

Photomicrographic Study of Atomization of Liquid Fuels Within a Combustion Chamber

PAPER N-6

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Critical illumination is correctly obtained by means of a very luminous vertical slit of variable width through which the image of any part of the jet is obtained. A microscope carries a precisely balanced rotating mirror whose speed is variable. If the sweeping speed of the mirror is adjusted to that of the droplets moving in the field of observation, their image in the plane of the eyepiece will be stationary, and then their photography, too, will be possible. The optical elements have been carefully determined, for lowering of contrast is mostly caused by optical aberrations. It is, on the other hand, the maximum contrast which permits the best perception of the droplets. The experimental study concerns the mechanics of atomization.

IT IS WELL KNOWN THAT atomization plays an important role in the complete combustion of injected liquid fuels; and the two decisive factors are the microstructure and macrostructure of the jet.

The microstructure is determined by the finest division of the liquid, or, in other words, the creation of droplets of the smallest possible diameter. The macrostructure is determined by the most homogeneous distribution of the droplets within the jet.

We know that the intensity of the combustion is inversely proportional to the time of combustion of the droplets and that the latter increases as the square of their diameter, which explains the interest in the fineness of the atomization.

Our studies are mainly concerned with this feature of atomization, and endeavor to explain the mechanism by employing photomicrography as a means of observation and recording.

This study consists of three parts: (1) a review of previous methods, (2) a description of the experimental apparatus, and (3) an analysis of atomization.

Review of Previous Methods

Numerous methods have been used for the study of atomization and fogs, for example,

(a) The method of collecting droplets resulting from atomization on a type of racket consisting of fine threads issuing from a solution of Plexiglas; and subjecting them quickly to a microscopic examination.

(b) The "fingerprint" method in which one records the impressions which the droplets have left in a soft substance such as Plastiline. A microscopic examination also follows in this case.

Both methods, however, have an inherent disadvantage: one never knows whether or not any coalescence occurred during the period between collection and examination.

According to another method the liquid is injected through a coating substance, such as molten paraffin or other molten wax, and the solidified spherules are counted afterward.

More often, however, high-speed single-shot photography or high-speed cinematography was used, making use of a microscope which was suitably illuminated by flashes of very short duration. Most of these experiments have led to the use of microscope objectives of very short focus in order to obtain a great enlargement. Unfortunately, the proximity of the objective and the jet modified the field of flow. Besides, and notwithstanding the very short exposure time, there was inevitably some blur during the time the image was being recorded on the emulsion.

During the last few years the combustion of single droplets has been studied using high-speed cinematography as a means of recording the event. The method consists in letting relatively large droplets, of the order of 1- to 2-mm diameter, drop freely into a chamber the temperature of which can be adjusted.

Although this method is very interesting, it introduces into the interpretation of the results a scale effect which should not be neglected. The ratio of the volumes of droplets of 20-micron diameter and 2-mm diameter is 1:1,000,000.

We have tried to avoid these drawbacks by using the techniques of the rotating mirror (in which optics play an important role). The experimental technique is called "the method of photomicrography by transparency"; the illumination and the microscope for observation are located on opposite sides of the jet.

Experimental Apparatus

We know that by using a rotating mirror together with a camera objective we will obtain a sharp picture of an object moving within the field, provided that the rotating speed of the mirror is properly adjusted. Figures 1 and 2 are schematic drawings, and Figs. 3 and 4 are views of the apparatus.

The light source includes a tungsten ribbon filament lamp of 1250 candelas/cm². (the wavelength of its maximum spectral radiation is 0.96 micron). A first condenser forms an image of this light source on a vertical slit of adjustable width (a spectrograph slit). A collector lens, placed against this slit, carries a reference scale on its plane face.

Presented on October 22, 1960, at the Fifth International Congress on High-Speed Photography in Washington, D. C., by Willy Diamant, 3 Ave. de la Marne, Champsigny-sur-Marne (Marne), France.

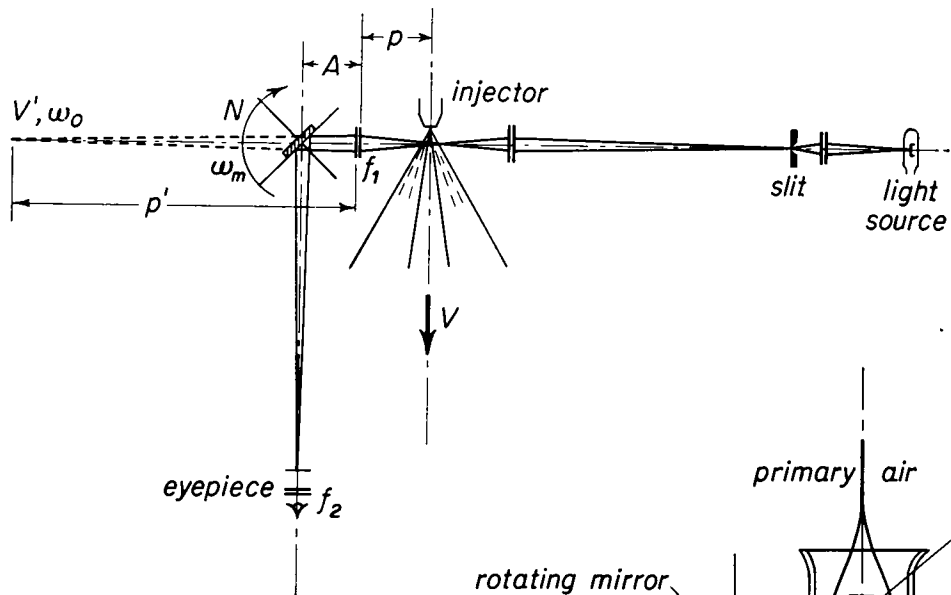


Fig. 1. Schematic drawing of optical device.

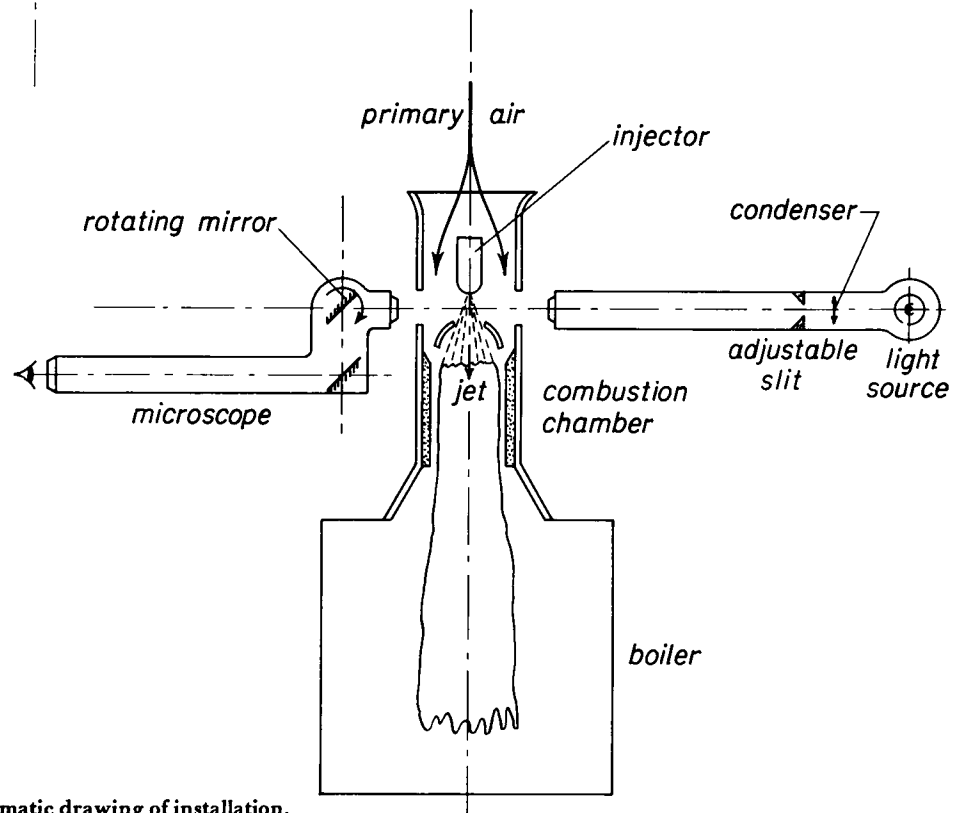


Fig. 2. Schematic drawing of installation.

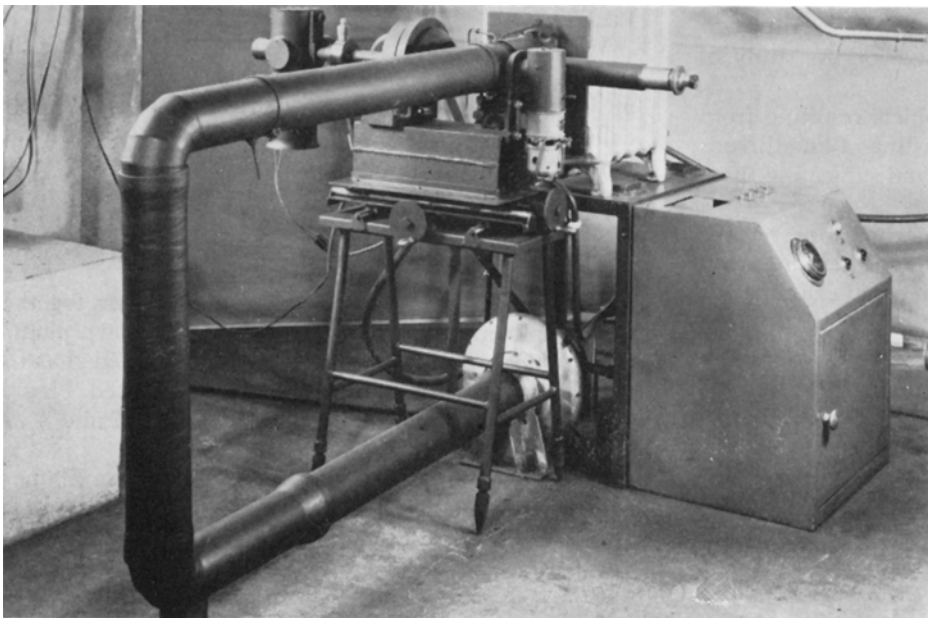


Fig. 3. Overall view of apparatus.

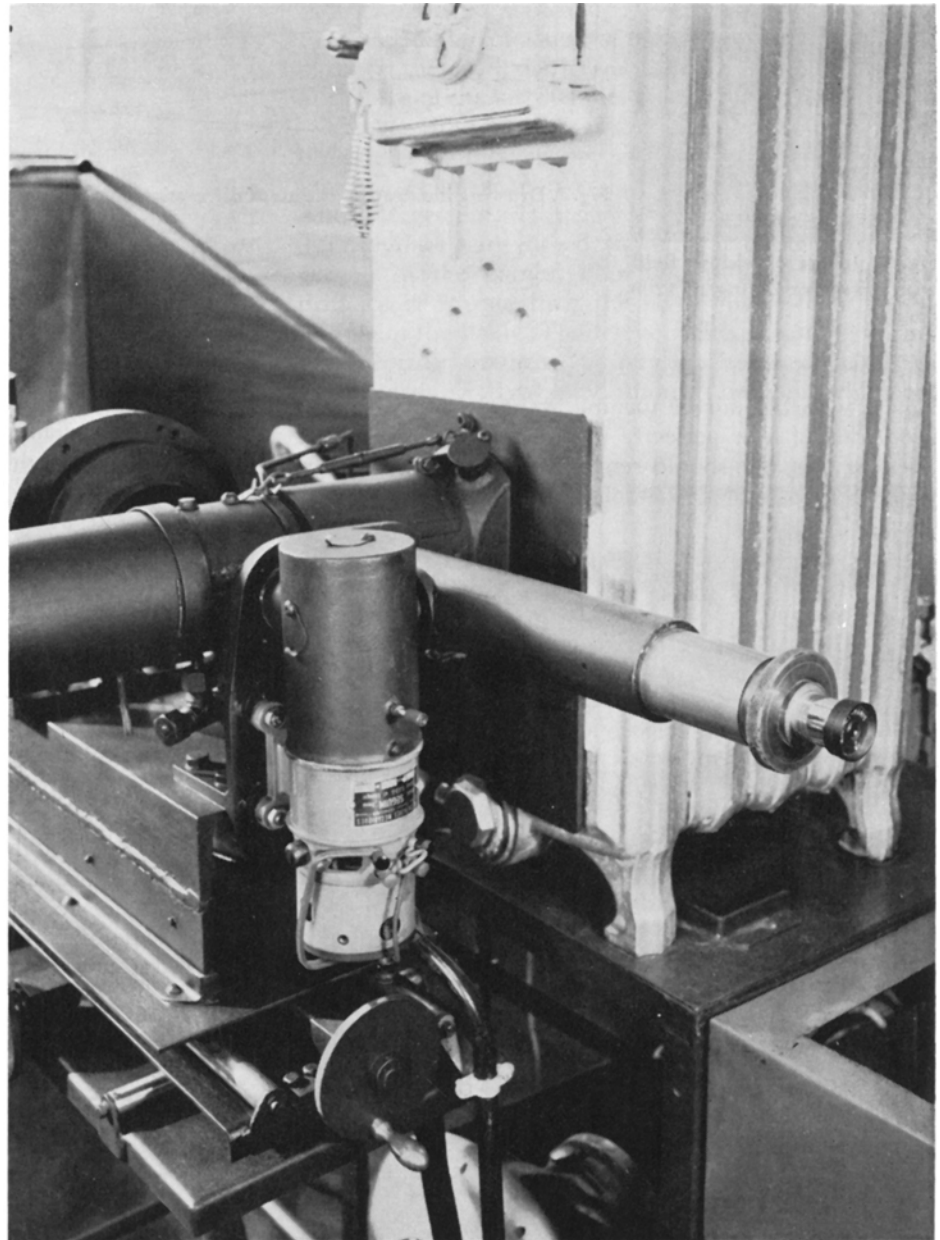


Fig. 4. Detail of apparatus showing microscope.

A second condenser, called the main condenser, transmits an image of the slit source to the plane of the jet under observation. Its numerical aperture is 0.055. We then obtain the image shown in Fig. 5.

The objective lens, located on the other side of the jet, is the objective of the microscope. Its numerical aperture is the same as that of the main condenser, i.e. 0.055. Because of the focal lengths of the lenses used, the distance between them is approximately 120 mm. In this space we have been able to place a combustion chamber.

We should mention another very important point, namely the balance of the rotating mirror. We know that it is absolutely necessary to have the mirror, which is driven by its adjustable-speed motor, perfectly balanced in order to prevent the unwanted blur at the moment of observation and photography. The rotational speeds for this work range from 800 to 10,000 rpm. By looking at the image of the visible field, as shown in

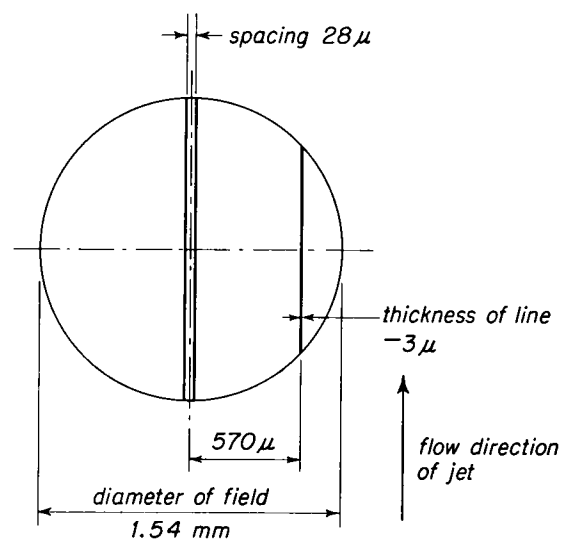


Fig. 5. Image of field of view.

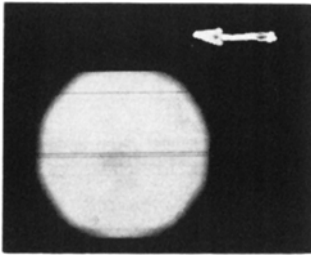


Fig. 6. Image of visible field with mirror revolving at 1200 rpm.

Fig. 6, with the mirror turning at 1200 rpm, we get a good idea of how perfectly the mirror is balanced. In assessing this, one should remember that the separation of the scale lines is 28 microns and their width about 3 microns.

We would like to recall briefly the characteristics of the photomicrographic arrangement. The main condenser forms a luminous slit with the width of 150 microns in the middle of the jet (this is the width which we have most frequently used in our photographs). The height of this slit (1.54 mm) is exactly the diameter of the object field of the microscope. The depth of field is approximately 330 microns.

The power of the microscope was chosen so as to give maximum resolving efficiency. This is known to be obtained for a given numerical opening, if the ocular ring reaches a diameter of approximately 0.7 mm. The necessary power was therefore 168 diopters, which gives the microscope a total enlargement of 42X. The photographic enlargement is 7X.

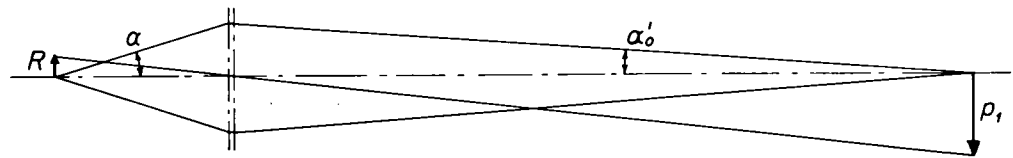


Fig. 7. Drawing illustrating radius of diffraction spot.

It is important that we stress the optical quality of such an arrangement. The perception and the contrast of small objects such as those we have to observe — which can be compared to little black discs on a light background — are subject to diffraction and to aberrations. Besides, any optical instrument subject to aberration leads to a widening of the diffraction curve and to a reduction of the illumination of the central spot.

We have made measurements of all the objective lenses of our photomicrographic bench and calculated the optical combinations. Diffraction theory makes it possible to determine the minimum perceptible diameter of the droplets. If the numerical aperture of the condenser and of the objective of the microscope are equal, it can be said that there is coherent illumination. Besides, the luminous slit is very narrow. One may admit, for the purpose of calculation, that the contrast of the objects is equal to one. If, on the other hand, one tolerates a minimum contrast in the image of 4/100, one can deduce the minimum observable diameter.

One should add that the minimum contrast is inversely proportional to the square of the wavelength, and proportional to the factor $2J_1(Z)/Z$, Z being a parameter defined as $Z = 2\pi\alpha_0\rho_1/\lambda$, ρ_1 being the radius of the diffraction spot. See Fig. 7.

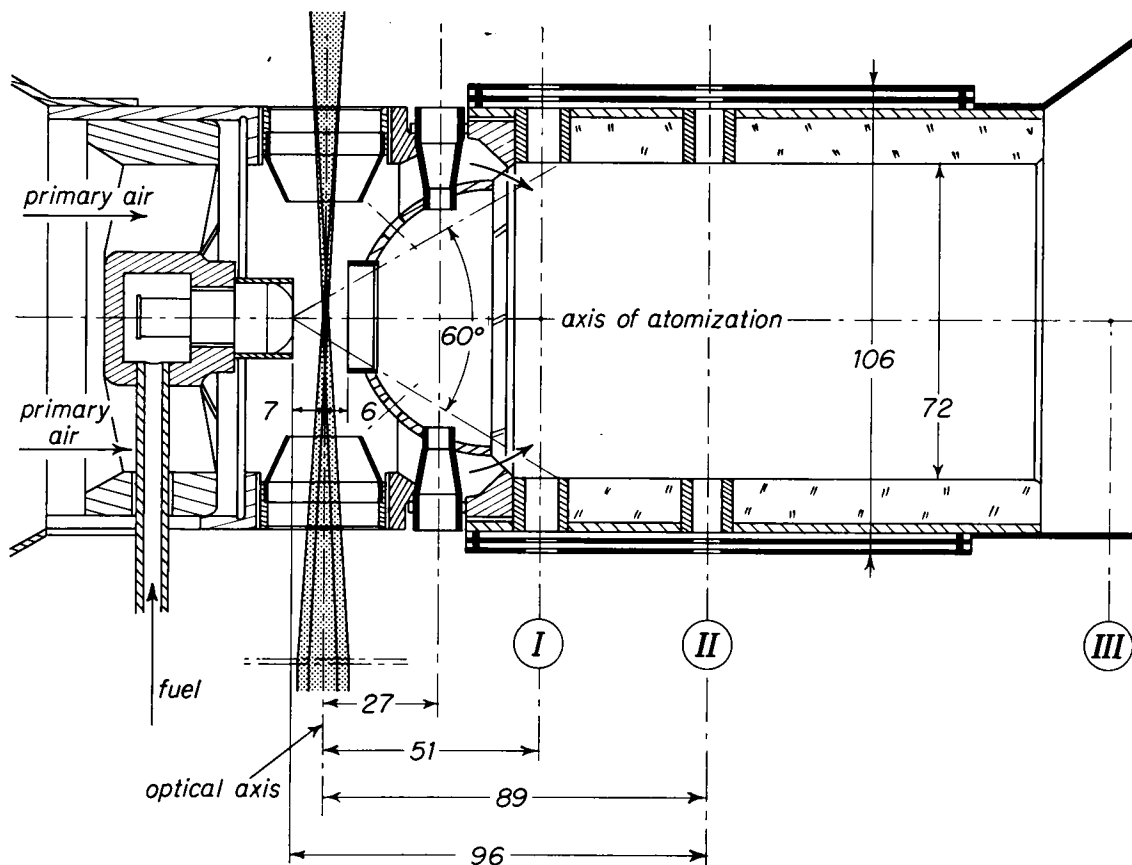


Fig. 8. Combustion chamber.

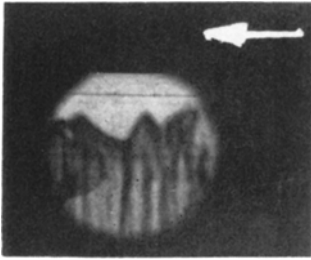


Fig. 9. Eddies appearing at rim of nozzle hole on periphery of jet.

By using the theoretical calculation of Professor Françon we arrived at the value of 0.92 micron. Experimentally — and this is shown on the photographs — we could record droplets of the thickness of the engraved lines, i.e., of approximately 3 microns.

While the aberrations tend to reduce the contrast, the light diffusion inherent in the presence of droplets in the jet also causes a reduction of contrast. In fact, the total intensity I of the diffused light can be put in the form of a product of three terms, namely, the incident illumination ϵ ; the square of the radius R of the droplets; and the square of a parameter x defined as the ratio $(2\pi R)/\lambda$. For the high values of x , ($x \doteq 100$), the total intensity I differs very little from $I = R^2\epsilon x^2/4$.

It is therefore important to use a light source with a maximum emission at long wavelengths. We have already mentioned that λ_{max} equals 0.96 micron for our particular light source. The advantage is confirmed by experiment.

As far as the combustion chamber is concerned, it is equipped with a burner with mechanical atomization and with an injector of a diameter of 0.25 mm. The angle of the jet reaches 60° for an injection pressure of 12 kg/cm² and the flow is of the order of 1.8 litres/hr for domestic fuel oil. See Fig. 8.

Atomization

We shall now discuss the atomization studies themselves. Only two types of liquid fuels were used: kerosene and domestic fuel oil.

An analysis of four different fuels, namely, kerosene, domestic fuel oil, gas oil and light fuel oil, has revealed two important things:

(1) The surface tension γ varies little from one fuel to another (27.7 dyne/cm for kerosene, and 31.6 for the light fuel oil).

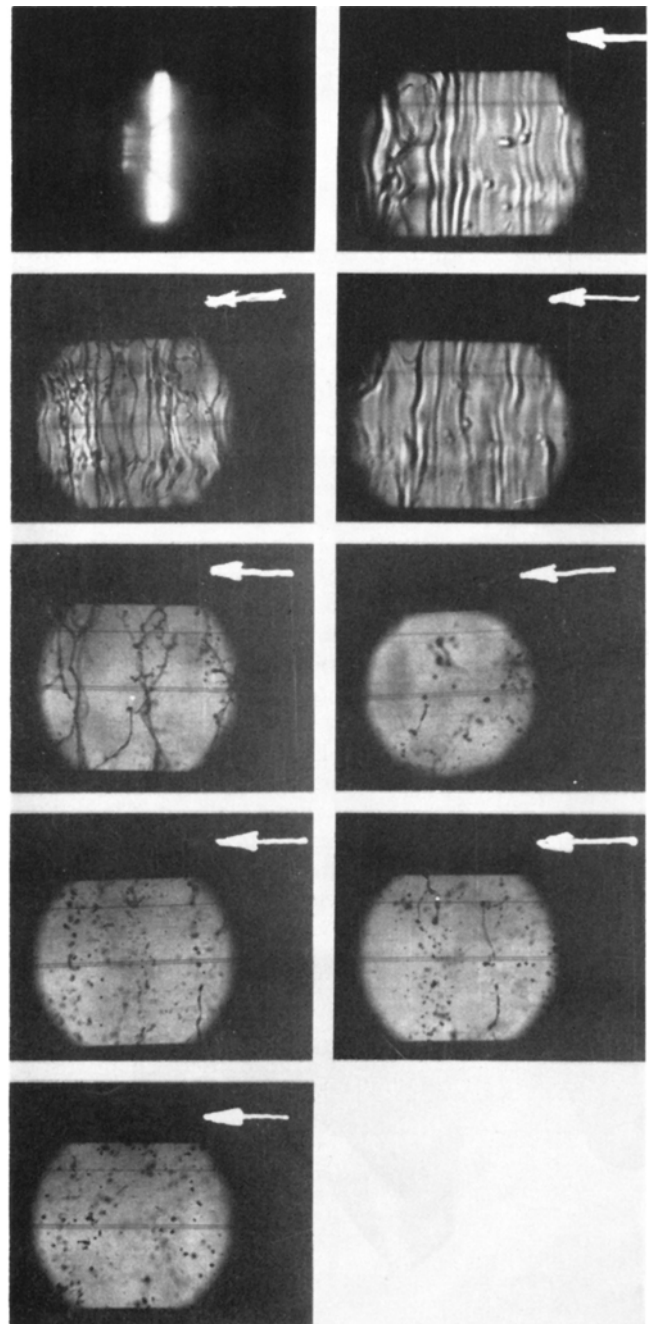
(2) The ratio of the surface tension γ and the specific gravity ρ of the fuels is practically constant (at about 35 cgs units).

Consider a liquid jet moving at a velocity V in the air, while around it the velocity of the environment is negligible. The velocity does not diminish suddenly from the value V within the jet to the value zero outside it. There is a region of discontinuity which is apparent in the form of an extremely thin *transition layer*. There is here a high rate of change of velocity. In reality there are two adjacent layers: one is liquid; and the other, which is much thicker, is air. The instability of the layer which separates the two fluids creates undulations

that give rise to a breakup which might be compared to the formation of a kind of emulsion. On the periphery of the jet there will therefore be eddies which commenced at the rim of the nozzle hole. See Fig. 9.

Figures 10 to 18 present the range of different results obtained with the two fuels used (kerosene and domestic fuel oil). The mean injection pressure was 12 kg/cm². The enlargement of the photographs is 21 \times .

Lastly, we had wished to verify if unburnt droplets existed in the flames. Photographs were taken at a distance of 96 mm from the tip of the injector, in the middle of the flame. The temperature, measured with a disappearing filament pyrometer, reached 1100 C. The records clearly showed unburnt droplets, which are



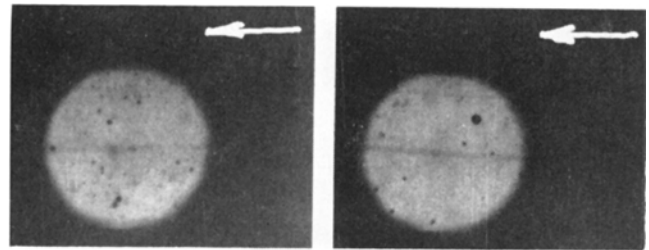
Figs. 10-18. Range of the different results obtained with the two fuels used (kerosene and domestic fuel oil). The mean injection pressure was 12 kg/cm². The enlargement of the photographs is 21 \times .

converted to solid combustion residues. See Figs. 19 and 20.

Conclusion

The originality of our method consists of the observation and permanent record of all stages of atomization. It has enabled us to demonstrate the turbulent region localized in the transition layer, and the successive stages which produce the liquid filaments and the droplets themselves. We should not forget that all of these phenomena take place within a very short time, of the order of 10^{-4} sec (for the particular pressure investigated).

The method is unquestionably advantageous, since it has found a direct application in the study of injection even within the interior of a combustion chamber, and even allowing observation within the flame itself.



Figs. 19 and 20. Unburnt droplets photographed at temperature of 1100 C.