NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 565

MEASUREMENTS OF FUEL DISTRIBUTION WITHIN SPRAYS FOR FUEL-INJECTION ENGINES

By DANA W. LEE

1936

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

2. GENERAL SYMBOLS

W, Weight $=mg$

g, Standard acceleration of gravity $=9.80665$ m/s² 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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MEASUREMENTS OF FUEL DISTRIBUTION WITHIN SPRAYS FOR FUEL-INJECTION ENGINES

By Dana W. Lee

SUMMARY

Two methods were used to measure fuel distribution within sprays from several types of fuel-injection nozzles. A small tube inserted through the wall of an airtight chamber into which the sprays were injected could be moved about inside the chamber. When the pressure was raised to obtain air densities of 6 and 14 atmospheres, some air was forced through the tube and the fuel that was carried with it was separated by absorbent cotton and weighed. Cross sections of sprays from plain, pintle, multiple-orifice, impinging-jets, centrifugal, lip, slit, and annular-orifice nozzles were investigated, at distances of 1, 3, 5, and 7 inches from the nozzles.

Sprays that were symmetrical about their axes were also tested by a second method in which the injection valve was inserted through the top of a pressure chamber containing a nest of eight concentric cups, the axis of which coincided with the nozzle axis. The injected fuel was caught by the cups, drained into receptacles below, and weighed. Tests were made at 1, 6, and 14 atmospheres, at the same distances from the nozzles used in the first method.

It was found that the distribution of the fuel within the sprays always improved with increasing distance from the nozzle and usually with increasing air density, the effect of both factors being greatest with sprays of high penetrating power. Distribution within sprays from plain nozzles improved slightly with an increase in the injection pressure or with a decrease in the fuel viscosity. Changing the orifice length-diameter ratio of plain nozzles had little effect on fuel distribution.

INTRODUCTION

Laboratory research on compression-ignition engines has resulted in recent years in continued increases in speed and mean effective pressure, particularly when some form of controlled air swirl is used to improve the distribution of fuel throughout the combustion chamber. Another effective method of increasing the specific power output is to improve the fuel distribution through changes in the nozzle design and injection pressure, and it is believed that the work described in this report will be useful to those who are working along such lines. Spark-ignition engines employing fuel injection having shown definite advantages over carburetor-equipped engines, distribution tests were also made at low air densities.

Outstanding among previous measurements of fuel distribution within sprays are those made at the Pennsylvania State College, where the weights of fuel reaching various stations on a "dispersion rack" were accurately determined (reference 1). The effects of injection pressure, air density, fuel viscosity, orifice diameter, and distance from the nozzle were determined using plain cylindrical nozzles. The results are complete only at 14 inches from the nozzle; at nearer stations the weights at the center of the spray could not be obtained. At a later date, the total amounts of fuel reaching various distances from the nozzle were caught and weighed by a "tipping cup" (reference 2).

Several previous experiments on the distribution of fuel in sprays have also been made at this laboratory. The relative amounts of fuel reaching different distances from the nozzle were obtained in connection with atomization measurements and the results are given in reference 3. The structure of fuel sprays and the process by which they are formed were studied by means of spark photographs taken under a wide variety of conditions (reference 4), and the study was continued by means of photomicrographs of the sprays (reference 5). The approximate dimensions of the high-velocity cores of sprays from several types of nozzles were obtained by injecting them against pieces of plasticine, and the outlines of the sprays were obtained from spark photographs. Cross-sectional sketches of the sprays made from these measurements are shown in reference 6.

The present tests, which were made to obtain quantitative data on the distribution of fuel within sprays from several types of nozzles, are divided into two parts, each using a different test method. The first method gave the relative amounts of fuel reaching any particular point in the spray; the second gave the actual weight reaching each of a series of annular areas concentric about the spray axis. The variables studied were: Air density, nozzle design, fuel viscosity, and injection pressure. Results were obtained at 1, 3, 5, and 7 inches from the nozzles with the air at 1, 6. and 14 times atmospheric density and at room temperature. The tests were made at the Committee's laboratories at Langley Field, Va., during the first 6 months of 1935.

APPARATUS

SAMPLING TUBE

The apparatus used to determine the relative amounts of fuel reaching different points in the sprays will be referred to as the "sampling-tube apparatus" because it consisted essentially of a small copper tube that removed a small amount of fuel from each spray passing its open end. The tube was soldered to a traversing-screw mechanism by which it could be moved linearly at right angles to the spray axis. (See fig. 1.) The tube could enter the chamber through

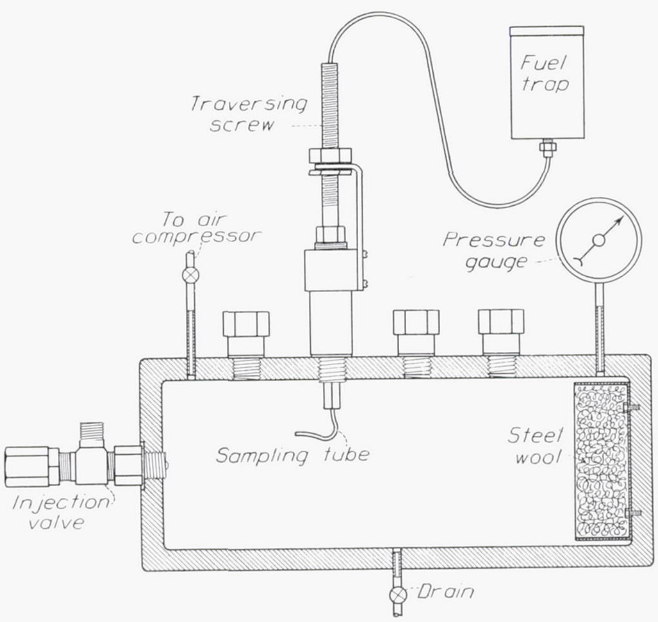


FIGURE 1.—Sampling-tube apparatus.

any one of the four holes shown, the others then being closed. The inside and outside diameters of the tube were 0.040 and 0.080 inch, respectively, and the open end was filed to a sharp edge to minimize splashing of the fuel. The tube extended through the hollow center of the traversing screw into the fuel trap. The inside of the spray chamber was 10¾ inches long, 3⅝ inches high, and 4 inches wide. Some of the early tests were made with a glass window installed in one side of the chamber, and it was found that steel wool was very useful in reducing the amount of fuel that splashed from the end wall and was carried back into the spray by the circulating air currents.

In order to make a test, the valve in the compressed-air line was adjusted until the desired pressure was maintained in the chamber and then the fuel-injection pump was started. Because the air pressure inside the chamber was greater than that outside, air flowed through the tube to the fuel trap, carrying with it all the fuel reaching the end of the tube. Absorbent cotton in the trap retained the fuel but allowed the air to escape. After about 400 sprays had been injected the pump was stopped, the pressure-release valve was opened, and the fuel trap was detached and weighed on an analytical balance. From its weight increment during the test and the number of sprays injected, the "grams of fuel collected per 1,000 sprays" was computed. This value was used as a measure of the fuel concentration in the spray at the end of the sampling tube. Although it is desirable to express the results as grams of fuel per square inch per injection, it is impossible because air flowed into the tube from an area greater than the tube area and the extent of that area is not known.

A series of exploratory tests was always made before starting the final traverse across the spray, the tube being bent sidewise by hand as well as being moved vertically by the screw. The purpose of these preliminary tests was to locate the regions of maximum fuel concentration, which were frequently quite small and might otherwise be missed.

The principal advantages of the sampling-tube method are: Sprays of any shape may be tested; as many readings may be made during a traverse as are necessary to determine the shape of the distribution curve; the traverse may be made at any distance from the nozzle; and the fuel distribution is only slightly altered by the presence of the small tube. The principal disadvantage is that the results cannot be expressed in terms of fuel weight per unit spray cross-sectional area.

CONCENTRIC CUPS

The apparatus used to obtain more accurate data on the distribution of fuel sprays will be referred to as the "concentric-cups apparatus." (See fig. 2.) The fuel sprays were caught by a nest of concentric cups mounted on a framework, which was lowered into a pressure chamber. Fuel caught by the cups drained through small tubes into receptacles on the shelf below. The distance between the nozzle and the upper edges of the cups was adjustable at 2-inch intervals from 1 to 7 inches. The inside diameters of the eight collecting cups were: 0.104, 0.25, 0.50, 0.75, 1, 1.50, 2, and 3 inches. The wall thickness of the cups was 0.010 inch and the rims were sharpened to minimize splashing. The inside diameter of the pressure chamber was 4 inches so that there was an annular space 0.5 inch wide outside the largest cup. This apparatus is suitable for testing only sprays that are symmetrical about their axes. Tests were made with the plain, the pintle, and the 4-impinging-jets nozzles; the nozzles, as well as the injection valves and the pump, were the ones used in the sampling-tube tests.

Before each test, several sprays were injected against a thin layer of plasticine mounted just above the cups. The framework was then adjusted so that the true spray axis, as indicated by the deepest part of the impression in the plasticine, coincided with the axis of the concentric cups.

After the eight fuel receptacles were weighed and placed in position, the entire framework was lowered into the pressure chamber and the cover bolted down. The injection tube from the pump was attached to the injection valve, and compressed air was admitted until the desired air density was reached. It was necessary to operate the injection pump intermittently, injecting for five cycles and idling for about 20 seconds, in order to let the fuel drain from the cups to the receptacles through the small tubes. When the pump was continuously operated, the fuel splashed from one cup to

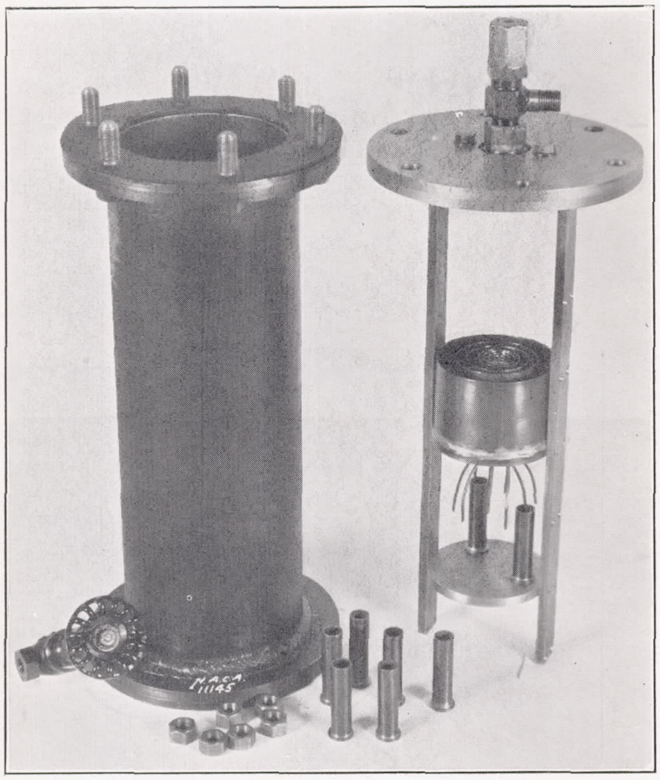


FIGURE 2.—Concentric-cups apparatus.

another. The cups were thoroughly drained after every 100 cycles, and the receptacles reweighed. From the weight increments, the areas of the corresponding compartments, and the number of cycles, the grams of fuel per square inch per cycle were computed for each annular area. The amount of fuel discharged from the nozzle during each test was determined by subsequent tests during which the pump was operated as before but in which the fuel was caught in a bottle and weighed.

The principal advantage of the concentric-cups method is that the results can be expressed in terms of fuel weight per unit spray cross-sectional area. The disadvantages are that only symmetrical sprays can be tested, the number of test readings is limited to the number of cups, and the presence of the cups somewhat alters the fuel distribution. The two test methods serve as a check on each other, the weak points of one being the strong points of the other.

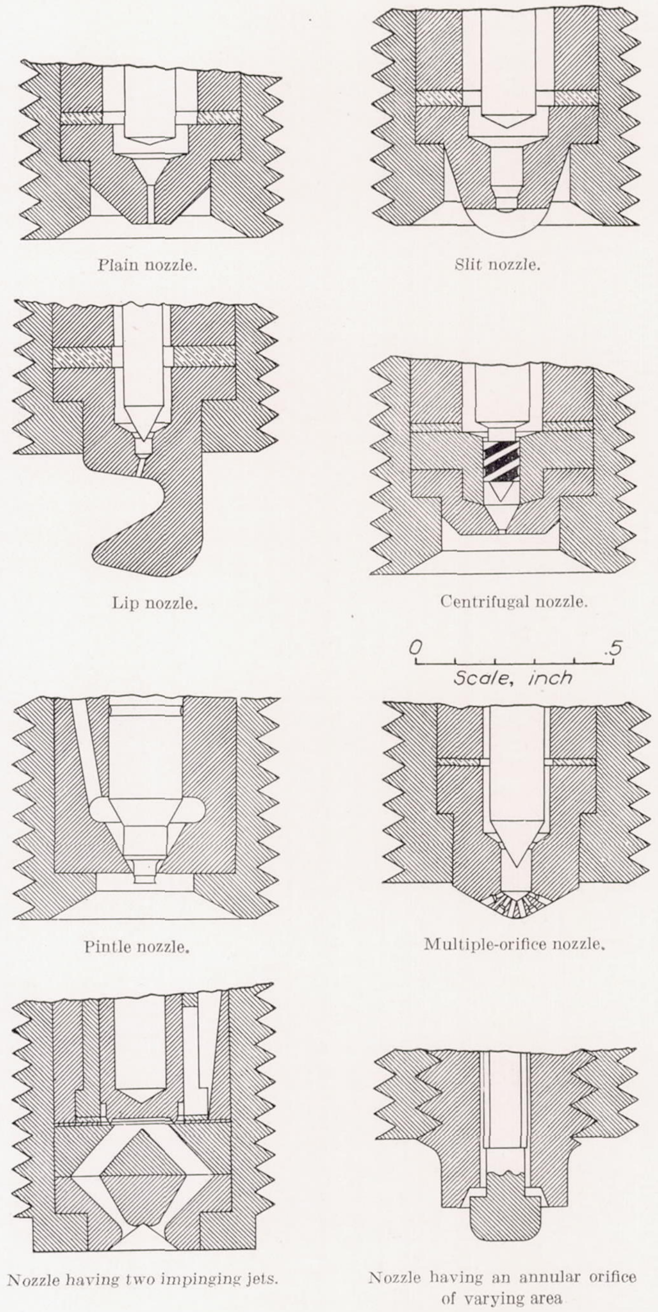


FIGURE 3.—Types of nozzles used.

INJECTION EQUIPMENT

Sketches of the types of nozzles used are shown in figure 3. Six *plain nozzles*, that is, nozzles having single cylindrical orifices, were tested. Nozzles with orifice diameters of 0.008, 0.014, 0.020, and 0.030 inch were used and, unless otherwise stated, the orifice length-diameter ratio was 2. Two *pintle nozzles* were tested, one having an orifice diameter of 0.063 inch and a nominal spray cone angle of 20° and the other having an orifice diameter of 0.059 inch and a nominal spray cone angle of 30°. The *lip nozzle* used had an orifice diameter of 0.014 inch, an orifice length of 0.028 inch, and the angle between the axis of the fuel jet and the surface of the lip was 45°. Two *impinging-jets nozzles* were tested, one having two orifices each 0.020 inch in diameter and the other having four orifices each 0.030 inch in diameter. In the 4-orifice nozzle (not shown in fig. 3) the plane through two of the orifices was at right angles to that through the other two, all four jets meeting at a common point. The angle between opposite jets was 74° in each case. With the *annular-orifice nozzle* the space between the enlarged end of the valve stem and the valve body constituted the orifice. This space varied with the injection pressure, and the cone angle of the hollow spray produced was about 45°. The *multiple-orifice nozzle* had six orifices in one plane. The two center orifices had diameters of 0.019 inch, the next two 0.014 inch, and the outer two 0.008 inch. The length of each orifice was twice its diameter and the angle between adjacent jets was 20°. The *slit nozzle* had an orifice width of 0.008 inch, a length of 0.055 inch, and an average depth of about 0.050 inch. The bottom of the short cylindrical passage above the slit was spherical, with a radius of about 0.060 inch; the radius of the spherical end of the nozzle was about 0.110 inch. The *centrifugal nozzle* had an orifice diameter of 0.020 inch and a length of 0.010 inch. There were four grooves on the valve stem to produce the whirling of the fuel; their helix angle was 30°, and the total area of the grooves and clearance space was 0.00052 square inch (equivalent to a single 0.026-inch orifice).

The nozzles were used in automatic spring-loaded injection valves, all but one valve being of the lapped-stem differential-area type. The exception was the valve with the annular orifice, the stem of which was not lapped but was guided by lands. Sketches of these injection valves may be found in reference 6. The injection valves used with the pintle and annular-orifice nozzles were obtained from commercial concerns; the other valves and nozzles were made at this laboratory.

Extensive tests of the rates of discharge of the Bosch fuel-injection pump that was used for these tests are reported in reference 7; some of the characteristics of fuel sprays produced by it are given in reference 8. The injection tube was 55 inches long and its inside diameter was 0.125 inch. The fuel discharged was practically independent of pump speed but varied slightly with orifice area, the extreme values being 0.27 gram per cycle with the 0.008-inch orifice and 0.31 gram per cycle with the annular orifice. An electrical revolution counter attached to the pump automatically recorded the number of injections made.

Except for some tests to determine the effect of fuel viscosity on distribution, the fuel used was a high-grade Diesel fuel. The following test conditions were considered standard: pump speed, 750 r. p. m.; injection-valve opening pressure, 3,500 pounds per square inch.

TEST RESULTS

SAMPLING-TUBE TESTS

The results of the sampling-tube tests of fuel distribution within sprays from the different nozzles are presented graphically in figures 4 to 15, values of grams of fuel collected per 1,000 sprays being plotted against distances from the spray axis. Distances above the spray axis are plotted to the left, those below to the right. When a spray was known to be symmetrical about its axis, only one traverse of the sampling tube was necessary at each condition, and it was not usually carried entirely across the spray but extended from the upper part of the chamber to a little below the spray axis. With unsymmetrical sprays, two traverses at right angles to each other were made for each condition. The test points are shown on the curves, connected by solid lines. The uncompleted traverses are extended with broken lines that match the solid parts. As the air in the chamber was not changed during any one test, it always became fogged with fuel particles. The fuel concentration in this mist is indicated by the level at which the curves flatten out to the horizontal, and this level should be considered as the zero line when comparisons are made between curves. Some of the tests showed a slightly higher fuel concentration in the lower parts of the spray than in the upper parts. This difference was probably caused by the increasing interference of the traversing screw as it was lowered into the chamber, deflecting more and more of the fuel from the central to the outer portions of the spray.

Sampling-tube tests were made only at air densities of 6 and 14 atmospheres. In order to obtain them at 1 atmosphere, it would be necessary to put the fuel trap in an evacuated chamber. The air velocity through the sampling tube was the same for all tests, for with an air density of either 6 or 14 atmospheres, the ratio of the pressures at the inner and outer ends of the tube was greater than the critical value of 1.9.

CONCENTRIC-CUPS TESTS

The results of the concentric-cups tests are given in table I. The cups are numbered from 1 to 8, beginning at the center. The term "percentage of fuel caught" means the total weight of the fuel collected by the cups divided by the weight discharged from the nozzle during the test, multiplied by 100. Vaporization can account for only a small part of the fuel not collected because at room temperature the rate of vaporization of Diesel fuel is negligible. Most of the fuel not caught by the cups was carried off by air currents set up by the sprays and was deposited on the walls of the chamber; from there it drained to the bottom and was removed at the end of the test.

Although tables of data are concise, any systematic trends are much more evident when the test results are presented in a graphical form. Therefore the data

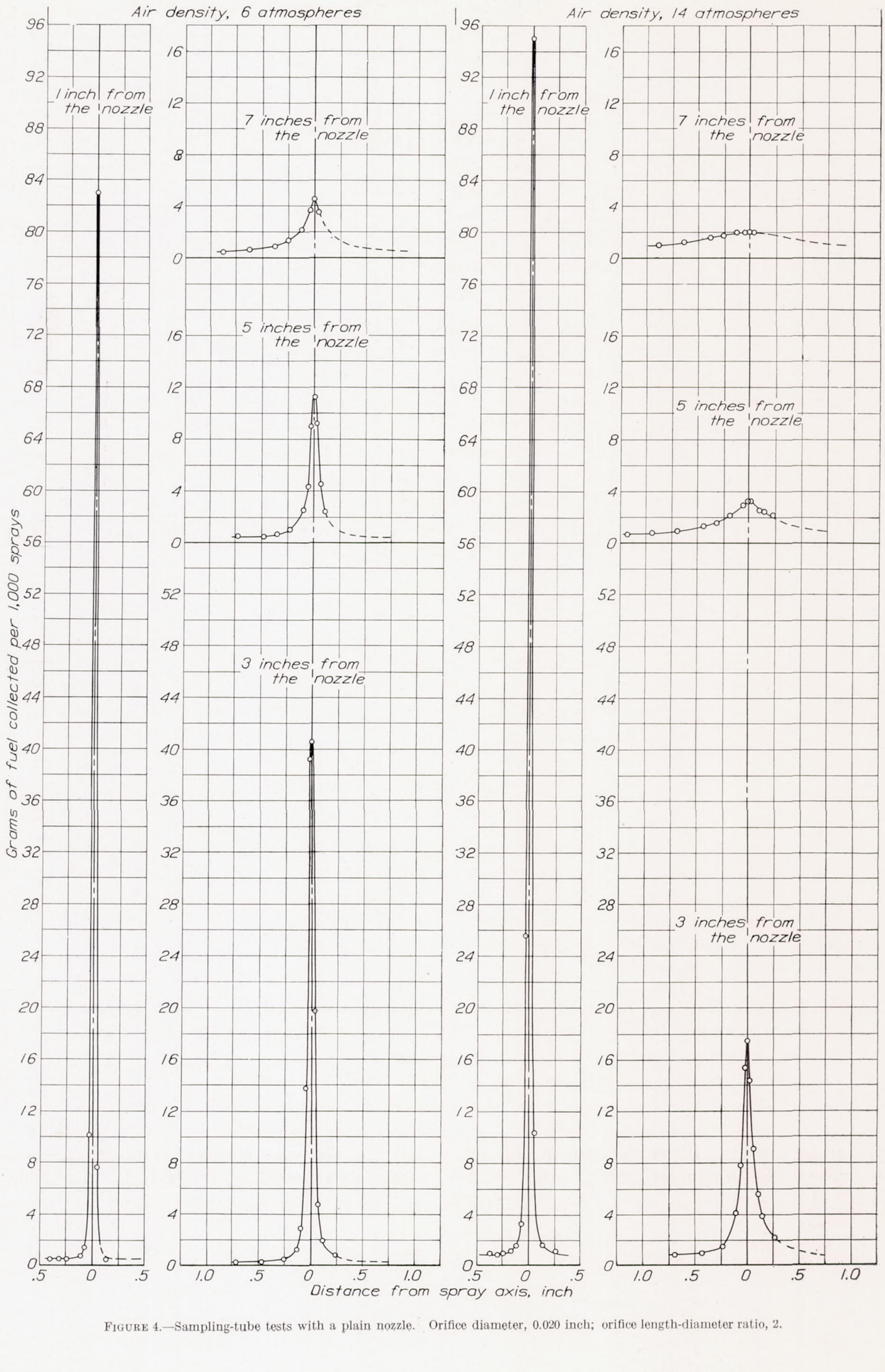


FIGURE 4.—Sampling-tube tests with a plain nozzle. Orifice diameter, 0.020 inch; orifice length-diameter ratio, 2.

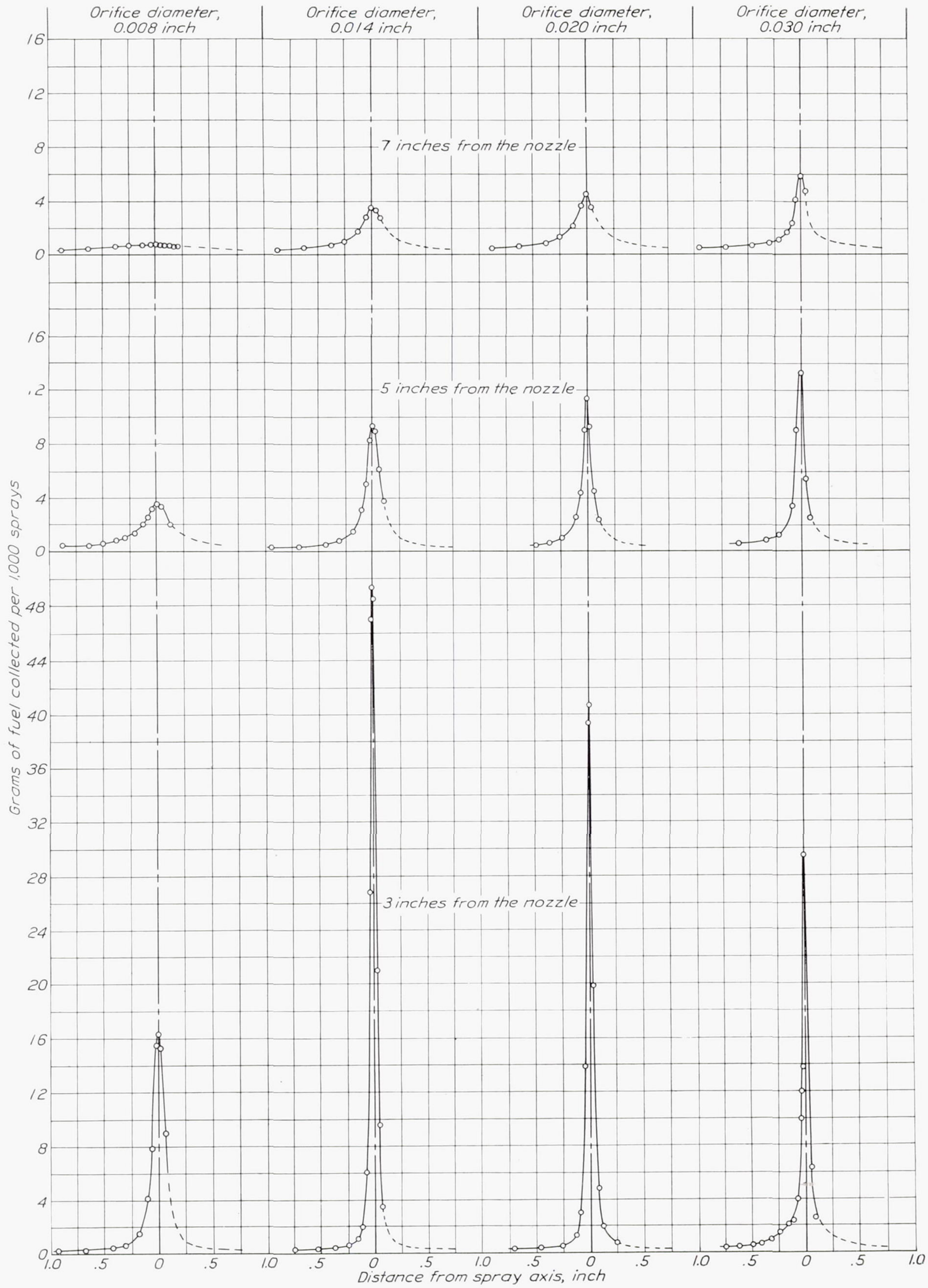


FIGURE 5.—Sampling-tube tests with plain nozzles having different orifice diameters. Orifice length-diameter ratio, 2; air density, 6 atmospheres.

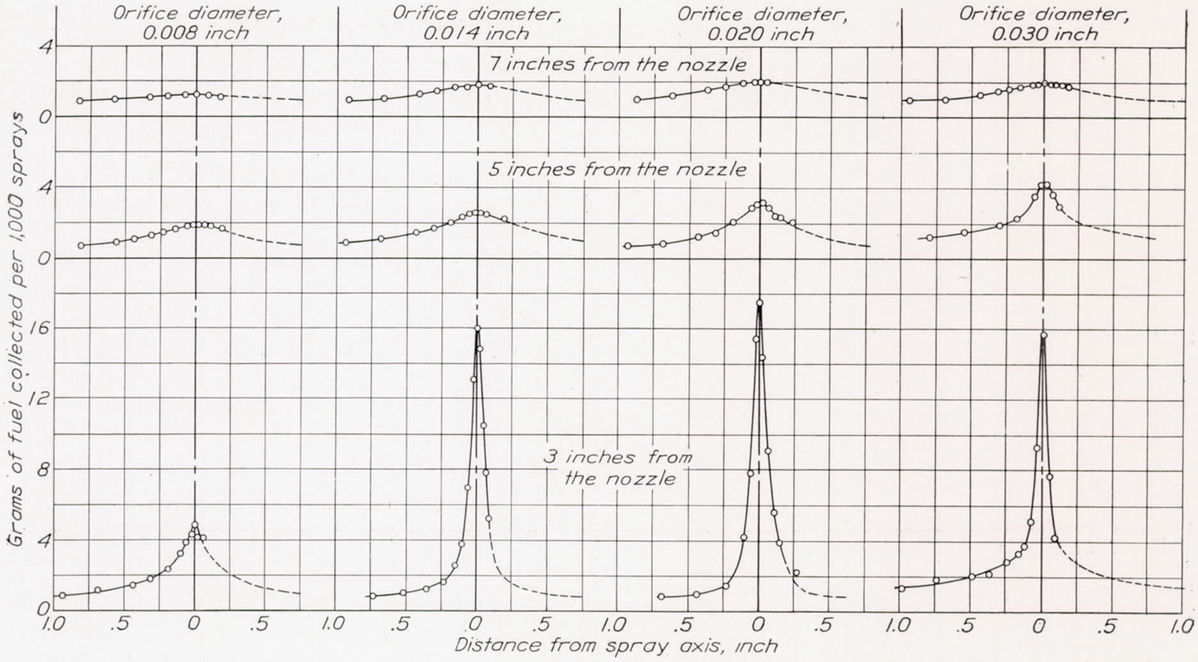


FIGURE 6.—Sampling-tube tests with plain nozzles having different orifice diameters. Orifice length-diameter ratio, 2; air density, 14 atmospheres.

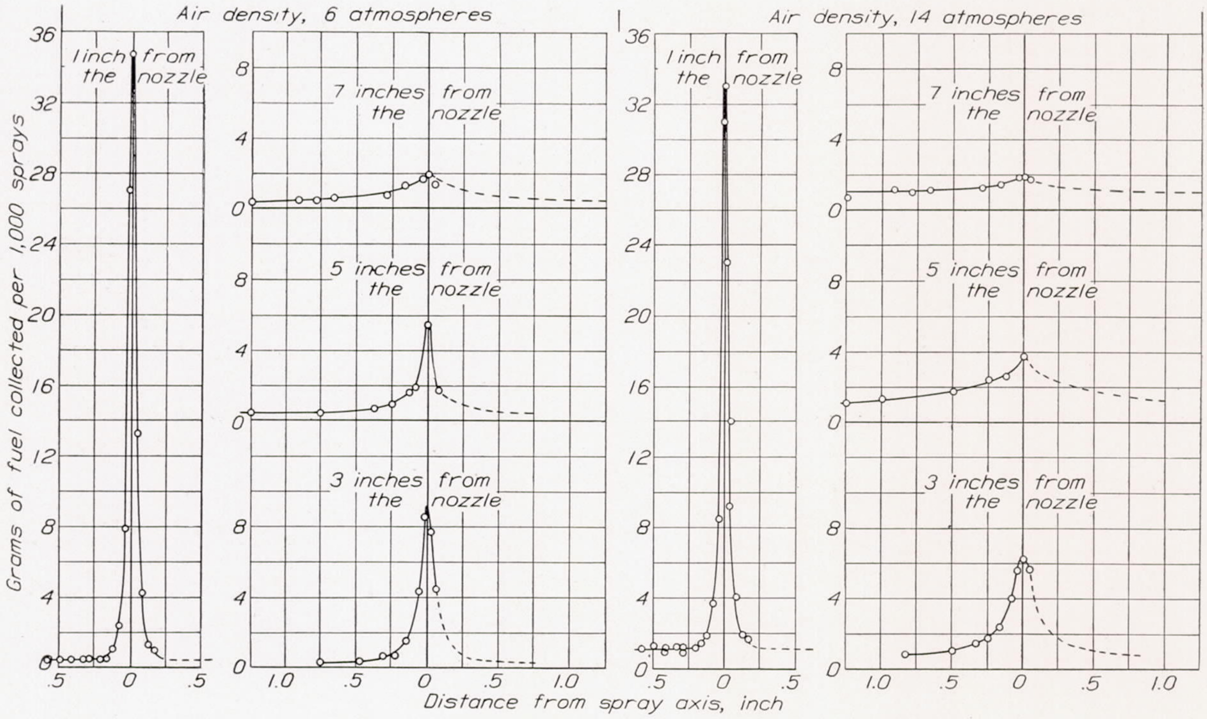


FIGURE 7.—Sampling tube tests with a pintle nozzle. Pintle dispersion angle, 20°.

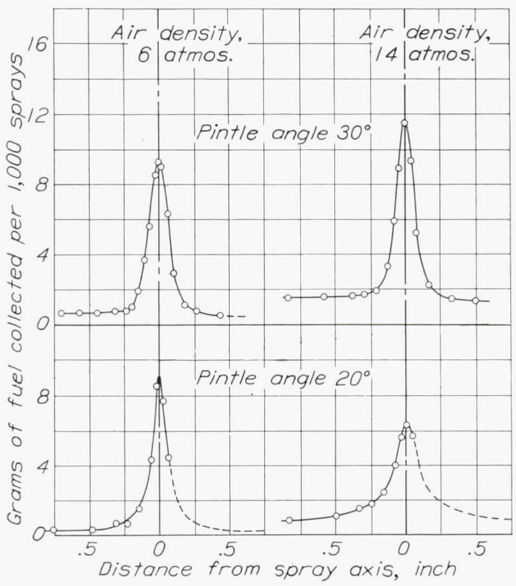


FIGURE 8.—Sampling-tube tests with pintle nozzles having different dispersion angles. All tests at 3 inches from the nozzle.

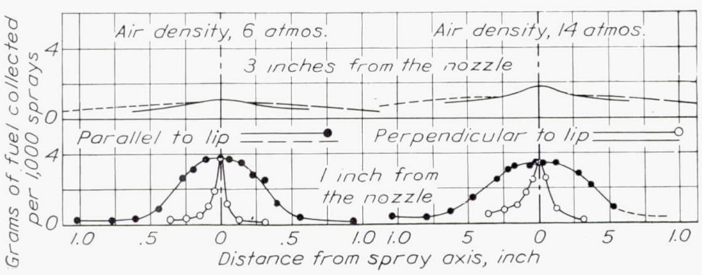


FIGURE 9.—Sampling-tube tests with a lip nozzle.

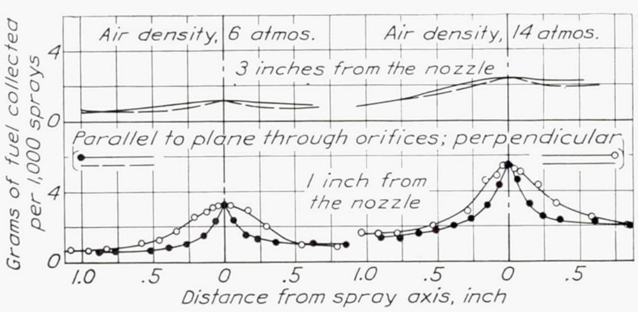


FIGURE 10.—Sampling-tube tests with a 2-impinging-jets nozzle.

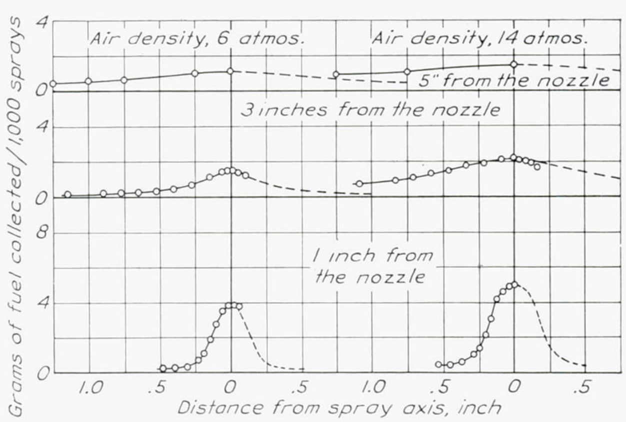


FIGURE 11.—Sampling-tube tests with a 4-impinging-jets nozzle.

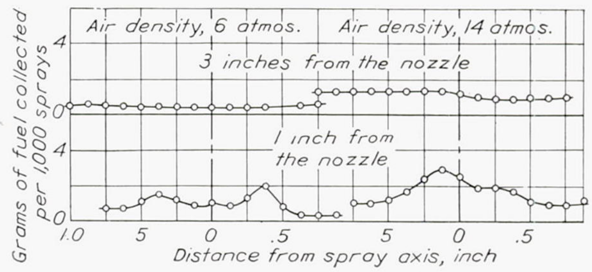


FIGURE 12.—Sampling-tube tests with an annular-orifice nozzle.

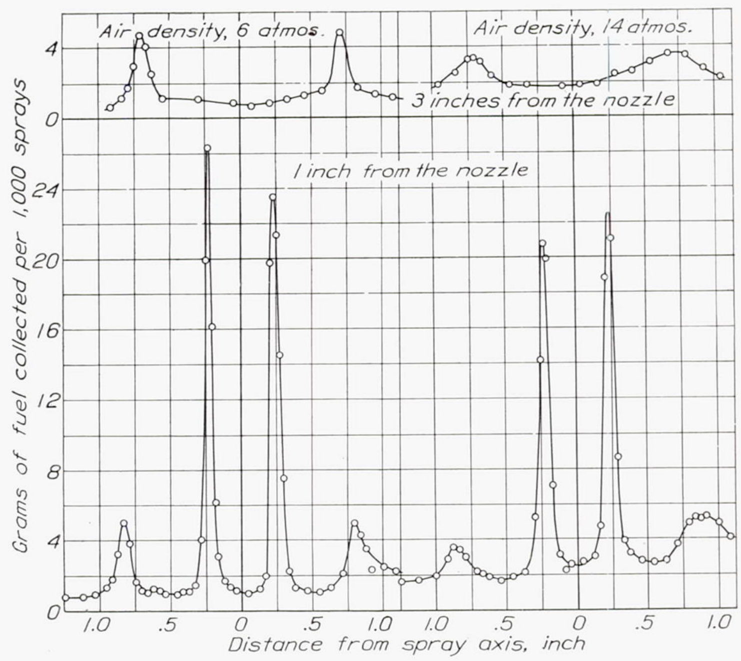


FIGURE 13.—Sampling-tube tests with a multiple-orifice nozzle.

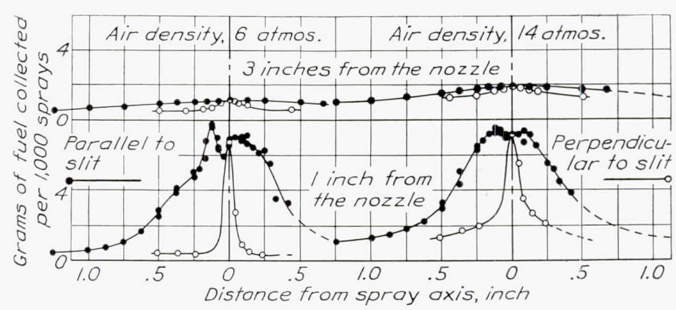


FIGURE 14.—Sampling-tube tests with a slit nozzle.

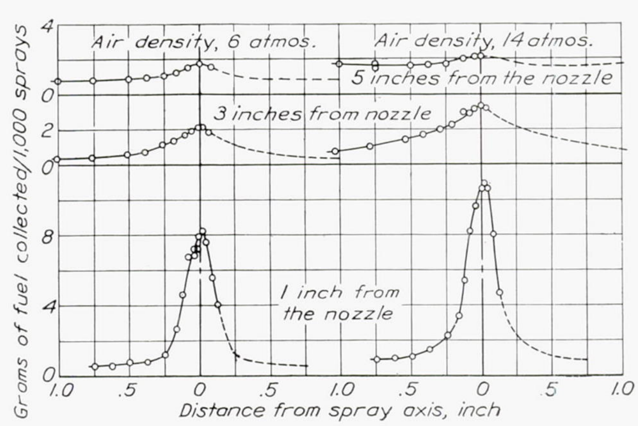


FIGURE 15.—Sampling-tube tests with a centrifugal nozzle.

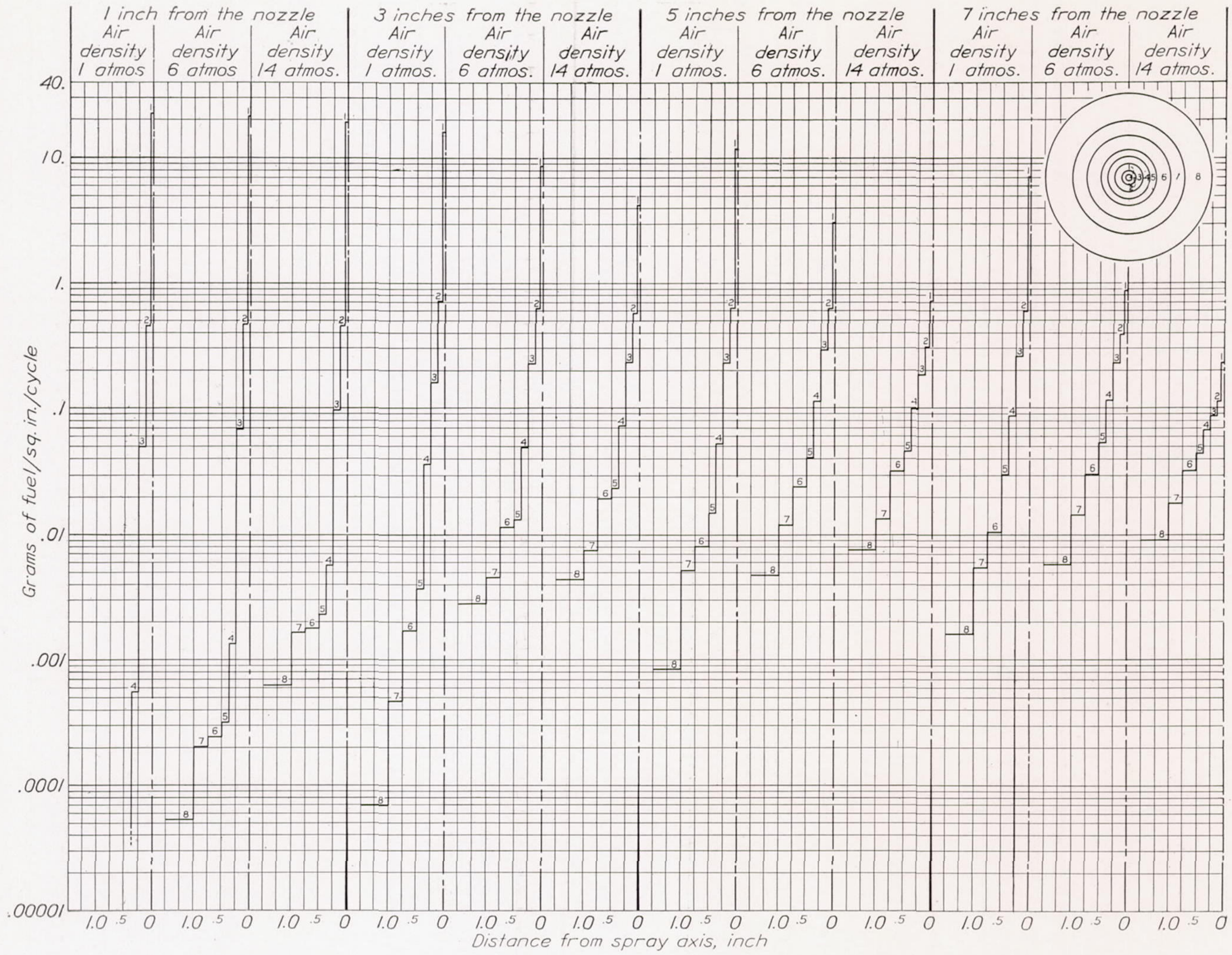


FIGURE 16.—Concentric-cups tests with a plain nozzle. Orifice diameter, 0.020 inch; orifice length-diameter ratio, 2.

given in table I for sprays from the plain nozzle with a 0.020-inch diameter orifice are also shown graphically in figure 16, grams of fuel per square inch per cycle being plotted vertically in steps, the widths of which are proportional to the distances between the walls of the cups. The great range of fuel concentrations (415,000:1) made it advisable to use a logarithmic vertical scale, thus making it much easier to read the smaller values. A sketch showing the relative diameters of the concentric cups is included, the scale being the same as the horizontal scale of the plots. The identifying numbers of the eight cups are shown, and the steps in the plots are labeled with the numbers of the cups they represent.

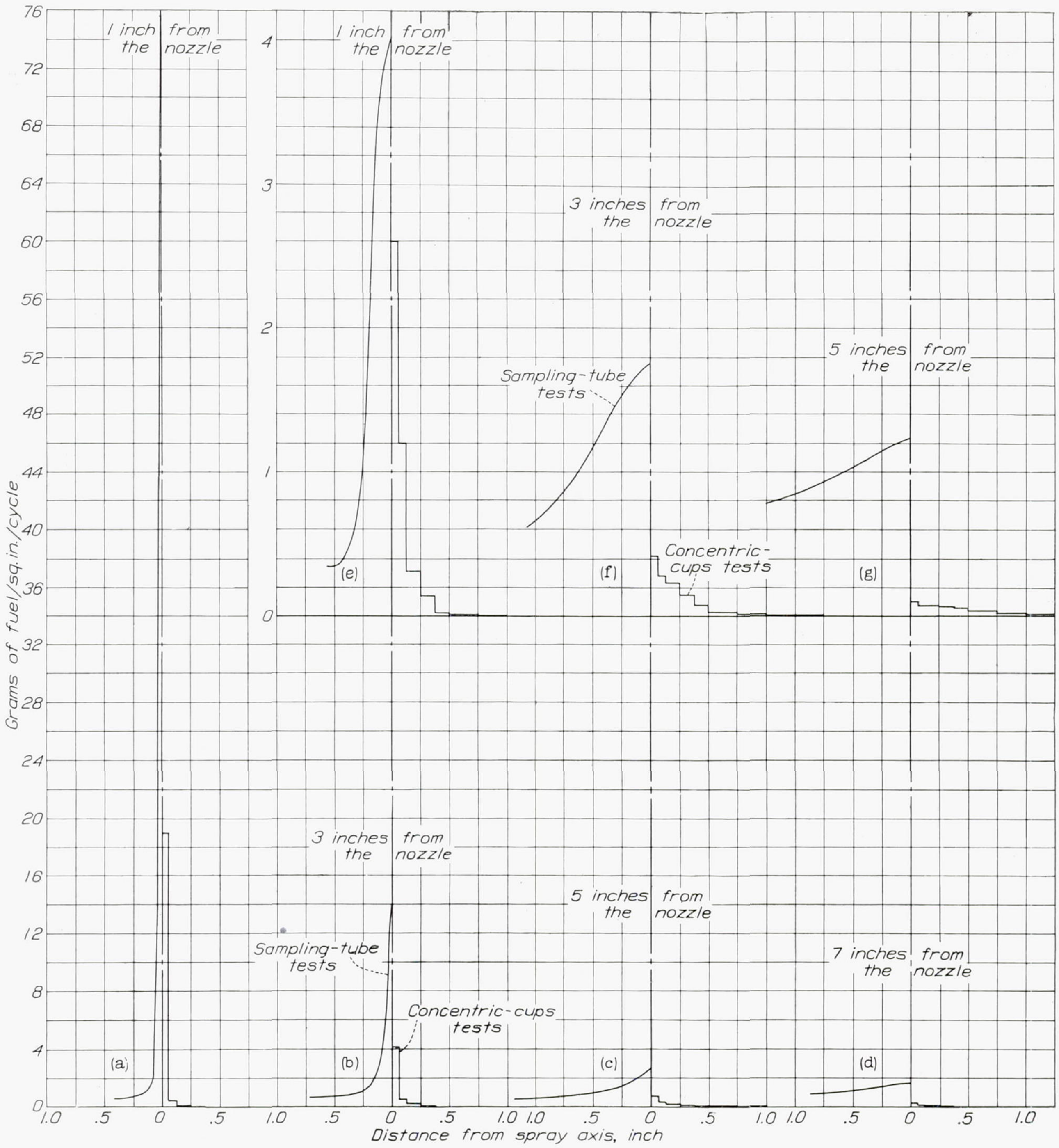
COMPARISON OF RESULTS OF THE TWO TEST METHODS

For each of the tests made with the concentric-cups apparatus at air densities of 6 and 14 atmospheres, a corresponding test was made with the sampling-tube apparatus. In order to make a direct comparison of the results of the two methods, the fuel weights obtained in some of the sampling-tube tests were divided by the tube area and the number of injections made and were then plotted opposite the concentric-cups data for the same conditions. (See fig. 17.) The comparison shows that there is good general agreement as to the effect of different variables on fuel distribution but that the values are much greater for the sampling-tube tests. It is therefore believed that the area from which fuel was gathered by the sampling tube was much greater than the area of the tube itself.

DISCUSSION

FUEL DISTRIBUTION IN SPRAYS FROM DIFFERENT TYPES OF NOZZLES

In the study of the results of the tests described in this report, it is necessary to keep clearly in mind the distinction between *distribution of fuel within a spray* and *distribution of fuel throughout a combustion chamber.* Distribution of liquid fuel within the sprays was measured in this investigation; but other factors such as spray penetration, air-flow velocity, and engine temperature also influence the distribution of fuel throughout a combustion chamber. For instance, wide sprays



e, f, g—Four-impinging-jets nozzle.

a, b, c, d—Plain nozzle; orifice diameter, 0.020 inch; orifice length-diameter ratio, 2.

FIGURE 17.—Comparison of sampling-tube and concentric-cups tests with a 4-impinging-jets and a plain nozzle. Air density, 14 atmospheres.

are desirable in cases for which high penetration is not required, such as the injection of fuel during the intake stroke of spark-ignition engines; but in compression-ignition engines such sprays usually fail to penetrate to all parts of the chamber and it becomes necessary to use plain, pintle, or multiple-orifice nozzles which, despite poorer distribution within the sprays, may produce better distribution in the combustion chamber. Data for the rates of penetration of the various types of sprays tested are presented in reference 6 and should be particularly useful in connection with the results herein presented because, in most cases, the same nozzles were used.

The following discussion refers only to the fuel distribution within the sprays and the conclusions reached are largely based on the rate at which the fuel concentration decreased with increasing distance from the center line of the spray.

Plain nozzles.—Figures 4 to 6 and the data in table I show that the distribution of the fuel within sprays from the plain nozzles was very poor and that it improved rapidly as the air density or the distance from the nozzle was increased. The results of the sampling-tube tests with plain nozzles having different orifice diameters indicate that at 5 and 7 inches from the nozzle the distribution became poorer as the orifice diameter was increased but at 3 inches from the nozzle the distribution was about the same for the 0.014-, 0.020-, and 0.030-inch nozzles and inferior to that for the 0.008-inch nozzle. Tests reported in reference 7 show that the injection pressure rapidly decreased as the orifice diameter was increased. As will be shown later, a decrease in the injection pressure results in poorer fuel distribution, and this factor is at least partly responsible for the change in distribution with orifice size shown by the present tests.

Some sampling-tube tests were made with plain nozzles having orifice diameters of 0.020 inch and orifice length-diameter ratios of 0.5, 2, and 5, but the effect of orifice length-diameter ratio on fuel distribution was very slight, and the results of the tests are not included in this report.

Pintle nozzles.—Figure 7 and table I show that the fuel distribution in the sprays from the 20° pintle nozzle was better than in those from all of the plain nozzles except the one with the 0.008-inch orifice. Increasing the air density from 1 to 6 atmospheres resulted in poorer fuel distribution, but a further increase to 14 atmospheres resulted in an improvement. The improvement with distance from the nozzle was not so rapid as with plain nozzles.

The results of sampling-tube tests with a 30° pintle nozzle at 3 inches from the nozzle are shown in figure 8 and corresponding curves for the 20° nozzle are included to facilitate comparison. The concentric-cups data in table I show that raising the air density from 1 to 6 atmospheres caused the fuel distribution to become much poorer, but a further increase to 14 atmospheres had little effect. The unusual change in fuel distribution between 1 and 6 atmospheres for both pintle nozzles was probably caused by narrowing of the spray core. (See reference 6.) At 1 atmosphere the fuel in sprays from the 30° nozzle was much better distributed than in those from the 20° nozzle, at 6 atmospheres there was little difference, and at 14 atmospheres the sprays from the 20° nozzle had the better distribution.

Lip nozzle.—Sprays from the lip nozzle are shaped like a narrow fan, extending outward from the lip surface. Two traverses by the sampling tube at each condition were therefore necessary to obtain a true picture of the fuel distribution. One traverse was made perpendicular to the plane of the lip surface, displacements above this plane (on side toward the orifice) being plotted to the left and those below it to the right. The results of the tests 1 inch from the nozzle (fig. 9) show that the plane of maximum fuel concentration coincided with that of the lip surface, but that more of the fuel was above that plane than below it. The second traverse was made in the plane of the lip surface, the nozzle having been rotated 90° after making the first traverse. The results show that at 1 inch from the nozzle the distribution of the fuel in the plane of the lip surface was much better than in the plane at right angles to it but that at 3 inches from the nozzle there was little difference. The curves for the two traverses made at 3 inches from the nozzle are so close to each other that the test points have been omitted. When the air density was increased from 6 to 14 atmospheres, the fuel distribution at 1 inch from the nozzle improved slightly in both planes but at 3 inches from the nozzle it became poorer.

Impinging-jets nozzles.—Cross sections of sprays from a 2-impinging-jets nozzle are approximately elliptical, the minor axis of the ellipse lying in the plane containing the axes of the two jets. Sampling-tube traverses were made first through the narrow parts and then through the wide parts of the spray. Figure 10 shows that fuel distribution along the lines of both traverses improved with distance from the nozzle but that increasing the air density from 6 to 14 atmospheres had very little effect.

Sprays from 4-impinging-jets nozzles are symmetrical about the spray axis so that only one traverse was necessary for each condition. Figure 11 shows that the distribution of fuel near the nozzle was very good and improved slowly with increasing air density and distance from the nozzle.

Annular-orifice nozzle.—The injection valve used for the annular-orifice nozzle tests was designed for the injection of gasoline into air at atmospheric density, a condition requiring relatively low injection pressures. The valve was set at its maximum valve-opening pressure, about 1,000 pounds per square inch, with the result that the mean injection pressure was considerably less for these tests than for those with the other nozzles.

Only one traverse was made at each condition when testing the annular-orifice nozzle, although previous work (reference 6) had shown that this particular nozzle does not produce symmetrical sprays. Figure 12 shows that this nozzle dispersed the fuel very quickly and that as the air density was increased the fuel distribution became poorer. Experience with several annular-orifice nozzles at this laboratory indicates that the production of unsymmetrical sprays is a common fault of this type of nozzle and that its usefulness is thereby decidedly reduced.

Multiple-orifice nozzle.—Each of the jets from a multiple-orifice nozzle is symmetrical about its axis, so that a single traverse in the plane of the jet axes was sufficient. The size of the pressure chamber limited the traverse at 1 inch from the nozzle to four of the six jets, and at 3 inches from the nozzle only the two central jets could be included. Figure 13 shows that the various jets remained distinct, very little fuel being deflected into the spaces between them. The traverse was carried in a straight line across the spray and intersected the two central jets at an angle of 80° and the other two jets at 60°. Before each jet was traversed, however, the end of the sampling tube was bent parallel to the axis of that jet. The test results show that the distribution of fuel in the two central jets from the multiple-orifice nozzle was better than in sprays from a plain nozzle having nearly the same orifice diameter. This difference may be attributed to the more turbulent flow through the orifices of the multiple-orifice nozzle, which have no conical approaches to help stabilize the flow. (See reference 5.)

Slit nozzle.—Results of sampling-tube tests with the slit nozzle are shown in figure 14. Sprays from this nozzle resemble those from the lip nozzle but are somewhat thinner and broader. Tests made at this laboratory have shown that the fuel distribution in sprays from slit nozzles is greatly influenced by the shape of the fuel passage between the stem seat and the slit. With nozzles having cylindrical passages, the shape of the bottom of that passage is important, a flat bottom resulting in a narrow spray and a conical bottom often breaking the spray into two parts. A spherical bottom has been found to be the best, but even with it the fuel distribution may be irregular, as shown by the results of sampling-tube traverses made parallel to the slit at 1 inch from the nozzle. The curves in figure 14 show that increasing the air density had little effect on fuel distribution along a line parallel to the slit but did improve the distribution at right angles to the slit. Fuel distribution in both directions improved with increasing distance from the nozzle.

Centrifugal nozzle.—As the whirling fuel leaves the centrifugal nozzle it spreads out to form a hollow cone. At the same time, however, the thin sheet of fuel begins to disintegrate into drops and, as the fuel gets farther from the nozzle, the sides of the cone thicken until the hollow center is entirely filled. The disintegration of the spray core continues to send fuel drops into the central part of the spray from all directions as well as to send them to the outer parts of the spray, with the result that the fuel concentration becomes greatest at the center of the spray. In air at atmospheric density the process may not be completed until the fuel has traveled an inch or more from the nozzle, but at 6 and 14 atmospheres it is completed in a shorter distance, as shown by the curves in figure 15. Distribution of the fuel improved with increasing distance from the nozzle but became slightly worse when the air density was increased from 6 to 14 atmospheres.

Comparison of the various types of sprays.—After a careful study of the data presented in this report, the following nozzles have been listed in the order of improving distribution of fuel within their sprays: Plain nozzle, pintle nozzle, centrifugal nozzle, lip nozzle, slit nozzle, 4-impinging-jets nozzle, 2-impinging-jets nozzle, and annular-orifice nozzle. There was little difference between the lip and slit nozzles, and the listing of the annular-orifice nozzle as producing sprays with the best distribution is questionable because of the nonsymmetry of the sprays. The multiple-orifice nozzle was not included in this list because only the central portion of its spray could be investigated.

EFFECT OF INJECTION PRESSURE ON FUEL DISTRIBUTION

Tests were made both with the sampling tube and with the concentric cups to measure the effect of injection pressure on fuel distribution. The plain nozzle with the 0.020-inch orifice was used; the valve-opening pressure was reduced to 730 pounds per square inch and the pump speed, to 487 r. p. m. These values were chosen because the tests of the injection pump reported in reference 7 showed that making these two changes resulted in reducing the mean effective injection pressure from 2,500 to 1,250 pounds per square inch. The curves in figure 18 and the data in table I show that the fuel distribution was slightly better at the higher injection pressure.

EFFECT OF FUEL VISCOSITY ON DISTRIBUTION

Sampling-tube tests were made with a hydrogenated safety fuel, a Diesel fuel, and S. A. E. 30 lubricating oil in air at a density of 14 atmospheres. The high volatility of the safety fuel made it necessary to apply a correction to the results of tests using this fuel. The correction was obtained by running an evaporation test at the end of alternate fuel-collecting tests; air flowed through the fuel trap for the same length of time as for the fuel-collecting tests, but there were no sprays in the chamber. The decrease in the weight of the fuel trap during each evaporation test was added to the fuel weight collected during the preceding and following tests to give the correct amount of fuel collected. This correction varied from 12 percent of the fuel collected at the centers of the sprays to 84 percent at the edges. Concentric-cups tests were made with the safety fuel and the Diesel fuel but not with the lubricating oil, as it would not flow through the small drain tubes. The plain nozzle with the 0.020-inch orifice was used at the standard injection conditions, and all the tests were made at 3 inches from the nozzle. The viscosities of the safety fuel, Diesel fuel, and lubricating oil were measured at 22° C. and at atmospheric pressure and found to be 0.0058, 0.052, and 3.1 poises, respectively.

The results of the sampling-tube tests (fig. 19) indicate that the fuel distribution became poorer as the fuel viscosity was increased, but the concentric-cups tests showed little difference between the distribution in Diesel and safety-fuel sprays.

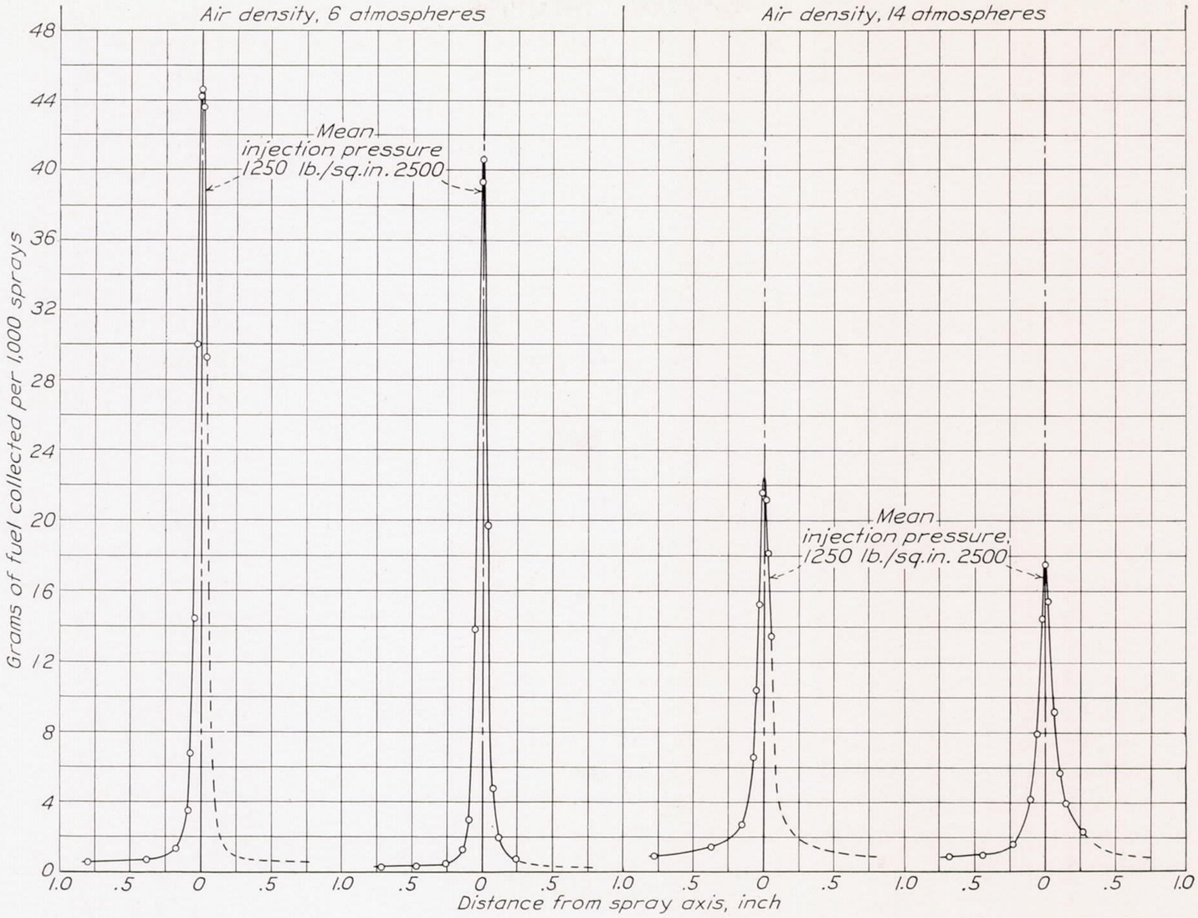


FIGURE 18.—Sampling-tube tests using different mean injection pressures. Plain nozzle; orifice diameter, 0.020 inch; orifice length-diameter ratio, 2; distance from nozzle, 3 inches; pump speeds, 487 and 750 r. p. m.; injection-valve opening pressures, 730 and 3,500 pounds per square inch.

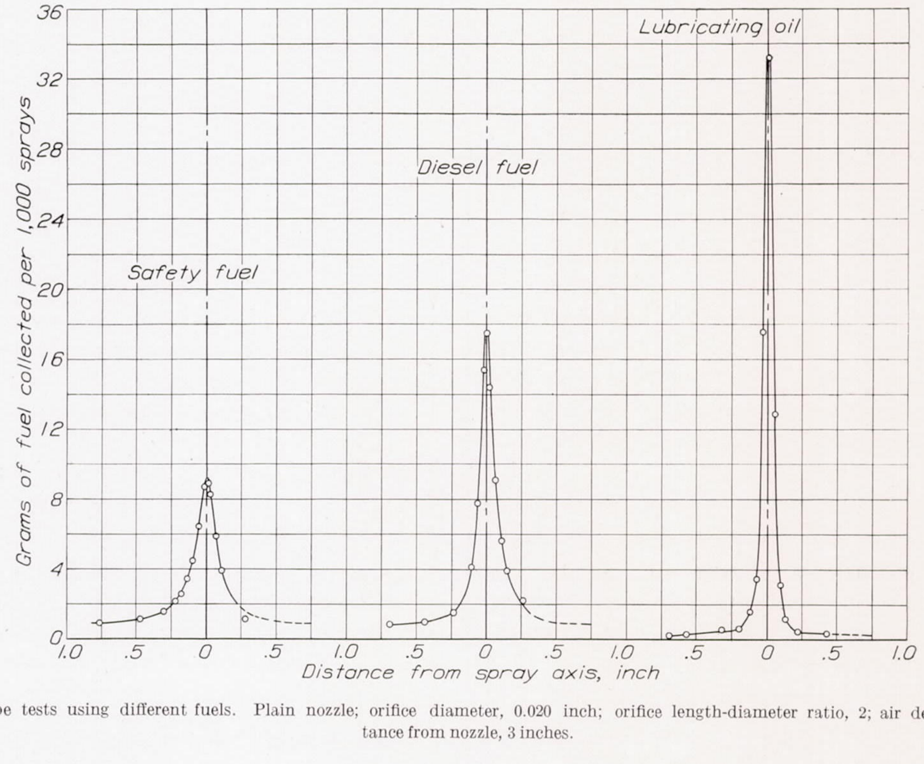


FIGURE 19.—Sampling-tube tests using different fuels. Plain nozzle; orifice diameter, 0.020 inch; orifice length-diameter ratio, 2; air density, 14 atmospheres; distance from nozzle, 3 inches.

EFFECTS OF VAPORIZATION AND AIR MOVEMENT ON FUEL DISTRIBUTION

The present results have shown the distribution of the fuel in the liquid phase. The additional effects of vaporization and diffusion and of air movement on the distribution of the fuel can be estimated by comparing these data with those presented in references 9 and 10. The photographs of the combustion in reference 9 show that the fuel was distributed over a larger area than indicated by the distribution in the liquid phase. With a plain nozzle, for example, the flame volume was more than five times the liquid spray volume and, although the present tests show that in the liquid phase without air flow there was very little fuel distributed between the jets of the multiple-orifice nozzle, the combustion photographs show that, when the same nozzle is used under conditions closely simulating engine conditions, a considerable amount of fuel reached the area between the visible sprays. Test results for an engine with very little or no air flow (reference 11) show that, although a combustible mixture is formed over a considerable area even with a single-orifice nozzle, the effectiveness of the combustion is low unless a sufficient number of orifices is used to give an angle between sprays of about 25°. When air flow is employed, the optimum angle between the sprays may be the same or greater. (See references 12 and 13.)

The photographs reproduced in reference 9 show that when high-dispersion nozzles, such as the slit or impinging-jets nozzles, are used, the distribution within the sprays is good but that apparently the air-fuel ratio is too low for good combustion efficiency.

CONCLUSIONS

Distribution of the liquid fuel within sprays is only one of the factors that determine whether the fuel will be well distributed to all parts of the combustion chamber; some of the other factors are rate of spray penetration, air-flow velocity, and engine temperature. Satisfactory combinations of these factors must be determined by engine tests, but the results herein presented and summarized as follows should reduce the required amount of such test work.

1. Fuel distribution in all types of sprays improved with increasing distance from the nozzle, the improvement being the most rapid in sprays of high penetrating power.
2. Fuel distribution within sprays having high penetrating power improved greatly when the air density was increased, but the improvement was much less in sprays having low penetrating power; in some widely dispersed sprays the distribution became poorer.
3. Increasing the injection pressure resulted in a small improvement in the fuel distribution in sprays from plain nozzles.
4. Sampling-tube tests showed that increasing the viscosity of the fuel resulted in poorer fuel distribution in sprays from plain nozzles.
5. The nozzles used for these tests are listed as follows in the order of improving distribution of fuel within their sprays: Plain nozzle, pintle nozzle, centrifugal nozzle, lip nozzle, slit nozzle, 4-impinging-jets nozzle, 2-impinging-jets nozzle, and annular-orifice nozzle.
6. Changing the orifice length-diameter ratio of one of the plain nozzles had very little effect on the fuel distribution in the sprays.
7. Fuel distribution in the two central jets of sprays from the multiple-orifice nozzle was better than in sprays from a plain nozzle having nearly the same orifice diameter.

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LANGLEY FIELD, VA., *April 8, 1936.*

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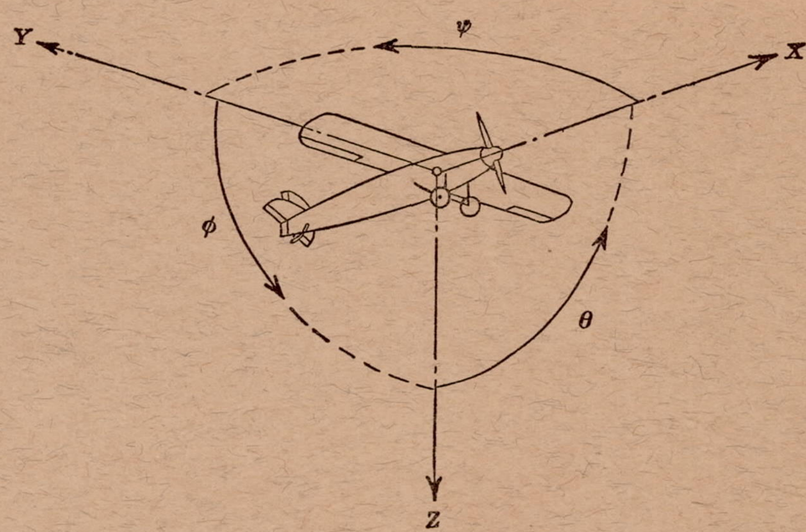
TABLE I

RESULTS OF THE CONCENTRIC-CUPS TESTS

Nozzle	Valve-opening pressure	Fuel	Distance from the nozzle	Air density	Grams of fuel per square inch per cycle — Cup no. 1	2	3	4	5	6	7	8	Percentage of fuel caught
	lb./sq. in.		*Inches*	*Atmospheres*									
Plain, orifice diameter 0.008 inch	3, 500	Diesel	1	1	24	0. 18	0. 0071	0. 00073	0	0	0	0	96. 2
				9	22	. 21	. 013	. 0012	. 00073	. 00021	. 00011	. 00003	91. 3
				14	19	. 36	. 072	. 0036	. 0016	. 0015	. 0020	. 00058	87. 5
			3	1	19	. 46	. 090	. 0071	. 00043	. 00026	. 00011	. 00004	89. 6
				6	5. 8	. 58	. 28	. 055	. 010	. 0058	. 0032	. 0022	67. 4
				14	1. 4	. 33	. 18	. 083	. 030	. 015	. 0067	. 0046	55. 6
			5	1	13	. 57	. 24	. 032	. 0089	. 0025	. 00061	. 00020	84. 4
				6	. 79	. 33	. 19	. 094	. 049	. 023	. 0073	. 0031	60. 0
				14	. 31	. 11	. 079	. 065	. 047	. 029	. 013	. 0061	54. 2
			7	1	7. 2	. 70	. 33	. 064	. 025	. 0087	. 0023	. 00061	79. 7
				6	. 30	. 16	. 11	. 080	. 052	. 031	. 014	. 0046	58. 3
				14	. 14	. 056	. 045	. 044	. 040	. 028	. 019	. 0094	56. 0
Plain, orifice diameter 0.014 inch	3, 500	Diesel	1	1	23	. 32	. 064	. 00097	0	0	0	0	97. 6
				6	23	. 27	. 032	. 0056	. 00041	. 00035	. 00030	. 00014	95. 8
				14	22	. 27	. 054	. 0021	. 00087	. 00047	. 00031	. 00018	94. 2
			3	1	19	. 59	. 14	. 015	. 0034	. 0011	. 00041	. 00025	96. 0
				6	14	. 40	. 16	. 042	. 012	. 0067	. 0029	. 0019	85. 0
				14	5. 6	. 41	. 23	. 058	. 018	. 014	. 0063	. 0045	71. 0
			5	1	15	. 61	. 14	. 047	. 012	. 0042	. 0012	. 00048	92. 0
				6	4. 7	. 55	. 27	. 087	. 035	. 019	. 0080	. 0038	81. 4
				14	. 78	. 26	. 15	. 084	. 041	. 032	. 014	. 0076	69. 4
			7	1	11	. 72	. 21	. 059	. 022	. 0090	. 0030	. 0010	87. 5
				6	1. 3	. 41	. 19	. 094	. 045	. 030	. 012	. 0054	73. 0
				14	. 20	. 091	. 067	. 055	. 039	. 029	. 016	. 0087	56. 7
Plain, orifice diameter 0.020 inch	3, 500	Diesel	1	1	22	. 46	. 050	. 00053	0	0	0	0	96. 4
				6	21	. 47	. 070	. 0013	. 00032	. 00024	. 00020	. 000053	94. 8
				14	19	. 45	. 097	. 0057	. 0023	. 0018	. 0017	. 00063	89. 3
			3	1	16	. 71	. 16	. 037	. 0037	. 0017	. 00047	. 000069	91. 7
				6	8. 6	. 61	. 22	. 049	. 013	. 012	. 0046	. 0028	79. 2
				14	4. 2	. 57	. 23	. 072	. 024	. 020	. 0075	. 0044	73. 5
			5	1	12	. 62	. 23	. 052	. 015	. 0081	. 0052	. 00084	83. 7
				6	3. 1	. 61	. 28	. 11	. 041	. 024	. 012	. 0047	81. 6
				14	. 72	. 31	. 19	. 098	. 046	. 032	. 013	. 0075	70. 7
			7	1	7. 2	. 59	. 26	. 088	. 031	. 011	. 0055	. 0016	79. 6
				6	. 87	. 39	. 23	. 12	. 054	. 032	. 014	. 0058	80. 0
				14	. 23	. 11	. 087	. 068	. 044	. 033	. 018	. 0091	65. 3
Pintle, spray angle 20°	3, 500	Diesel	1	1	8. 3	. 41	. 50	. 097	. 016	. 0046	. 0021	. 00016	83. 0
				6	13. 2	. 54	. 15	. 017	. 0047	. 0038	. 0022	. 00013	70. 9
				14	13. 3	. 51	. 12	. 021	. 0095	. 0079	. 0042	. 00018	75. 5
			3	1	2. 6	. 52	. 23	. 19	. 082	. 021	. 0043	. 0020	77. 8
				6	4. 7	. 52	. 16	. 066	. 023	. 014	. 0065	. 0042	62. 0
				14	2. 5	. 49	. 21	. 078	. 030	. 019	. 010	. 0063	66. 8
			5	1	1. 1	. 46	. 26	. 12	. 061	. 034	. 015	. 0038	78. 0
				6	1. 5	. 43	. 23	. 11	. 043	. 020	. 0095	. 0045	63. 7
				14	. 60	. 23	. 17	. 092	. 047	. 029	. 014	. 0072	64. 2
			7	1	. 19	. 20	. 16	. 12	. 078	. 035	. 015	. 0063	70. 3
				6	. 29	. 18	. 15	. 095	. 062	. 031	. 014	. 0059	62. 5
				14	. 17	. 08	. 078	. 064	. 046	. 030	. 018	. 0092	57. 6
Pintle, spray angle 30°	3, 500	Diesel	3	1	. 21	. 17	. 18	. 21	. 17	. 054	. 012	. 0017	89. 7
				6	4. 1	. 61	. 21	. 083	. 025	. 016	. 0093	. 0046	67. 4
				14	5. 4	. 63	. 23	. 068	. 026	. 019	. 011	. 0062	77. 3
4-impinging-jets	3, 500	Diesel	1	1	1. 6	1. 3	. 52	. 21	. 055	. 014	. 0016	. 00010	95. 6
				6	2. 3	1. 6	. 27	. 21	. 031	. 0078	. 0025	. 0010	85. 0
				14	2. 6	1. 2	. 31	. 14	. 021	. 0080	. 0040	. 0022	74. 8
			3	1	. 29	. 25	. 20	. 15	. 10	. 056	. 019	. 0042	89. 3
				6	. 62	. 42	. 29	. 16	. 080	. 028	. 0071	. 0035	76. 9
				14	. 42	. 28	. 23	. 15	. 078	. 026	. 0094	. 0061	73. 7
			5	1	. 10	. 087	. 086	. 076	. 061	. 045	. 027	. 010	74. 6
				6	. 13	. 10	. 10	. 090	. 080	. 044	. 019	. 0067	69. 3
				14	. 10	. 069	. 069	. 064	. 055	. 036	. 019	. 0092	61. 2
Plain, orifice diameter 0.020 inch	730	Diesel	3	1	19	. 89	. 18	. 020	. 0036	. 0016	. 0012	. 00067	89. 2
				6	15	. 87	. 15	. 033	. 010	. 0055	. 0032	. 0024	84. 0
				14	8. 0	. 81	. 21	. 060	. 023	. 015	. 0082	. 0049	76. 5
Plain, orifice diameter 0.020 inch	3, 500	Diesel	3	1	16	. 71	. 16	. 037	. 0037	. 0017	. 00047	. 000069	91. 7
				6	8. 6	. 61	. 22	. 049	. 013	. 012	. 0046	. 0028	79. 2
				14	4. 2	. 57	. 23	. 072	. 024	. 020	. 0075	. 0044	73. 5
Plain, orifice diameter 0.020 inch	3, 500	Safety	3	1	16	. 43	. 085	. 036	. 0064	. 0020	. 0020	. 00088	74. 9
				6	9. 6	. 52	. 12	. 052	. 017	. 0098	. 0059	. 0032	68. 5
				14	3. 7	. 45	. 20	. 074	. 030	. 022	. 011	. 0049	66. 5



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 $=\sqrt[5]{\frac{\rho V^5}{P n^2}}$
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 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.