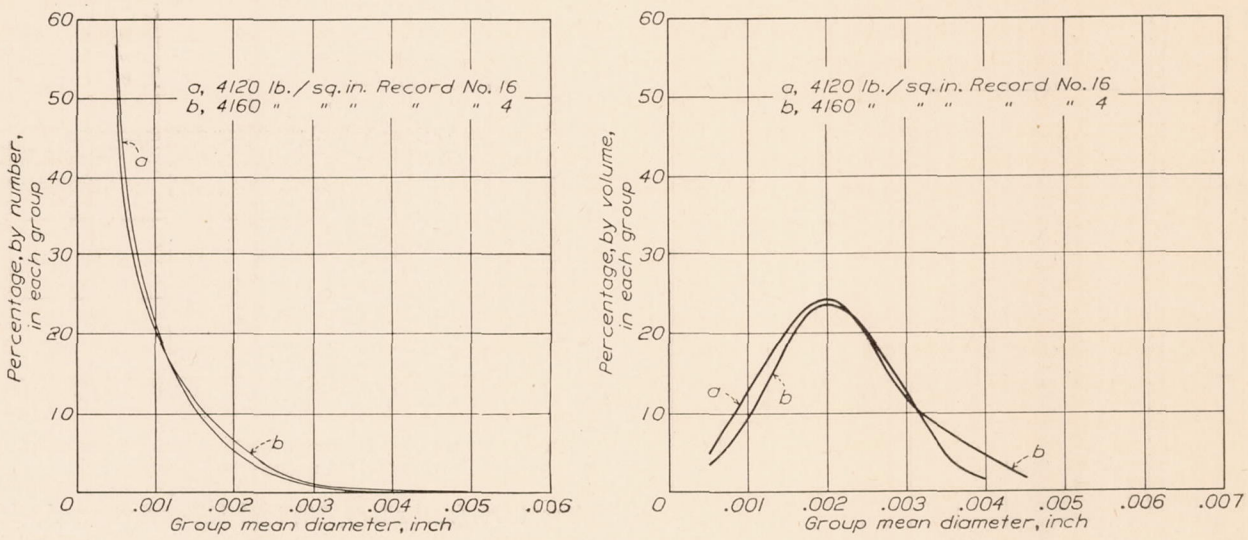


FIGURE 6.—Atomization curves for two sprays produced under the same conditions, showing experimental variations

Figure 8 shows a summary of the results of several investigations of the effect of the jet velocity on the mean drop size. The size is expressed on a volumetric basis in each case. Kuehn's results were therefore used directly, but those of Sass and Wöltjen had to be recomputed from their frequency curves.

Figure 8 includes also a curve plotted from the theoretical equation developed by Triebnigg. (Reference 8.) According to this theory, the atomization is uniform at all times. The size of the drops varies directly as the specific gravity and surface tension of the fuel and inversely as the specific gravity of the air, the jet velocity, and the coefficient of the air resistance.

Chamber-air density.—Atomization curves showing the effects of the density of the air in the experimental chamber are shown in Figures 9 and 10. In these figures, and in most of those referred to in the following discussion, frequency curves are given in terms of percentage by volume only. Curves for percentage by number were drawn for each case, but they did not express the results as clearly as the volume curves. The results shown in Figure 9 were obtained first, indicating that the drops became larger as the density was increased. These results are contradictory to those of Sass, whose frequency curves for this factor are given in reference 1. Because some combination of errors might have caused this reversal of results the series

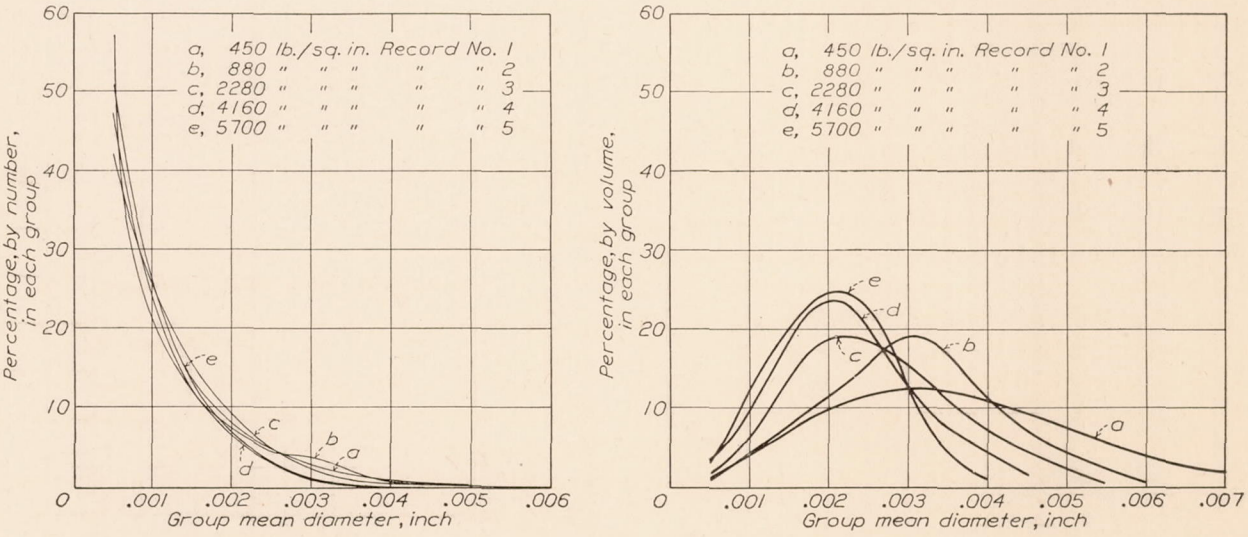


FIGURE 7.—Atomization curves for sprays from a nozzle having a 0.020-inch orifice injected at different velocities

was later repeated, using a different nozzle and injection period. The range of air densities was also extended. The curves for these tests (fig. 10) again indi-

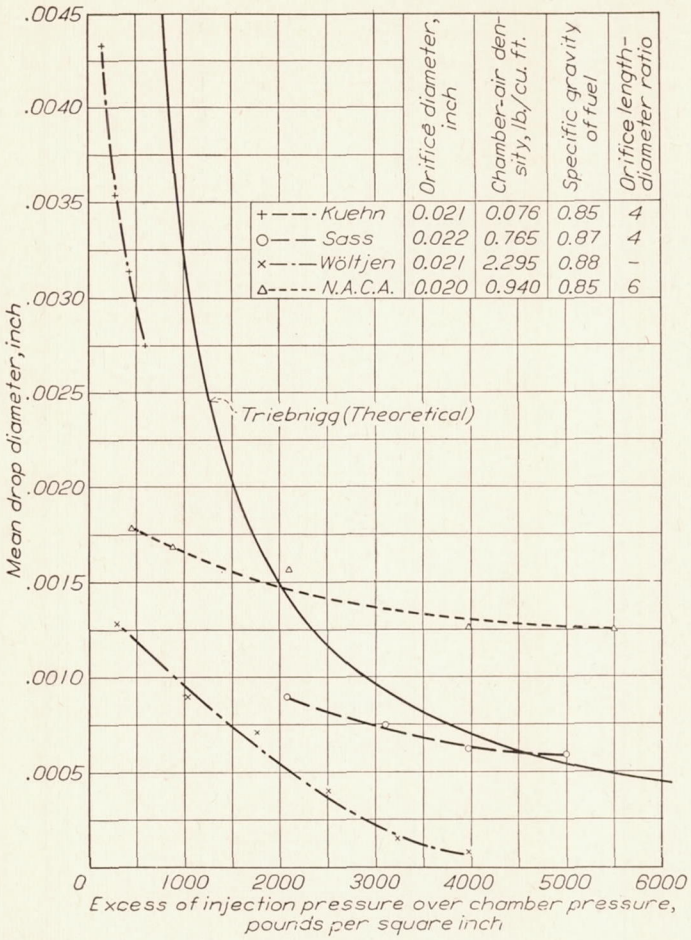


FIGURE 8.—Comparison of the results of various investigators concerning the effect of injection pressure on mean drop size

cated that the best atomization was produced at the lowest air density, but the poorest atomization was obtained at the intermediate density.

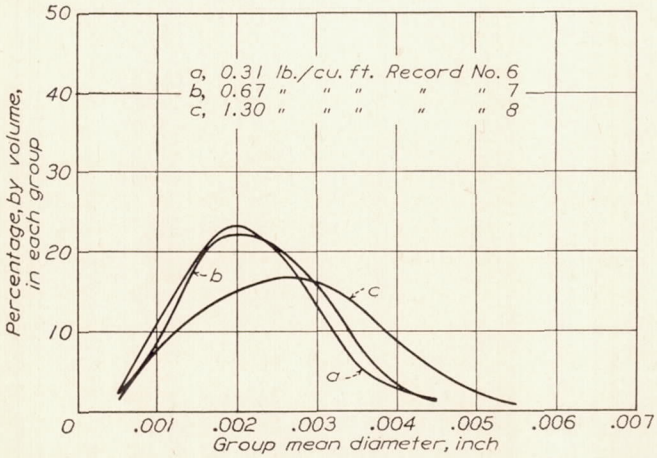


FIGURE 9.—Effect of chamber-air density on fuel atomization. Effective injection pressure, 4,100 lb. per sq. in.

Kuehn worked at atmospheric air pressure only, so that his data include no information on the effect of air density. Wöltjen reported a series of tests at different air densities, but was unable to detect any change in the atomization due to changes in the air density.

The effects of the chamber-air density on the volumetric mean drop size as measured by Sass and by this

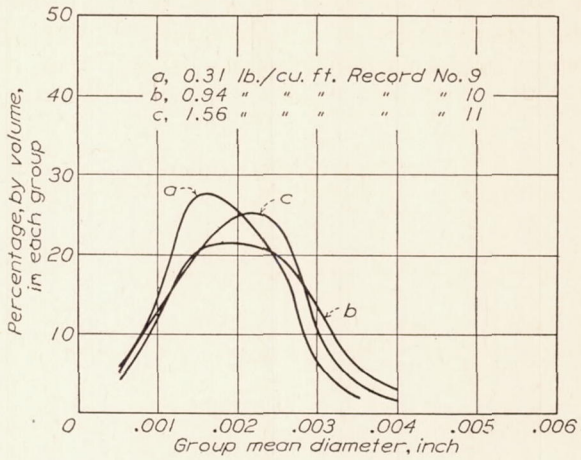


FIGURE 10.—Effect of chamber-air density on fuel atomization. Effective injection pressure, 4,140 lb. per sq. in.

laboratory (records 9, 10, and 11) are shown in Figure 11. Triebnigg's theoretical curve, computed with the same constants used for Figure 8, is also included. His assumption that the atomization is inversely proportional to the air density is not supported by the experimental results.

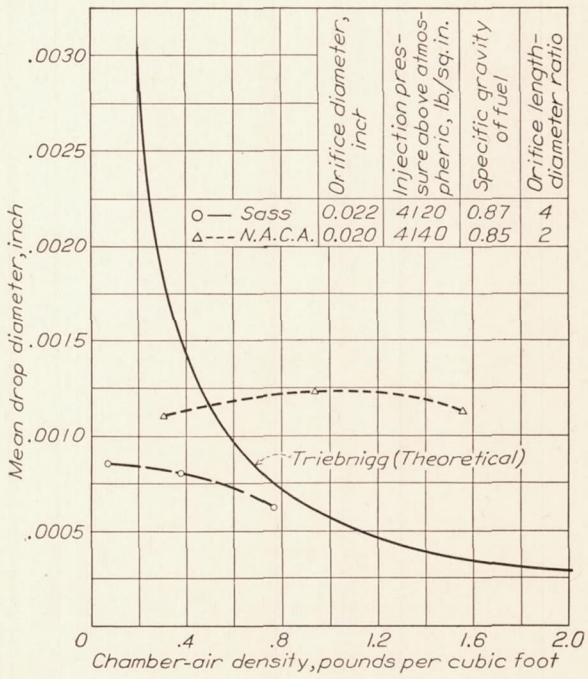


FIGURE 11.—Comparison of the results of various investigators concerning the effect of chamber-air density on mean drop size

In view of these conflicting results and incomplete experimental work, the only conclusion to be drawn regarding the effect of air density on atomization is that it is not as great as has commonly been thought.

Nozzle dimensions—Orifice diameter.—Next to jet velocity, probably the most important factor in fuel atomization is the orifice diameter. Figure 12 shows

the results of tests made with three nozzles, geometrically similar, but having different orifice diameters. These curves show that the atomization became finer and more even when smaller orifices were used. In these tests care was taken to have the effective injection pressure the same with all nozzles. Owing to the differ-

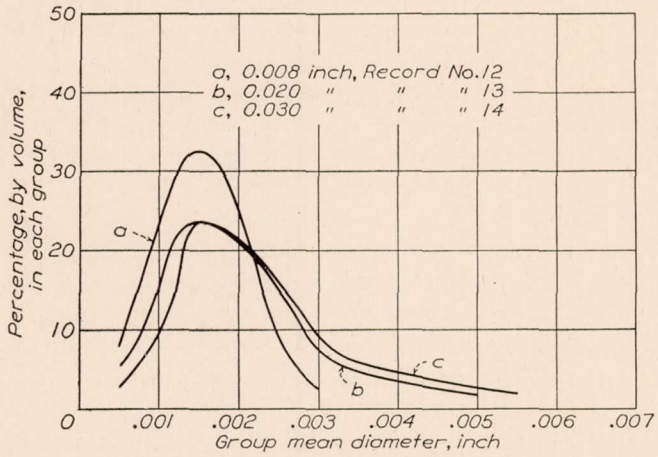


FIGURE 12. Effect of orifice diameter on fuel atomization. Mean effective injection pressure, 3,913 lb. per sq. in.

ence in flow area, the same reservoir pressure could not be used with the different nozzles. Instead, it was varied for the second and third tests until the stem-lift records showed that the pressure at the nozzle was the same as for the first test. The experiments of Sass agree with these as to the effect of orifice diameter on

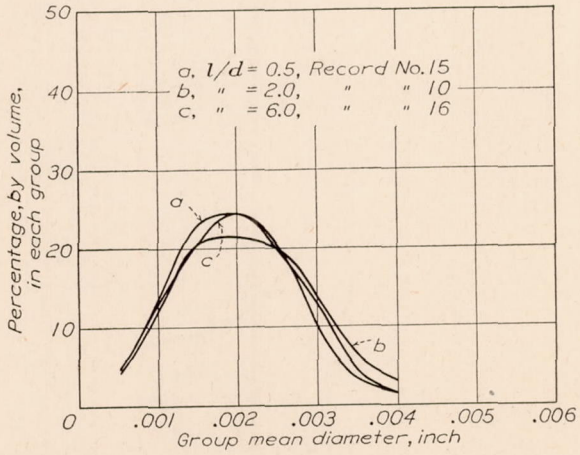


FIGURE 13.—Effect of orifice length-diameter ratio on fuel atomization. Mean effective injection pressure, 4,133 lb. per sq. in.

the atomization, but he again found the average drop size smaller.

Orifice length-diameter ratio.—Figure 13 shows the results of atomization tests with orifices having different length-diameter ratios. No definite changes in the atomizations could be measured.

ATOMIZATION OF SPRAYS FROM SPECIAL TYPES OF NOZZLES

Although fuel sprays from plain nozzles have been found by many engine tests to be satisfactory whenever the shape of the combustion chamber will allow their use, there are many cases where greater dispersion and less penetrative power are desirable. These features are sometimes obtained by replacing the single hole by a number of smaller ones having the same total area. This case has been covered by the tests on the effect of orifice diameter on atomization.

Centrifugal-type sprays.—The use of helical grooves in the valve stem through which the fuel must pass before going through the nozzle is another means of spreading out the spray. Many attempts have been made to use this principle in injection valves, but the engine test results have usually been disappointing.

To determine what effect a spirally grooved stem had on the atomization of the fuel, the combination shown in Figure 2 (b) was tested, and the results were compared with those obtained with the same nozzle using a plain stem. As Figure 14 shows, a pressure of 2,280

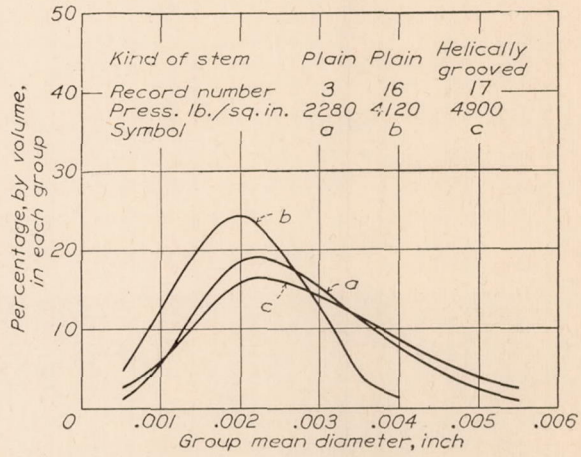


FIGURE 14.—Atomization curves for a helically grooved stem and a plain stem in the same injection valve

pounds per square inch with the plain stem produced an atomization of the same degree of fineness but of greater uniformity than 4,900 pounds per square inch with the spirally grooved stem. The value of the coefficient of discharge for the centrifugal spray was only 0.37 as compared with 0.94 for the same nozzle without the grooved stem. Assuming no jet contraction, the computed discharge velocity for the centrifugal spray at a pressure of 4,900 pounds per square inch was found to be 342 feet per second, whereas that for the straight spray at 2,280 pounds per square inch was 590 feet per second. These results indicate that it is the jet velocity rather than the injection pressure that controls the fineness and uniformity of atomization.

Impinging-jets sprays.—Another means of increasing the dispersion of fuel sprays is to have two fuel jets impinge upon each other immediately after leaving their orifices. To study the effect of such impingement on the atomization and distribution of sprays, tests were made using the nozzle shown in Figure 2 (d). In Figure 15 curves are shown comparing the atomiza-

tion produced by this nozzle and by a plain nozzle having an orifice diameter nearly the same as that of each of the impinging-jets orifices. Here again care was taken to keep the pressure at the nozzle the same

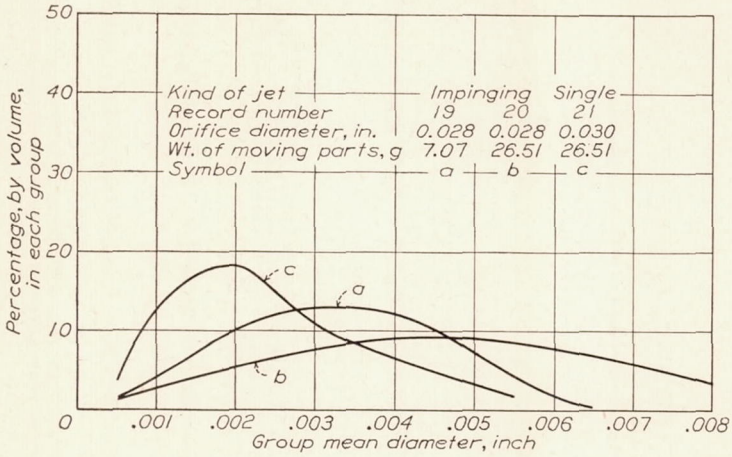
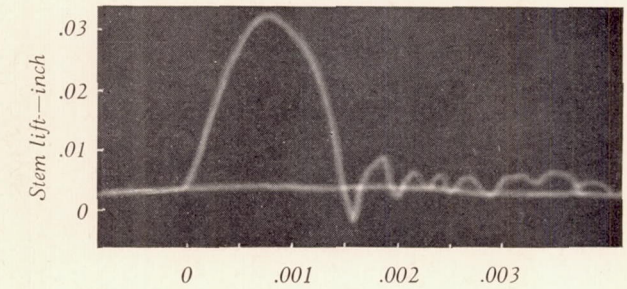
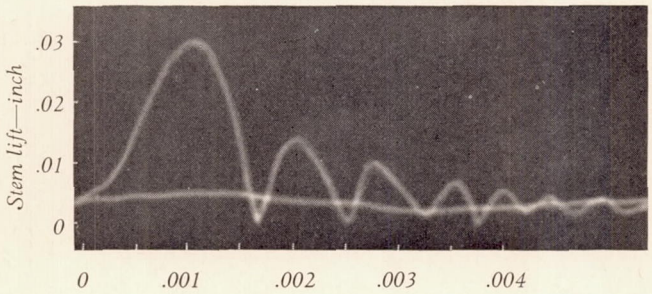


FIGURE 15.—Atomization curves for sprays from impinging jets and from a single jet. Effective injection pressure, 1,730 lb. per sq. in.

in all tests. The results of these tests showed a much poorer atomization for the impinging jets than for the single jet. However, the design of the impinging-jets nozzle may partly account for this poorer atomization. The jet velocity of the impinging jets was probably less



(a) Weight of the moving parts—7.07 grams



(b) Weight of the moving parts—27.51 grams

FIGURE 16.—Stem-lift records made with the impinging-jets valve

than that of the single jet, because of the long and angular passage between the valve-stem seat and the orifices, and such a lowered velocity would make the atomization poorer. Unfortunately, the apparatus used at this laboratory to measure the coefficients of discharge of nozzles is not capable of handling such large rates of flow as prevail in this impinging-jets nozzle, so that the discharge velocities could not be computed. Another factor which probably caused the atomization to be poorer for this nozzle was the larger volume of fuel injected at low velocities during the secondary discharges, which are caused by the bouncing of the valve stem on its seat after cut-off.

To determine whether these secondary discharges had a decided effect on the atomization, a test was made with the impinging-jets nozzle and valve in which weights were added to the valve stem until its mass was increased to four times the normal value. Stem-lift records (fig. 16) showed a very pronounced increase in the bouncing of the stem, and the atomization was found to be much poorer. (Compare curves for records Nos. 19 and 20 in fig. 15.)

Sprays from a lip nozzle.—The next nozzle to be tested was one having a steel lip placed in the path of the fuel jet. (See fig. 2 (c).) The results are shown in Figure 17, which also shows the curve for a plain nozzle under nearly the same conditions. The orifice diameter of the lip nozzle was a little less than that of the plain nozzle, but the injection pressure was also a little lower. From the results of the tests on these two variables it was computed that the increase in the volumetric mean drop diameter due to the lower pressure nearly offset the decrease due to the smaller orifice, so that the results of this test are comparable. The curves are almost identical, so that it may be con-

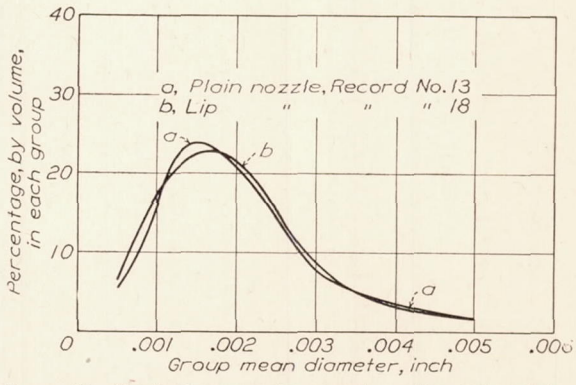


FIGURE 17.—Atomization curves for sprays from a lip nozzle and from a plain nozzle. Orifice diameter—lip nozzle, 0.018 inch; plain nozzle, 0.020 inch. Effective injection pressure—lip nozzle, 3,600 lb. per sq. in.; plain nozzle, 3,920 lb. per sq. in.

cluded that the lip had no measurable effect on the atomization.

Visual observation of sprays.—When these various types of low penetration sprays are injected into the air for visual observation, they always appear to be more finely atomized than the sprays from plain nozzles. They appear so because the drops distribute themselves more quickly throughout the air, soon losing their high velocity and then settling slowly downward. It is believed that these atomization experiments have shown the futility of attempting to

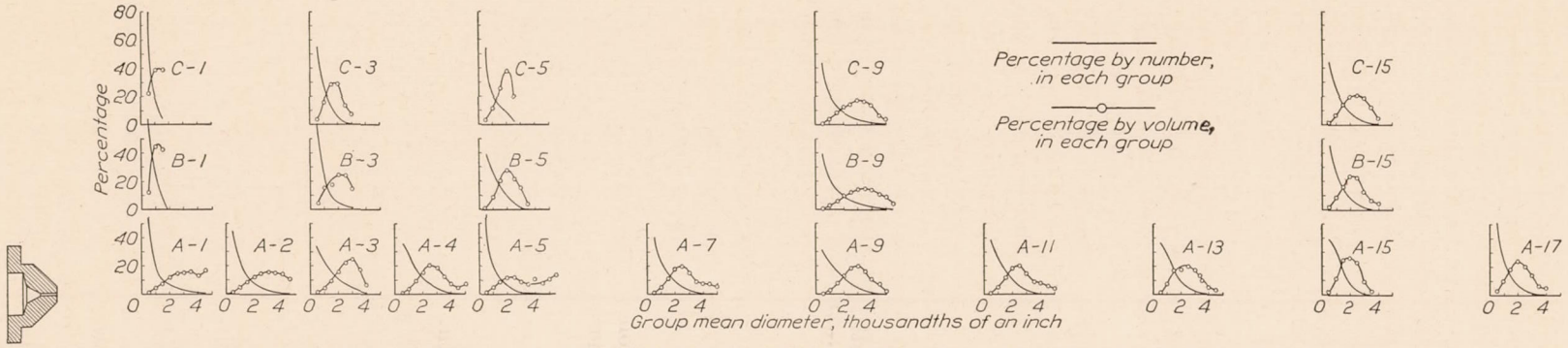


FIGURE 18.—Atomization curves obtained from record No. 3, using a plain cylindrical nozzle. Effective injection pressure, 2,280 lb. per sq. in.; chamber-air density, 0.94 lb. per cu. ft.; orifice diameter, 0.020 inch

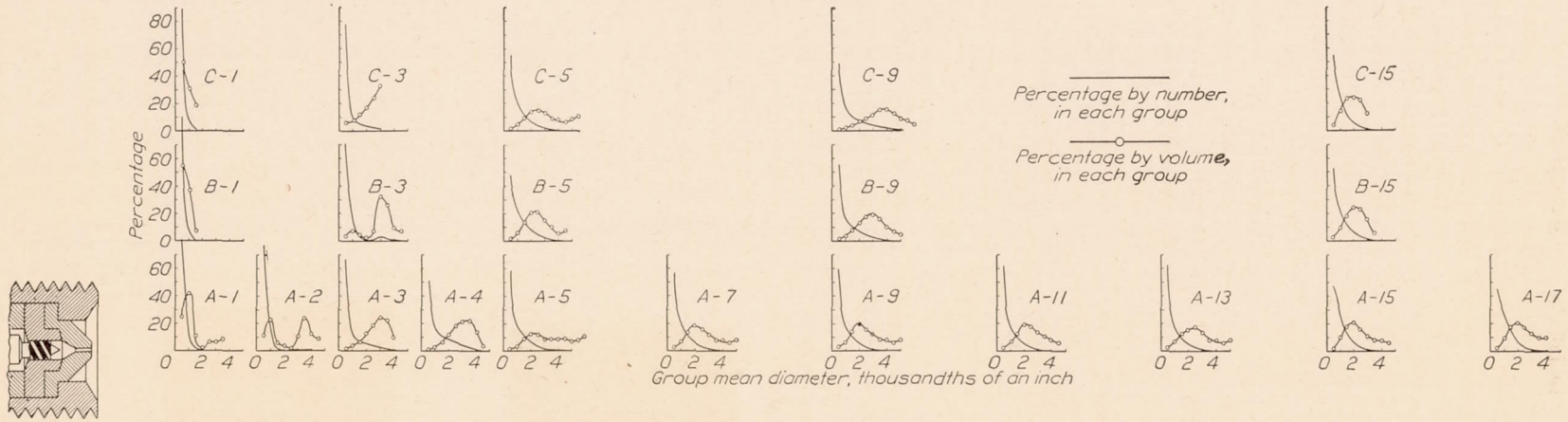


FIGURE 19.—Atomization curves obtained from record No. 17, using a helically grooved valve stem. Effective injection pressure, 4,900 lb. per sq. in.; chamber-air density, 0.94 lb. per cu. ft.; orifice diameter, 0.020 inch

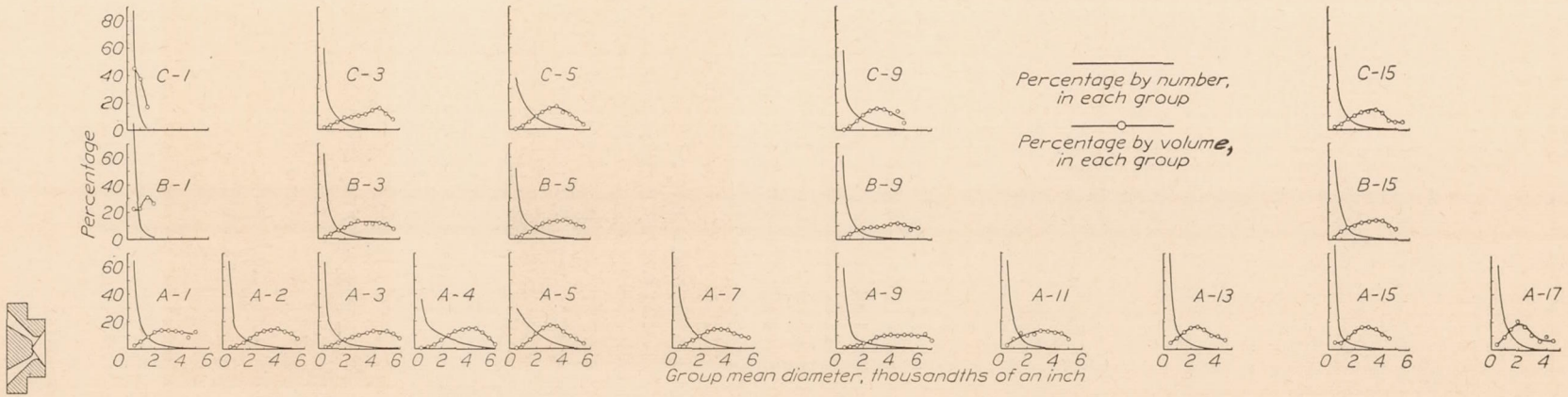


FIGURE 20.—Atomization curves obtained from record No. 19, using an impringing-jets nozzle. Effective injection pressure, 1,730 lb. per sq. in.; chamber-air density, 0.94 lb. per cu. ft.; diameter of each orifice, 0.028 inch

judge the relative atomization of fuel sprays by such observations.

DISTRIBUTION OF THE DROPS IN FUEL SPRAYS

Up to this point the discussion has been limited to the average atomization of the sprays. However, the atomization of different parts of the sprays may be studied by plotting the data obtained from each photomicrograph as separate curves, and arranging these in the same order as the positions on the lampblack records at which the photomicrographs were taken. Figures 18 to 20 show atomization curves arranged in this manner, the letter and number beside each set of curves designating its location, according to the system shown in Figure 4.

In the study of these figures it is necessary to keep in mind that they represent conditions in the sprays after the drops had lost most of their forward velocity. The records showed that this did not occur in many cases until they had reached a point 17 inches or more away from the nozzle. In an engine the drops would have struck the chamber walls or have been burned before they had traveled this distance, so that these figures do not picture the atomization as it would be at the time of combustion. The best that can be done with the present test method is to try to reason backward, being guided by the knowledge of spray characteristics gained by other means.

Computations on the penetration of single fuel drops in compressed air made by Kuehn (reference 9) show that the energy possessed by them as they leave the nozzle is sufficient to enable them to penetrate the dense air of the combustion chamber only about 1 inch. The fact that they do travel much farther from the nozzle he attributed to the presence of the large number of drops in each spray, all of which transmit their kinetic energy to the surrounding air, and thus establish an air current in the direction of the jet. The drops soon lose their velocity with respect to the air, but continue to move forward, carried by the moving air. Experiments have been performed at this laboratory (reference 10) which indicate that this explanation is correct. Sprays were produced under a wide variety of conditions, their form was studied by taking spark photographs, and their penetrating power measured by injecting them against targets made of Plasticine. The results showed that in sprays from plain nozzles which were injected at high pressure (4,000 pounds per square inch) into compressed air (density = 1.1 pounds per cubic foot) the fuel drops had lost most of their relative air velocity by the time they reached a point 4 inches from the nozzle. Until this penetration was attained the spray was composed of a central core containing drops which still had a high velocity relative to the air, surrounded by an envelope of spray in which the fuel concentration was much less, and in which the fuel drops had little velocity relative to the air. Some of the drops in the outer portions of the core were torn off and entered the envelope, but the greater number of them remained in the core. Beyond about 4 inches, there was no longer a distinct core and envelope, but the entire spray was composed of drops in a swirling air current.

The distribution of the drop impressions on the lampblack records furnished additional evidence that fuel sprays are formed in this manner. On the records made with the test chamber in the horizontal position, the portions representing the first few inches of spray penetration always showed a definite pattern, very narrow under the nozzle, but flaring out until it filled the width of the record at about 5 inches from the nozzle end. Beyond this region the records were never similar. The dots in the sketch of a typical lampblack record (fig. 4) show the distribution of the impressions that were visible to the unaided eye on this record. The photomicrographs shown in Figure 5 (a), (b), and (c) were made of the same record, and show how the size of the impressions varied in different parts of the records.

When the test chamber was mounted vertically and smoked plates were placed at the bottom of the chamber perpendicular to the spray axis and 18 inches from the nozzle, the distribution of the impressions was usually very regular. There were often a few very large drops directly under the nozzle, probably due to dribbling of the valve.

If the process of spray formation as outlined in the preceding paragraphs be kept in mind, the atomization curves for a spray from a plain nozzle (fig. 18) may be used to visualize the distribution of the drops at the start of combustion. If, for instance, it is assumed that combustion starts when the spray has become 4 inches long, all of the fuel represented by curves beyond this point must be thought of as coming from the inner core of the spray, and the curves which are in rows B and C and are 4 inches or less from the nozzle position represent fuel in the envelope. Curves A–1 to A–5 probably represent fuel leaving the nozzle at the end of the main injection, or during the secondary discharges.

A comparison of Figure 18 and a similar plot for a spray from the same nozzle at 5,700 pounds per square inch injection pressure showed that the curves at positions A–1 to A–5 had the greatest differences. This fact supports the supposition that these curves represent the secondary discharges, for, as Figure 8 shows, equal pressure changes have a greater effect at low than at high injection pressures. The comparison also showed that the increase in the injection pressure had a greater effect on the fuel in the envelope than on the fuel in the core of the sprays.

Sprays made with a helically grooved stem in the injection valve are quite different from those made with a plain stem. Both spark photographs and injections against Plasticine targets showed that the spray in the former case was composed of a central core of

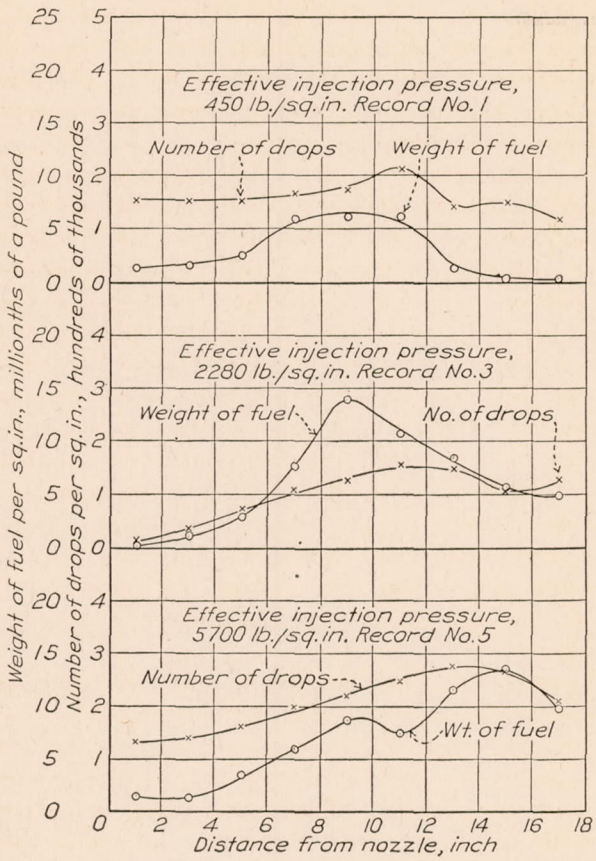


FIGURE 21.—Effect of injection pressure on spray penetration. Chamber-air density, 0.94 lb. per cu. ft.

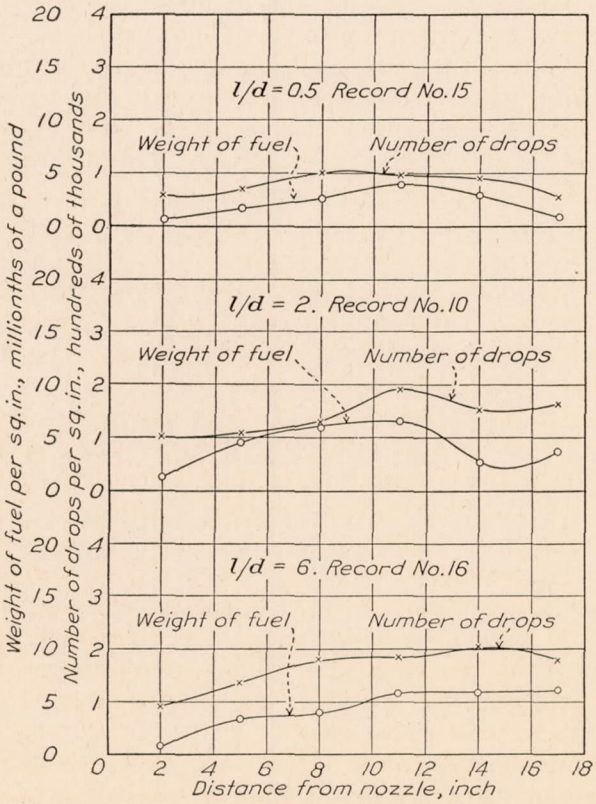


FIGURE 23.—Spray penetration curves for nozzles with different orifice length-diameter ratios. Mean effective injection pressure, 4,133 lb. per sq. in.; chamber-air density, 0.94 lb. per cu. ft.

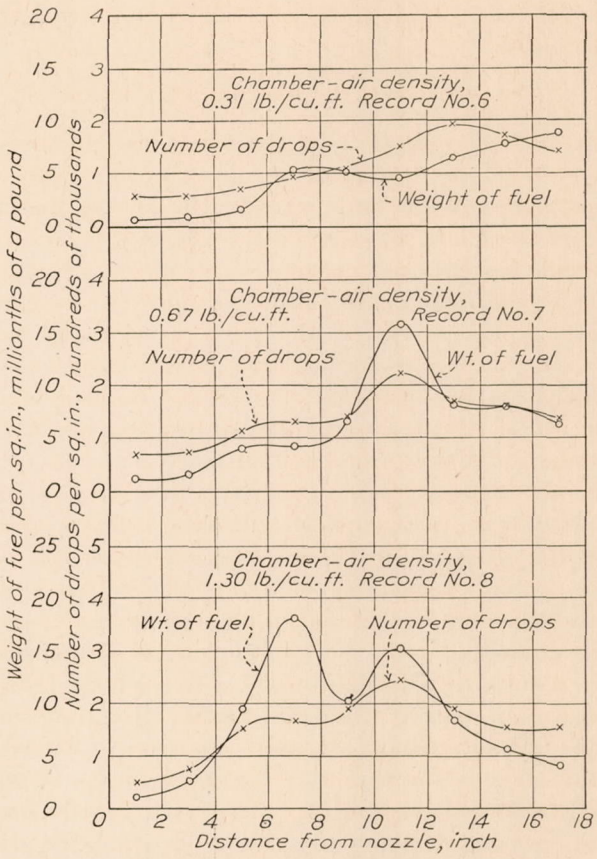


FIGURE 22.—Effect of chamber-air density on spray penetration. Effective injection pressure, 4,100 lb. per sq. in.

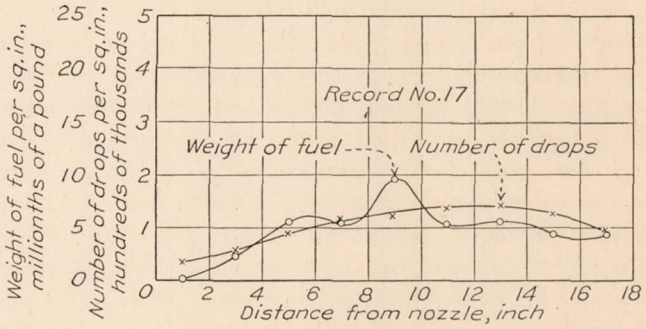


FIGURE 24.—Spray penetration curves for a centrifugal-type spray. Chamber-air density, 0.94 lb. per cu. ft.; effective injection pressure, 4,900 lb. per sq. in.

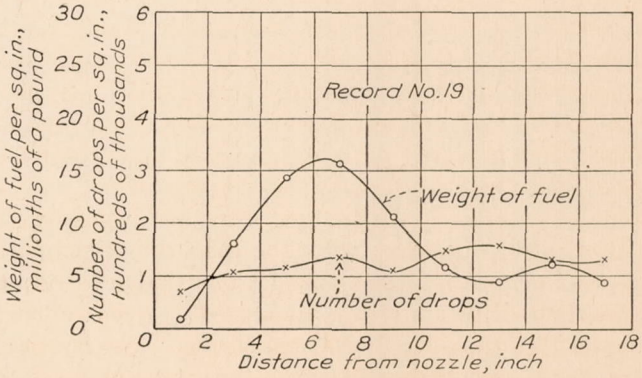


FIGURE 25.—Spray penetration curves for an impinging-jets spray. Chamber-air density, 0.94 lb. per cu. ft.; effective injection pressure, 1,730 lb. per sq. in.

approximately cylindrical form surrounded by a thin sheet of fuel in the form of a hollow cone having an apex angle of about 50°. When injected into air at atmospheric density, this hollow cone was very distinct and maintained its shape for several inches beyond the nozzle. At an air density of 0.94 pound per cubic foot, however, the conical sheet of fuel was less distinct and lost its penetrative power much sooner than the central core.

The atomization in different parts of such a spray is shown in Figure 19. Under the conditions used for this test the fuel drops lost their relative air velocity somewhere between 1 and 3 inches from the nozzle. The shapes of some of the atomization curves in this figure are different from any obtained with the other nozzles. At three positions near the nozzle there is a scarcity of drops from 0.0015 to 0.0025 inch in diameter, and at position C–3 the drops of the largest size contain the greatest percentage of fuel. This latter curve may be the result of photographing and measuring a nonrepresentative group, but the other abnormal type was found too many times to be accidental. The best explanation of the double peaks of these curves seems to be that they represent the two distinct parts of the spray. The peak showing the finer atomization was caused by fuel from the outer cone, and the other peak represents the fuel from the central core. A comparison of the curves at positions A–1 and B–1 supports this explanation. This double-peaked type of curve appears most distinctly at the position A–2. At 2 inches from the nozzle the fuel from the outer cone had probably lost its relative air velocity and settled, together with that from the inner core, onto the lampblack below.

Sprays from the impinging-jets valve had the form of a semicircular disk, the plane of which was perpendicular to that through the two nozzles. The results from the tests with this valve illustrate the importance of investigating both the atomization and the distribution of sprays, although for this valve the atomization is very poor the distribution is excellent. (See fig. 20.)

PENETRATION OF THE FUEL IN SPRAYS

In the computations that were made for the curves of average atomizations of sprays, the lampblack records were divided into sections, and the average data for each section were first computed. To obtain curves which would show the penetrating power of the sprays, these data were converted to the average number of drops and their weight per square inch of record surface for each section, and these values were plotted against the distance from the nozzle to the center of the corresponding section.

Figure 21 shows how the penetration increased with an increase in the injection pressure, and Figure 22 shows how it decreased when the chamber air density was increased. Figure 23 shows the effect of the length-diameter ratio of the orifice on spray penetration. As the ratio was changed from 0.5 to 6, the penetrating power increased slightly. The penetration of a spray from the helically grooved valve was about the same as that from a plain valve injected at the same jet velocity (fig. 24), but the spray from the impinging-jets valve had a very low penetration. (See fig. 25.)

CONCLUSIONS

The experiments which were made during this investigation furnish the basis for the following conclusions:

1. Each spray is composed of several million fuel drops, whose diameters vary from less than 0.00025 inch up to 0.0050 inch and sometimes more. By far the greatest number of drops have diameters of 0.0010 inch or less, but those between 0.0015 and 0.0025 inch usually contain more than half the weight of the fuel charge.
2. When the velocity of the fuel through the nozzle is increased, either by raising the injection pressure or by improving the design of the injection system, there is a reduction in the relative number of the large drops. The result is a more uniform atomization and a smaller mean drop size.
3. A decrease in the orifice diameter also results in a more uniform atomization and a smaller mean drop size.
4. The density of the air into which the fuel is injected has little effect on the final atomization attained.
5. Within the range of orifice sizes and operating conditions commonly used, the variation in the mean drop size is small. The factor having the greatest effect on the atomization is the velocity of the fuel as it leaves the orifice, the increase in velocity resulting from an increase in the injection pressure from 2,280 to 5,700 pounds per square inch causing a reduction of only 20 per cent in the volumetric mean drop diameter.
6. Whirling of the fuel as it is injected has, in itself, no decided effect on the atomization. However, the jet velocities for the same injection pressures are lower for centrifugal than for plain sprays, and the degree of atomization correspondingly less.
7. Impinging of a fuel jet against a metal lip close to the orifice results in no measurable change in the atomization.
8. Visual observation of sprays injected into the air can not be used to estimate their relative fineness of atomization.
9. Centrifugal sprays and sprays produced by the impinging of two fuel jets have a more even distribution of the fuel than those from plain nozzles, but their penetrating power is much lower.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *February 19, 1932.*

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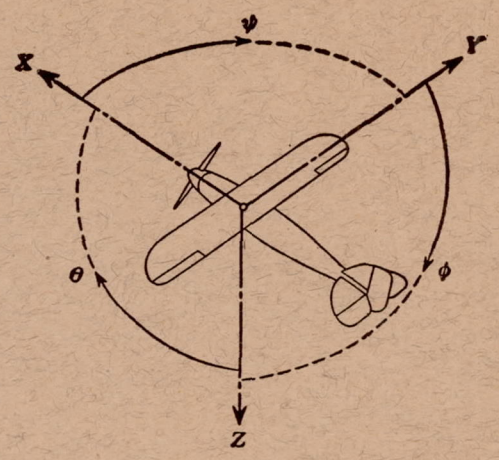

Positive directions of axes and angles (forces and moments) are shown by arrows

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

$$C_l = \frac{L}{qbS} \qquad C_m = \frac{M}{qcS} \qquad C_n = \frac{N}{qbS}$$

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 $= \sqrt[5]{\frac{\rho V^5}{P n^2}}$.
η, Efficiency.
n, Revolutions per second, r. p. s.
Φ, Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp = 76.04 kg/m/s = 550 lb./ft./sec.
1 kg/m/s = 0.01315 hp
1 mi./hr. = 0.44704 m/s
1 m/s = 2.23693 mi./hr.
1 lb. = 0.4535924277 kg.
1 kg = 2.2046224 lb.
1 mi. = 1609.35 m = 5280 ft.
1 m = 3.2808333 ft.