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No. 644

ON ATOMIZATION IN CARBURETORS

By F. N. Scheubel

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20

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ON ATOMIZATION IN CARBURETORS*

By F. N. Scheubel

One of the most important of the problems which are still rather hazy in the construction of modern light engines is the formation of the mixture. While this problem may be regarded as partly solved for heavy internal combustion engines, so far as engines for gaseous fuels are concerned, and in some other cases the fundamental principles at least have been studied, as in solid injection oil engines, in the wide field of carburetor engines (which, with a few scattered exceptions, are identical with the light engines of the present day) one of the most important problems of mixture formation, that of fuel subdivision or atomization, as it is usually called, is entirely untouched. It is, indeed, well known that fuel atomization is improved by high carburetor air speed; that is concluded from engine performance at low engine speed. Attempts have also been made to improve atomization by changes in the fuel nozzles, etc. But the fundamentals of the atomization problem are still very obscure. One knows the influence neither of the physical properties of the fuel, nor of the air speed, nor of the shape of the carburetor throat.

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*From Jahrbuch der Wissenschaftlichen Gesellschaft für Luftfahrt, 1927, pp. 140-6.

Translator's note: This lecture, which was translated with the permission of Dr. Scheubel, appears to the translator to contain the best pictorial description he has yet seen of the phenomena attending atomization in an air stream. As it also seems to him (reference 1) that solid injection has a physical background quite similar to that of air stream atomization, as regards the relative motion of air and liquid at their interface, this investigation also appears to have an important bearing on solid injection. Since the latter is of interest in regard to the study of compression-ignition engines for aircraft, it seems important to have an English translation available.

As this problem, besides its great practical importance, is also very interesting hydrodynamically, a study of atomization in carburetors was begun in the Aerodynamic Institute of the Technical High School at Aachen, which had already been working for a long time on the elucidation of the physical questions of carburetor construction.

Photography was chosen as the only suitable means of recording the phenomena which occur when the fuel enters the air stream. The difficulties are serious. On account of the fineness of the droplet measurement and the high speed of motion, the illumination must be very brief, as a short calculation will show: If a drop 2/100 mm in diameter is moving with a speed of 100 m/s, it travels the length of its diameter in

$$\frac{2}{100 \times 100 \times 10^3} = \frac{2}{10000000} \text{ s}$$

If one wishes to obtain a useful picture of such a small particle moving so fast, he must use an illumination which lasts less than 10^{-7} s. Such short times may be obtained by electric instantaneous photography, where the object to be photographed is illuminated by an electric spark, whose duration is the illumination time. The principal difficulty is in obtaining very brief sparks with the maximum energy content possible. I cannot go further into details here. I must refer to a paper in the next volume of the "Luftfahrt" transactions.

It would also lead too far to go into details on the possibility of error in the work. Only one sort of error, which is unavoidable and the recognition of which is necessary for the correct interpretation of the pictures, which I shall show later, will be briefly considered. The photographs are instantaneous pictures of a definite portion of space, and therefore show the distribution of the drops in this space at this instant. This spatial distribution, however, does not correspond to the actual constitution of the mixture, since different parts, according to their size and position, acquire different speeds and hence do not remain for the same time in the field of view.

Rather will the larger drops, on account of their smaller ratio of surface to volume, be accelerated more slowly, and therefore need more time to cross this portion of space, than the smaller drops. Hence the photographs show more large drops than correspond to the actual constitution of the mixture. The actual constitution is given by the drops crossing a given section in unit time. A measurement by kinematic photography is conceivable, which is fundamentally possible, but in the present case, could only be carried through with considerable expense.

The apparatus (fig. 1) is very simple: A blower supplies air through a measuring tube to the carburetor model. The liquid under investigation flows to the carburetor from a measuring vessel and a float chamber with regulating arrangement. The mixture is led to a separator, where most of the liquid is precipitated. The carburetor models are built into a photographic apparatus. They are illuminated by a built-in spark, whose light is guided by a concave mirror to these, and then to the objective and to the plate. The models themselves (fig. 2) are made of pieces of cardboard with plate glass windows. They are fastened in with metal frames, so that they may easily be changed. I show later, with the results, the particular forms which were investigated.

Alcohol and water were the liquids studied. The customary fuels could not be used on account of their high degree of inflammability and their bad effect on the breathing organs. Alcohol is very similar to the customary fuels like gasoline and benzol in those physical properties which are important in atomization, such as density, surface tension and viscosity, and hence seems a good substitute. Water was chosen on account of its high surface tension (which is about three times that of the usual fuel), since hydrodynamic considerations, to which I shall return later, indicate that the value for atomization is proportional to the ratio of the static pressure of the air stream to the surface tension of the liquid

$$\frac{K}{2} = \frac{\rho U^2}{2T} \text{ cm}^{-1}.$$

This quantity will be called the atomizing characteristic.

The next pictures were chosen from the results. First a comparison between water (with surface tension T about 75 dyn/cm) and alcohol (with T about 24 dyn/cm). The first picture (series I) shows the carburetor set-up, a Venturi throat with a smooth tube of 3.5 mm diameter as fuel nozzle. Pictures 2 and 3 show the atomization of water at air speeds of 105 and 53 m/s, respectively; hence $K = 1780$ and $450\ cm^{-1}$, respectively. Pictures 4, 5, and 6 show the atomization of alcohol at air speeds of 100, 55, and 28.5 m/s, respectively. The corresponding values of K are 5020, 1460, and $415\ cm^{-1}$, respectively. The pictures show very clearly that the atomization of alcohol is significantly better than that of water at the same air speed (pictures 2 and 4, 3 and 5, respectively. They also show that the atomization is similar at similar values of K (pictures 2 and 5, 3 and 6, respectively). Both the form of the liquid stream at exit and its ramifications and the drop diameters appear very much alike. Thus the correctness of the characteristic value is at least qualitatively demonstrated.

Series II shows in four pictures approximately the lower limit of K at which one can still speak of atomization. The liquid is water; the air speed is 27 m/s; hence $K = 120\ cm^{-1}$. The water comes out in a closed stream which, however, does not break up into many separate threads, as at high values of K, but is drawn out into a long, thin main-thread, from which separate threads are drawn. In time the main-thread also disintegrates into discrete drops, giving the appearance of a string of pearls. From the separate pictures, especially II_3 and II_4, which show pictures taken, about 1/4 second apart, on the same plate, the separate phases of exit and break-up can be clearly recognized. At the same time one sees strong precipitation on the walls. The air speed is no longer sufficient to carry along the coarsely atomized drops. An engine would certainly not be very satisfactory with such a poorly atomized mixture.

The next two series (III and IV) show a comparison of two forms of fuel nozzle, with alcohol as liquid. The first picture of each series shows the carburetor set-up, in both cases a Venturi throat into which a fuel nozzle is built. In series III, the "P nozzle," the opening is just behind an abrupt widening of the cross section of the air stream. I do not know a scientific reason for this shape; however, as this or a similar design is quite a favorite in carburetor construction at present, it was investigated. Series IV shows a nozzle, the AI nozzle, with opening in front of an abrupt widening of the air stream cross section. The purpose was, that the liquid be snatched off from the edge as a thin band at exit. How far that is attained is shown by the separate pictures, taken for air speeds of 110, 58, 39, and 32 m/s. Corresponding values of K are given in each picture.

The first pictures of the two series show no important differences. The only thing that is shown is a gathering together of the fuel in the stagnant space behind the nozzle for the P nozzle (series III), while it is snatched off abruptly with the A nozzle. No remarkable differences in the fineness of atomization is apparent. In the next pictures, at a lower value of K (about 1700 cm^{-1}) the A nozzle already shows a slight superiority, for the fuel is torn off abruptly, while the gathering together in the stagnant space has increased with the P nozzle. The fuel breaks off and forms rather large drops. The condition persists to the lowest value of K in picture 5, which shows the first great gathering together in the stagnant space for the A nozzle. The atomization with the A nozzle appears somewhat finer throughout. I am sorry that I cannot give a measure for comparison of the two nozzles, since the pictures do not have enough contrast.

On the other hand, the two next series (V and VI), which show a comparison between Venturi air nozzle, could be counted out and measured under a comparator. The pictures themselves show nothing new in comparison with the preceding. Differences in the degree of atomization can hardly be recognized by the naked eye. But evaluation with respect to the number and size of the drops in the right half of a picture gave surprising results. These are shown in two different kinds of curve. The first (fig. 3) shows the frequency curves usual in statistics. It is striking that velocity has less influence on the position of the maximum (the displacement on the diameter axis is trivial) than on the steepness at the maximum. As K decreases, the slope of the curve on the side of increasing diameters gets steadily less. What significance that has is clearly shown in the next graphs, the volume distribution curves. (Fig. 4.) These show what percentage of the total atomized volume breaks up into drops whose diameters lie between zero and that corresponding to the abscissa. This manner of showing results has greater practical interest, as one can deduce from it a measure of the value of the atomization. For it is clear that that carburetor which, under otherwise equal conditions, atomizes 90% of the fuel supplied to it into drops whose diameters lie between zero and a certain limit is more efficient than another carburetor with which, for example, only

75% lies below this limit. One can perhaps take as the simplest measure of the value of the atomization the diameter below which lie the drop diameters of 90% of the atomized volume. For short, this will be called the "90% diameter." From the curves of this chart (fig. 5) which contains the results of a survey for quite a range of velocities, the "90% diameters" have been chosen and are applied in the next chart; Figure 6 is abscissa. The "90% diameters" range from $d = 0.18$* mm at $U^* = 53.3$ m/s, $K = 1420\ cm^{-1}$ to $d = 0.8$ mm at $U^* = 15.5$ m/s, $K = 120\ cm^{-1}$.

A conformity to law may now be recognized. It is, however, not very easy to formulate, for the process is rather complicated. One must first get clearly in mind what physical properties of the two media, air and fuel, may in general, be expected to influence the result. The most important are density, surface tension, and viscosity. All the inertia forces are proportional to the density; the surface tension tends to draw the surface together; the viscosity plays the more passive role of damping force. From the dimensions of these quantities a line on the "law" can be drawn. If one considers first an ideal liquid, and therefore omits consideration of frictional forces, he sees that the mean drop diameter d can be a function only of the density ρ, the surface tension T, and the relative air speed U of the two media; $d = f(\rho, T, U)$. The only combination of the three independent variables that has the dimensions of length is $T/\rho U^2$, the reciprocal of K. The drop diameter law may therefore be written:

$$d = c\,\frac{T}{\rho U^2}.$$

The dimensionless quantity c need, of course, not be a constant. Rather is it, in general, considering the viscosity in both media, a function of some dimensionless combination of the above-named three variables and the viscosity μ. The only dimensionless combination of these quantities is

$$D = \frac{T}{\mu U}.$$

The dependence of the mean drop size may now be written:

$$d = c\left(\frac{T}{\mu U}\right)\frac{T}{\rho U^2}.$$

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*Translator's changes.

This is the similarity law of the atomization problem. The function c will perhaps take different forms for different forms of exit nozzle. For one case the curves shown above (fig. 5) indicate its course. It is, of course, unsettled what diameter to use as the "mean." Physically the maximum of the size-distribution curve is of more importance. Since, however, it could not be determined with sufficient exactness in the cases under consideration, on account of insufficient auxiliaries, I have chosen the "90% diameter," which has the advantage over the other of being practically more important, and may be expressed more exactly; for only about 10% of the total atomized volume lies in the part of the frequency curve between zero and the diameter of the maximum.

In conclusion I should like to give a brief resume of those results which are the most important from a practical point of view.

The outstanding quantity of the whole atomization problem is the characteristic K, and therefore the ratio of the static pressure of the air stream with respect to the liquid to the surface tension of the liquid. The higher its value, the better the atomization. One should, if possible, avoid letting K fall below about 300 to 400 cm^{-1}, if one wishes flexible engines. This means the use of a carburetor of narrow section and a narrow intake pipe, as is done in American practice. The high pressure drop at high speeds is undesirable, but unavoidable, and is not disagreeable in automobile engines. But conditions are different for aircraft engines, which need have only a good idling and a narrow full-load speed range. In my opinion the best arrangement for this would be a carburetor for full-load, and an accelerating arrangement for passing from idling to full load.

The shape of the Venturi (fig. 7) plays a secondary role. The increase of section beyond the throat had best not be too abrupt. The insertion of a cylindrical piece would improve the atomization somewhat, but probably has a greater resistance also.

More is to be expected from improvements in the design of the nozzle. (Fig. 8.) Even if the object of the study described were only the discovery and establishment of the similarity law for atomization, yet two series of studies have established the view that it is advantageous to introduce the fuel in front of a sharp-edged widening of the air-stream section, so that it enters the region of highest air velocity as gradually as possible. Nozzle shapes I and II are superior to III and IV, which are quite popular at present.

How much effect the viscosity of the fuel may have is still a matter for investigation. But these results suffice for modern fuels, whose viscosity is usually less than that of alcohol or water. The conditions for the somewhat more viscous fuels, especially the heavy oils, may perhaps be found on the grounds of the capillary-wave theory. But heavy oils, for other reasons, may never be considered as fuels for carburetor engines. They will, indeed, always be applied exclusively to injection engines. Atomization in these, however, is much simpler than that in the carburetor engine, since they can work at constant injection velocity at all rotative speeds. Hence all the atomization difficulties encountered at low rotative speeds (i.e., air speeds), vanish. The carburetor engine will not, however, be disposed of for a long time on this account, for the carburetor itself is, in spite of all its faults, such an ingenious and simple device that it will probably reign supreme in the field of light engines for many years to come.

Translation by R. A. Castleman, jr.,
Bureau of Standards,
Washington, D. C., August 27, 1931.

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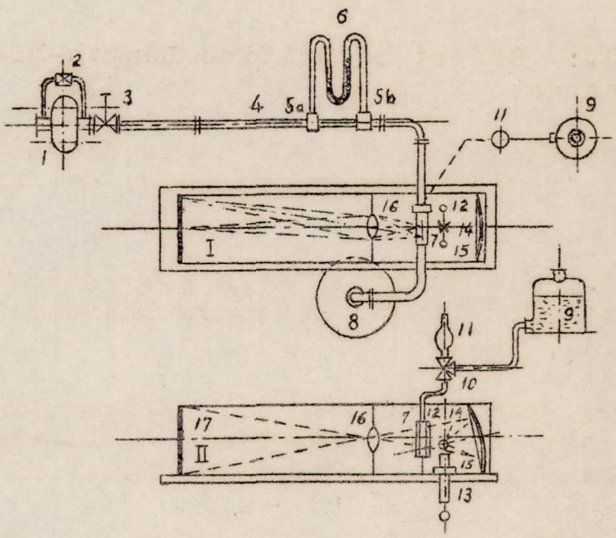


Fig. 1 Schematic sketch of apparatus.

I Plan view
II Side view

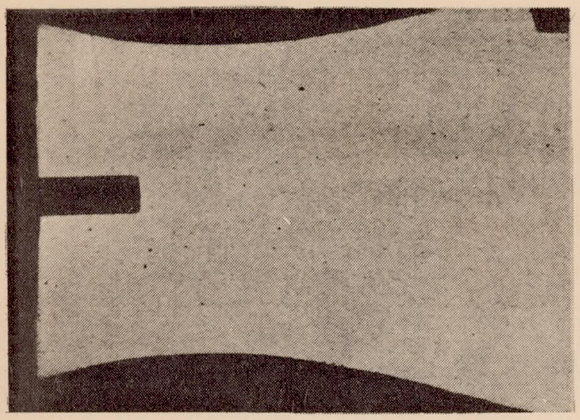
1, Blower
2, By-pass valve (for fine regulation)
3, Check valve (for coarse regulation)
4, Jacob-tube
5a, 5b, Pressure-measuring places
6, Manometer
7, Carburetor model
8, Separator
9, Vessel for liquid
10, Three-way cock
11, Measuring vessel
12, Tube to carburetor model
13, High voltage arrangement
14, Illuminating spark
15, Concave mirror
16, Objective
17, Photographic plate

"ATOMIZATION" PICTURES

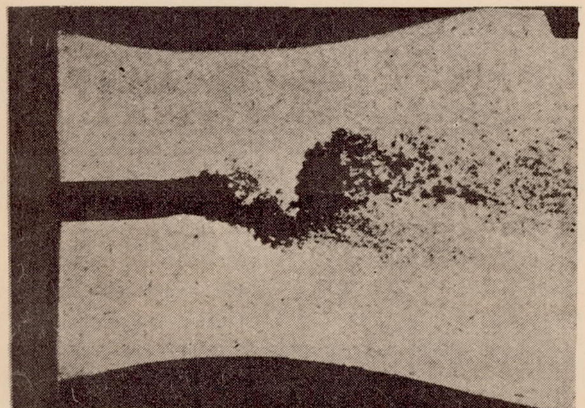
Scale 1.4 to 1 Liquids.

Water, T about 74 dynes/cm. Alcohol, T about 24 dynes/cm.

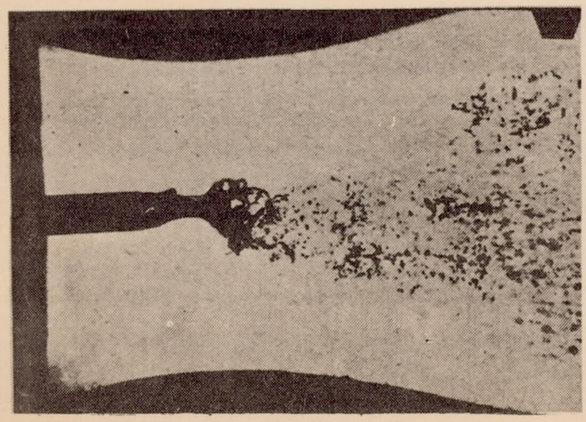
U is the mean air speed in the narrowest section.



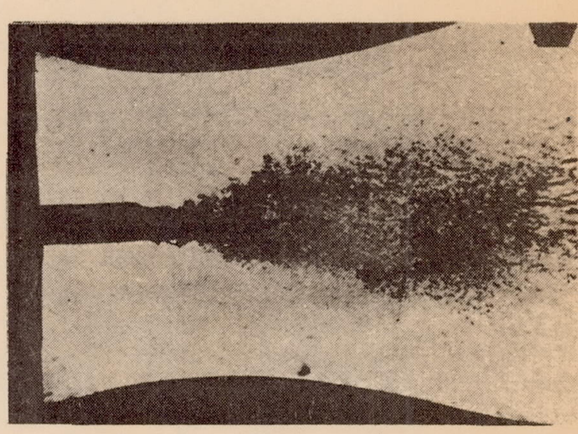
I_1, Series I, Picture 1,
Carburetor set - up.



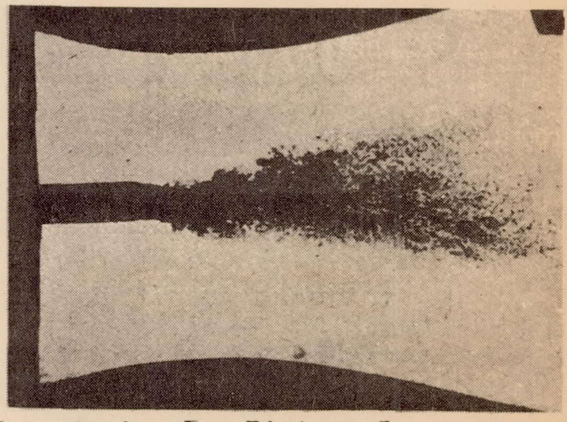
I_2, Series I, Picture 2,
Water, U= 105 m/s, K= 1780 cm^{-1}



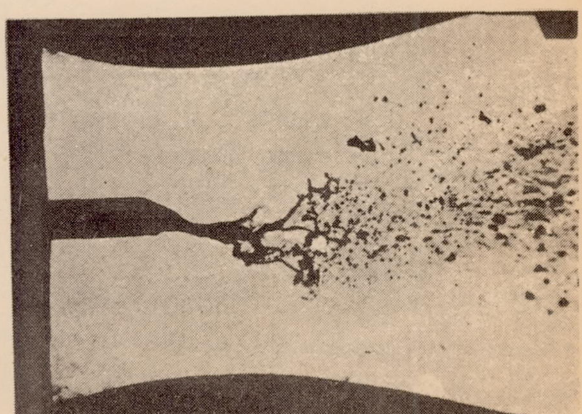
I_3, Series I, Picture 3,
Water, U= 53 m/s, K= 450 cm^{-1}



I_4, Series I, Picture 4,
Alcohol, U= 100 m/s, K= 5020 cm^{-1}



I_5, Series I, Picture 5,
Alcohol, U= 55 m/s, K= 1460 cm^{-1}



I_6, Series I, Picture 6,
Alcohol, U= 28.5 m/s, K= 415 cm^{-1}

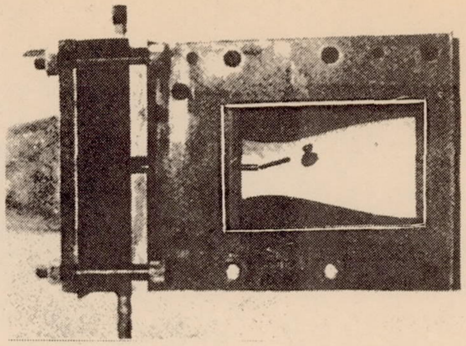
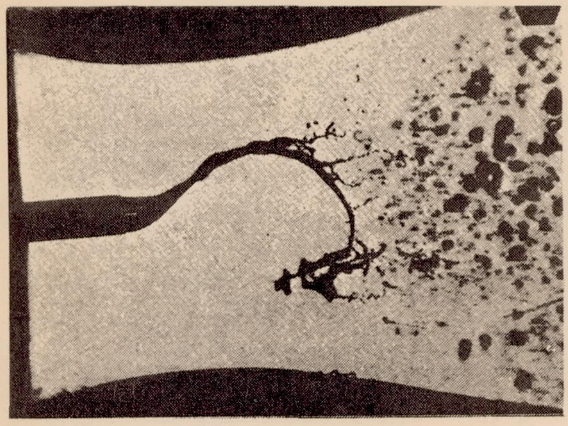
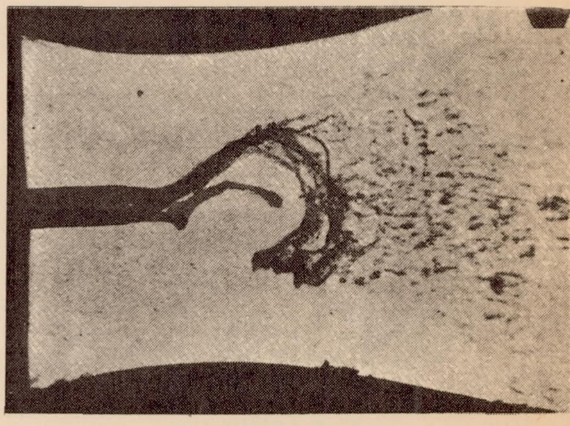


Fig. 2 Carburetor model.

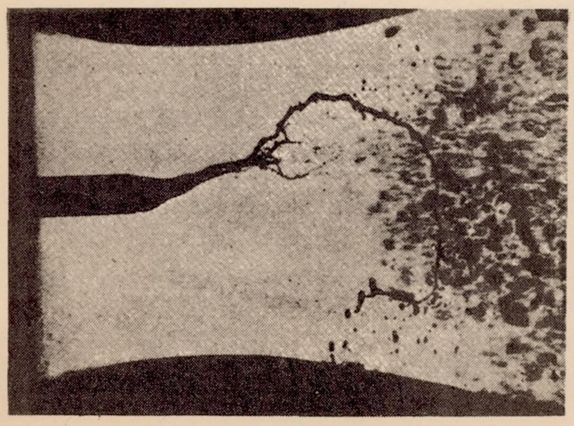
Water U= 27 m/s. K= 120 cm^{-1}



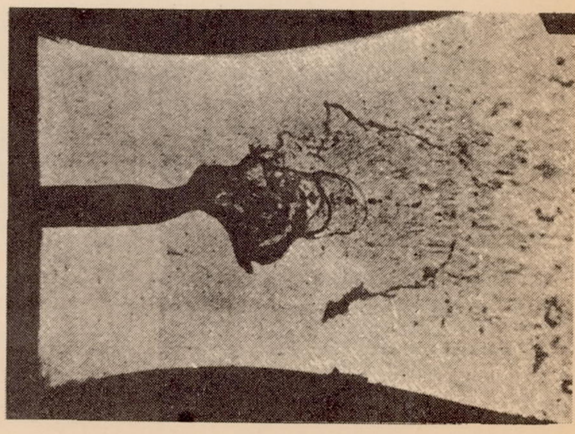
II_1, Series II, Picture 1,



II_3, Series II, Picture 3.



II_2, Series II, Picture 2.

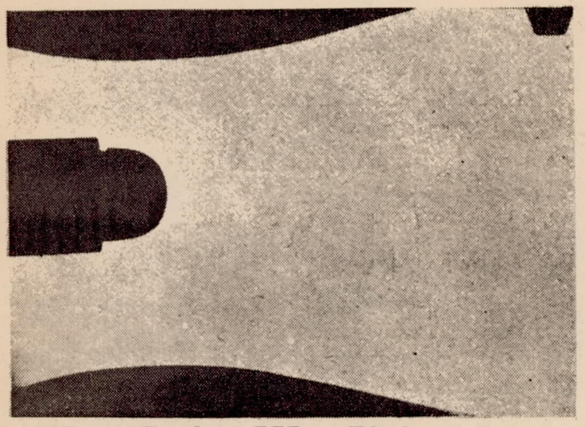


II_4, Series II, Picture 4.

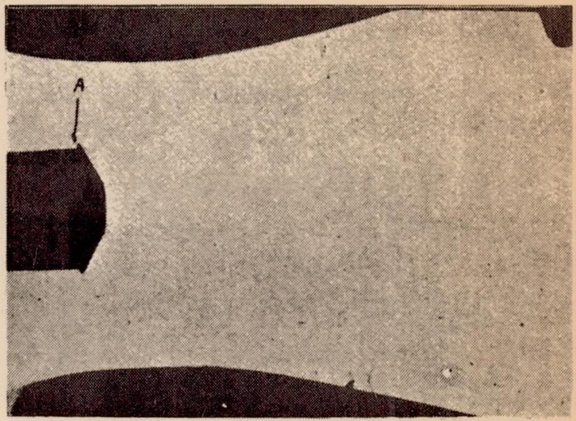
Alcohol

Series III

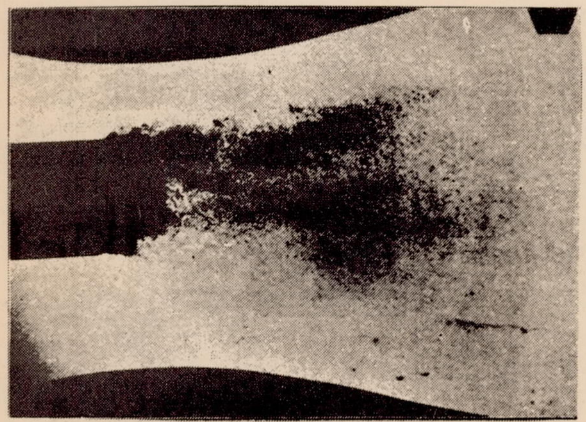
Series IV



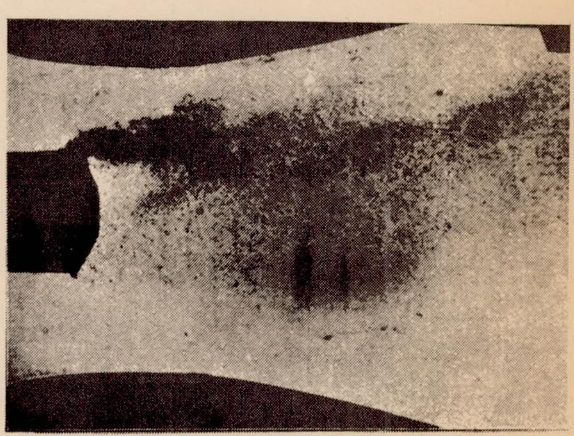
III$_1$, Series III, Picture 1, Carb. set - up. "P-nozzle".



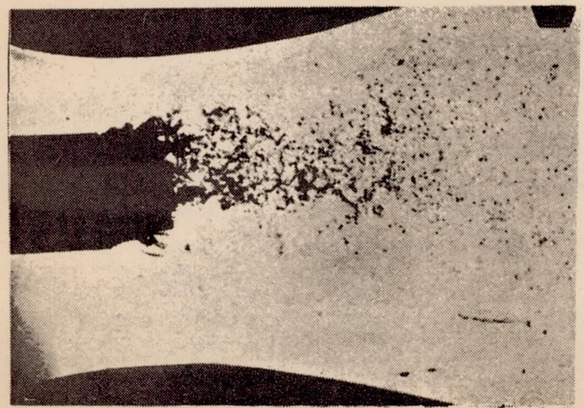
IV$_1$, Series IV, Picture 1, Carb. set - up, "A nozzle"



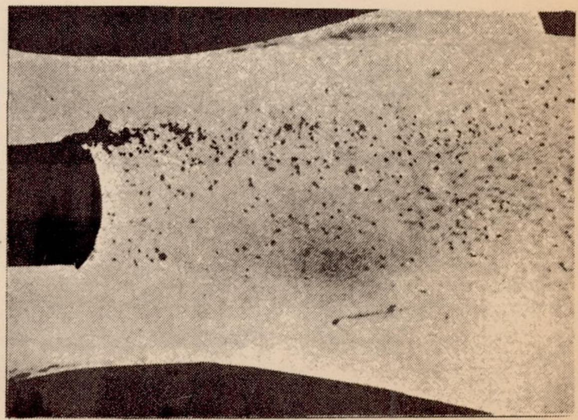
III$_2$, Series III, Picture 2, U= 118 m/s, K= 6890 cm^{-1}



IV$_2$, Series IV, Picture 2, U= 104 m/s, K= 5420 cm^{-1}



III$_3$, Series III, Picture 3, U= 57.2 m/s, K= 1640 cm^{-1}

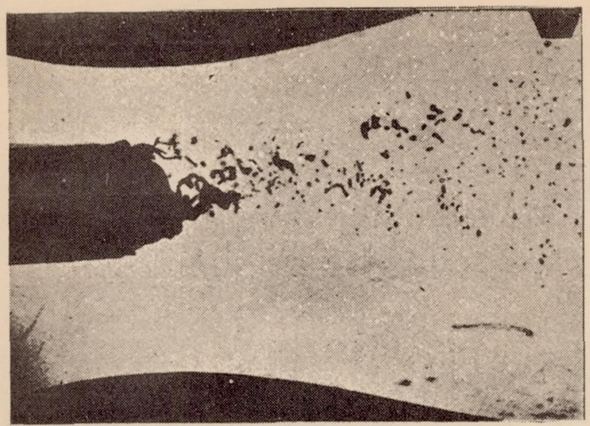


IV$_3$, Series IV, Picture 3, U= 58.2 m/s, K= 1700 cm^{-1}

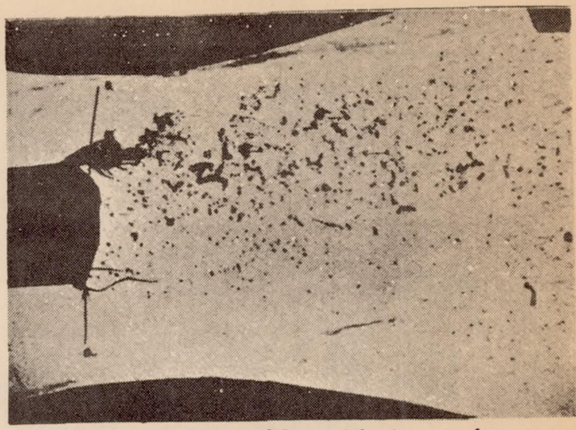
Alcohol

Series III

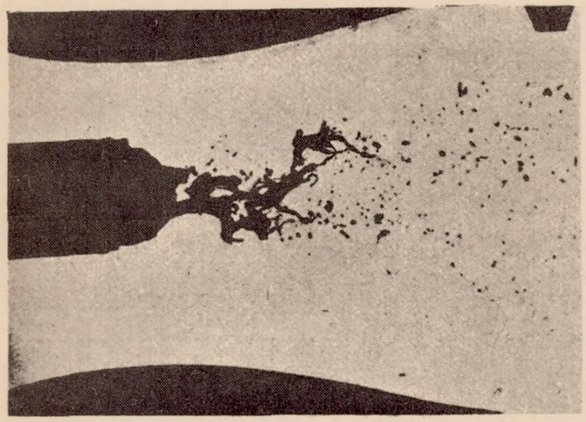
Series IV



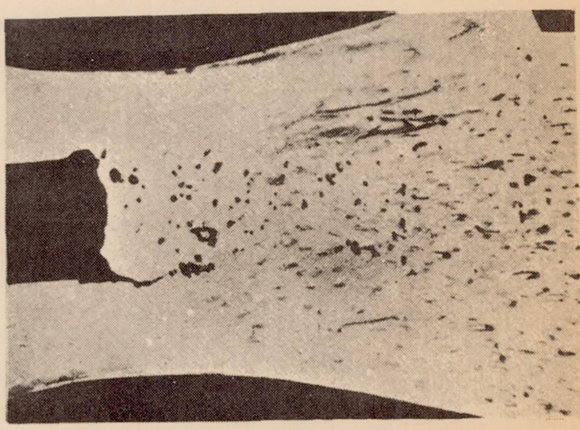
III_4, Series III, Picture 4, U= 38.7 m/s, K= 750 cm^{-1}



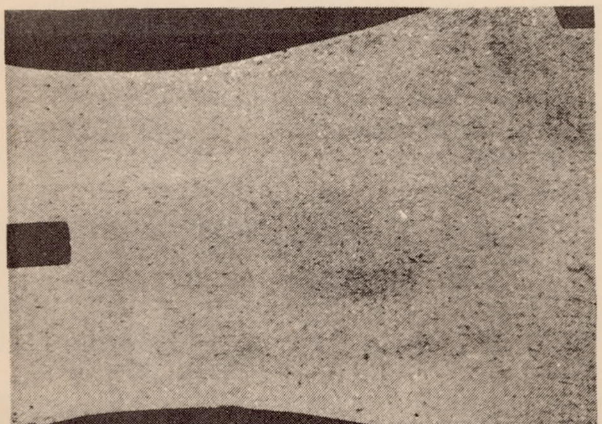
IV_4, Series IV, Picture 4, U= 38.5 m/s, K= 740 cm^{-1}



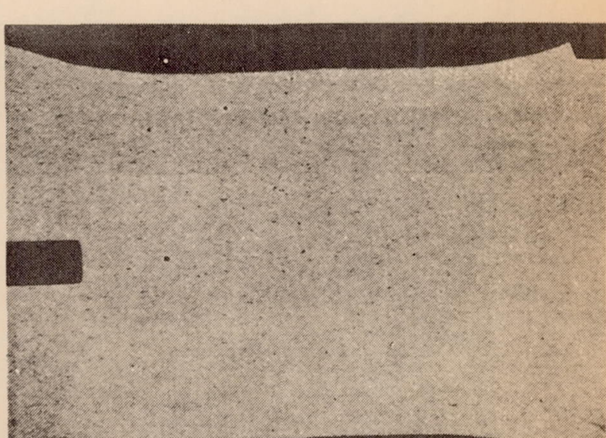
III_5, Series III, Picture 5, U= 32.1 m/s, K= 515 cm^{-1}



IV_5, Series IV, Picture 5, U= 31 m/s, K= 480 cm^{-1}



V- Plain Venturi



VI- Parallel Venturi

Carburetor set - up for series V and VI

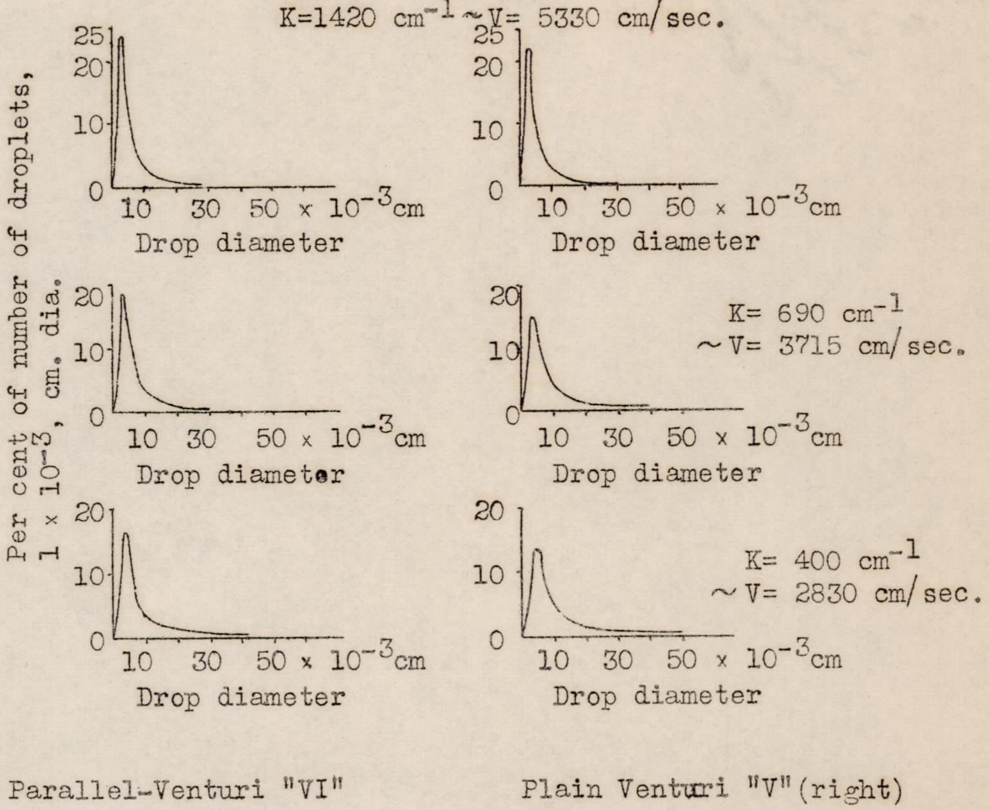


Fig. 3 Drop distribution curves.

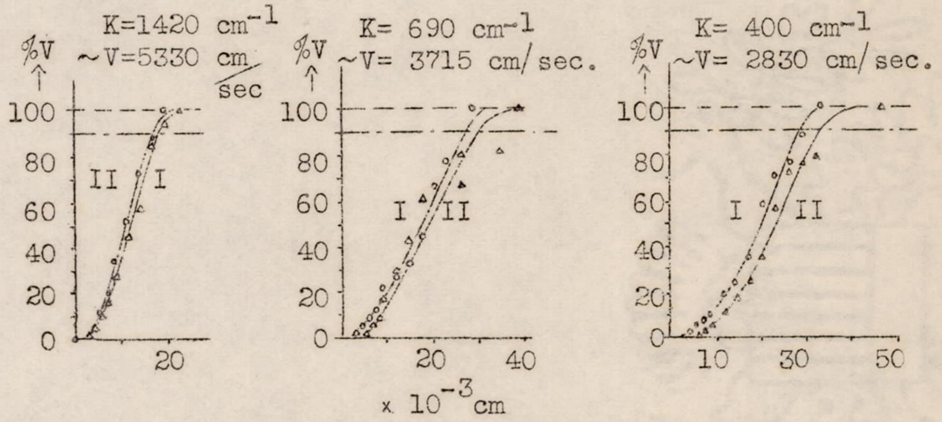
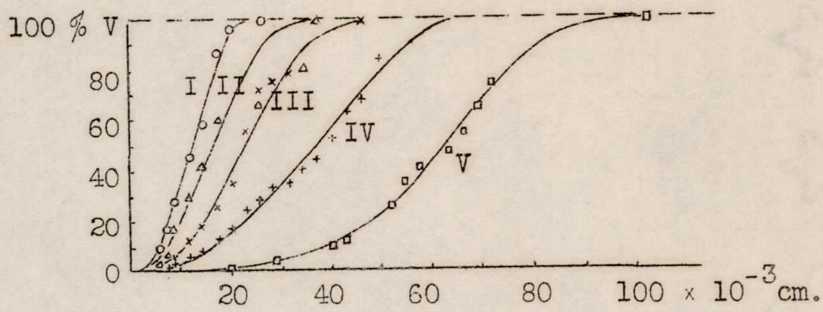
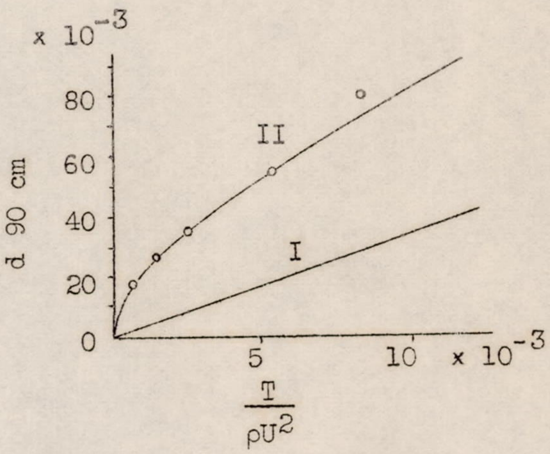


Fig. 4 Volume distribution curves for plain venturi and parallel venturi.



		Kcm^{-1}	$\sim Vcm/sec^{-1}$
I	○	1420	5330
II	△	690	3715
III	×	400	2330
IV	+	190	1950
V	□	120	1550

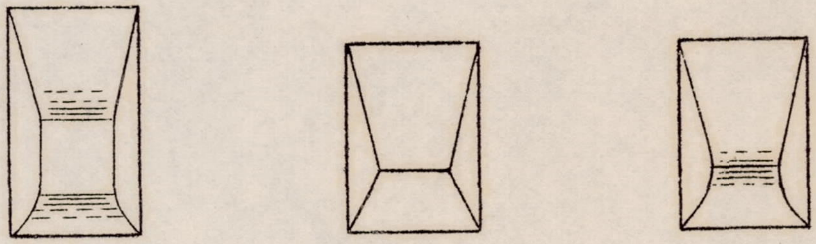
Fig. 5 Volume distribution curves for various values of K.



I From capillary wave law, neglecting viscosity.

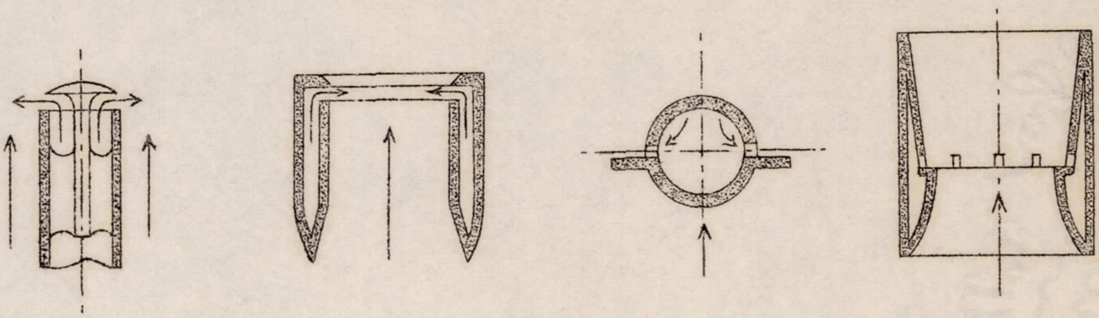
II From capillary wave law, taking account of viscosity.

Fig. 6



I II III

Fig.7 Venturi nozzles.



I II III IV

Fig.8 Fuel nozzles.