RP281

THE MECHANISM OF THE ATOMIZATION OF LIQUIDS

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ABSTRACT

A discussion is given of the general problem and of some applications of the phenomena of liquid atomization, with especial reference to fuel preparation in internal combustion engines. It is pointed out that both "air" and "solid" injection seem to have physical backgrounds quite similar to that of air stream atomization, and the discussion is limited to the latter.

Some previous work which seems to bear either directly or indirectly on this problem is reviewed, and it is assumed that a necessary step in atomization is the tearing of ligaments from the unatomized mass, these ligaments being of such sizes that they will eventually break up into drops of the sizes observed in the spray.

Brief discussions are given of the applicability of Rayleigh's work on the rate of collapse of liquid columns to the collapse of these ligaments, and of what values of the $\frac{\text{length}}{\text{diameter}}$ ratio and of the degree of instability may be expected to be effective. It is then shown how the sizes of the ligaments can be determined from those of the drops in the spray. Finally, combining (*a*) measurements of the sizes of drops, (*b*) geometrical and physical considerations, and (*c*) Rayleigh's work, it is shown that these ligaments will collapse so quickly at sufficiently high air speed—that is, when true "atomization" sets in—that the droplets will then appear to be picked directly from the main mass, as has been observed.

Certain other observations are shown to be in qualitative agreement with this theory.

CONTENTS

I. INTRODUCTION

The problem of liquid atomization is of interest and importance in the study of internal combustion engines because the great majority of such engines at present do, and probably for some time in the future will, derive their energy from a liquid fuel; which fuel must be supplied under time and temperature conditions not suitable for complete vaporization. While complete vaporization may have occurred in old slow-speed carburetor engines, using the highly volatile gasoline formerly available, it does not occur in modern high-speed engines of this type, which must use gasoline of much lower volatility. The problem seems even more acute with engines of the Diesel type, in which a fuel of very low volatility is injected directly into the cylinder just before ignition.

This phenomenon is also in other important commercial and technical use (for example, the manufacture of evaporated milk, metal spraying, etc.). It is, in general, employed when it is desired to put a mass of liquid into the finest possible state of subdivision under conditions not suitable for complete vaporization. So far, progress (particularly automotive) has demanded that industry shall not pause for explanation of the mechanism of atomization, but merely investigate the circumstances favoring its production, so that one may supply these and thus obtain the phenomenon. To utilize such processes to the best advantage, however, it is necessary to understand the mechanical background. The problem is evidently of a physical nature; indeed, the very use of the phenomenon in design work—the knowledge that it is only necessary to supply certain physical conditions in order to be sure of obtaining the phenomenon—is tacit acknowledgment of the existence of a definite physical background.

The object of this paper is to put in enlarged and more tangible form a theory of this mechanism advanced in a letter to the editor of the Physical Review.[1] This theory involved two assumptions: (1) That ligament formation is a necessary step between the large mass of liquid and the discrete droplets; (2) that Rayleigh's analysis of the rate of collapse of liquid columns applies, without modification, to these ligaments.

As this work is primarily concerned with the preparation of fuel for combustion in internal-combustion engines, this theory, to be satisfactory, should cover cases found useful for this purpose. There appear to be two of these: (1) Air-stream atomization. In this process air at high speed is passed over the surface of the liquid to be atomized. It is found that, when the relative air speed is sufficiently high, the liquid is broken up into minute drops. This process is outstanding in commercial importance at the present time (gasoline carburetor). High-pressure air injection is a special case of air-stream atomization. (2) "Solid" or "airless" injection. It is found that when liquid is forced under very high pressure (300 to 600 atmospheres) into still air it is finely atomized. (This method was invented years ago, but finds its maximum application to the modern small or high-speed Diesel.) As the high-injection pressure merely gives a high initial velocity to the injected liquid, we see that this case also is similar to air-stream atomization: the fast-moving liquid loses ligaments to the still air in the same way that the fast-moving air drags ligaments from the quiescent liquid.

Since, then, both forms of fuel atomization appear to be physically similar, this analysis will be limited to air-stream atomization. The following symbols will be used:

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[1] Castleman, Phys. Rev., 35, p. 1014; 1930.

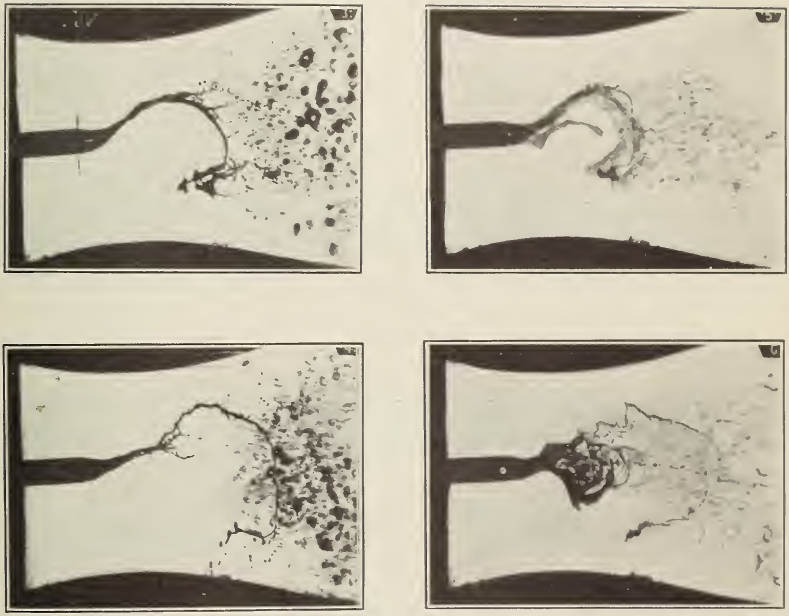

FIGURE 1.—*Atomization of water in model of carburetor throat (Scheubel). Air speed about 2,700 cm/sec.*

Figure 2.—*Atomization of water in model of carburetor throat (Scheubel). Air speed about 5,300 cm/sec.*

Figure 3.—*Atomization of water in model of carburetor throat (Scheubel). Air speed about 10,500 cm/sec.*

TABLE 1

Symbol	Quantity
S	Air speed.
r	Radius of drop.
R	Radius of ligament.
L	Length of ligament.
Z	Ratio $\frac{L}{2R}$.
σ	Density of liquid.
T	Surface tension of liquid.
a	Amplitude of surface disturbance.
t	Time.

II. PREVIOUS WORK

1. DIRECTLY BEARING ON ATOMIZATION IN AN AIR STREAM

(a) DROP SIZE

Sauter,[2] measuring photometrically the mean size of the drops formed when water is atomized in an air stream, found that this varies with the air speed, thus: At low air speeds the mean radius r is relatively large. As the air speed is increased r rapidly decreases, finally asymtotically becoming about 6 μ at an air speed (at the point where the liquid is introduced) of 10,000 to 12,000 cm/sec. Remembering that Sauter's definition of the mean size gives more prominence to the larger drops and that others have shown that the degree of inhomogeneity of the spray decreases with increase in air speed, it seems that we may take $r=5\ \mu$ as a conservative estimate for drop size of water atomized in a high-speed air stream.

(b) MECHANISM OF ATOMIZATION

F. N. Scheubel [3] has obtained some interesting and instructive spark pictures of the process as it occurs in the carburetor throat. He atomized both water and alcohol in an air stream. Figure 1[4] shows some of his results with water at a low air speed of about 2,700 cm/sec. The ligaments torn off are clearly visible. Figure 2 was taken at a higher air speed, about 5,300 cm/sec. The ligaments, while still visible, appear both finer and shorter. In Figure 3, taken at the comparatively high air speed of 10,500 cm/sec., the ligaments have largely vanished, and the small drops appear to be torn directly from the main mass. This, it may be assumed, happens at all higher air speeds.

While Scheubel's work constitutes an excellent description of the process of atomization in an air stream, his interpretation of the results, by dimensional analysis, throws little light on the intermediate physical processes.

2. THE COLLAPSE OF A LIQUID COLUMN

Plateau [5] showed that a round cylindrical liquid column whose length exceeds its circumference is unstable and will, therefore, even-

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[2] J. Sauter, Forschungsarbeiten auf dem Gebiete des Ingenieurwesens, No. 312; 1928.

[3] F. N. Scheubel, Wissenschaftliche Gesellschaft für Luftfahrt (WGL), p. 140; Jahrbuch, 1927.

[4] Figures 1, 2, and 3 were copied from Scheubel's article in the 1927 W. G. L. Jahrbuch. The scale of reproduction of Figures 2 and 3 is about 50 per cent greater than that of Figure 1.

[5] J. A. F. Plateau, "Statique expérimentale et théorique, etc."; Paris, 1873. (Cited by Rayleigh.)

tually collapse under the influence of any disturbance, even one of arbitrarily small amplitude. He was not concerned with the time required for the collapse to take place. As disturbances are always present, any long column of liquid, such as a jet, will eventually break; but, as the disturbances vary greatly, both in initial size and in rate of growth, such a collapse is ordinarily a very irregular affair.

This collapse can, however, be made so beautifully regular that it may readily be viewed by stroboscopic means, if the chamber from which the jet issues be influenced by a periodic vibration of proper amplitude and frequency. Pictures, taken by the writer, showing such phenomenon in a falling jet of water, are shown in Figure 4. Figure 4 (*a*) is a spark picture, while Figure 4 (*b*) was taken through a stroboscopic disk, which allowed an exposure frequency equal to that of the disturbance (in both these cases a tuning fork produced the disturbance). It is to be noticed that the amplitude is, for some time, of hardly perceptible depth, then it grows rapidly until it equals the jet's radius, when the jet breaks. Such a manner of growth suggests that it is of the exponential type.

Lord Rayleigh seems to have been the first to recognize clearly the practical importance of the rate of collapse, and, therefore, of certain geometrical and physical properties of the column influencing its dynamic behavior. In his analysis of this effect[6] an infinitely long cylinder of liquid at rest and initially in equilibrium under the influence of the tension of its envelope was assumed, and the relative upsetting efficiency of disturbances cutting off various lengths of the surface of this cylinder was investigated. For this purpose the change in potential energy from that prevailing in the equilibrium configuration was computed from geometrical considerations; while that portion of the kinetic energy that arises from the deformation of the column was determined on the assumption that the velocity of growth of α could be derived from a potential. Application of Lagrange's method then gave the time rate of variation of α; and this equation was solved on assuming a relation of the form:

$$\alpha = \alpha_0 \cdot e^{qt} \tag{1}$$

where α_0 is the initial value of α. It followed that

$$q = \left(\frac{T}{\sigma R^3}\right)^{1/2} \cdot F \tag{2}$$

where F is a (dimensionless) function of Z only.

Rayleigh pointed out that the disturbance which results in the largest value of q will preponderate if the time of collapse is long enough; therefore, as he was primarily interested in comparatively coarse and slowly collapsing jets, it seemed sufficient to determine the maximum value of F. In many other cases, however, particularly the present one, the argument does not seem so simple, and it has seemed desirable to put Rayleigh's results in a form better adapted to the general case. This has been done by the writer,[7] and some values of F are thus shown in Figure 5.

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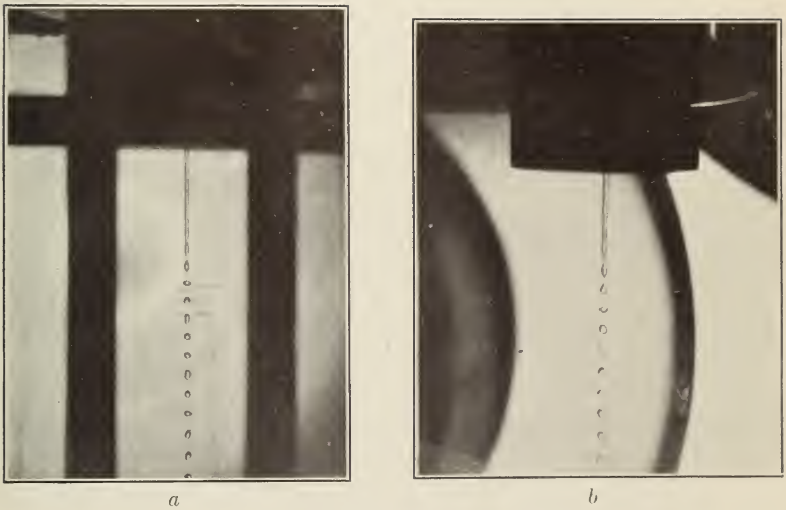
[6] Rayleigh, Proc. Lond. Math. Soc., **10**, 4; 1879. (Sci. Papers, art. 58); Theory of Sound, Chap. XX.

[7] Castleman, Nature (Lond.) **114**, p. 857; 1924.


a

b

FIGURE 4.—*The collapse of a round jet falling in still air*

a, Spark pictures; *b*, stroboscopic picture.

III. MECHANISM OF ATOMIZATION

1. GENERAL

What we wish to explain is, how a stream of air at high speed can tear small drops directly from the main mass of liquid, so that the liquid appears to explode into droplets. The procedure that will be followed is indicated in Scheubel's pictures, though this theory was virtually worked out before these pictures were noticed.[8] We assume that a necessary step in atomization is the tearing of ligaments from the unatomized mass, these ligaments being of such sizes that they will break up into drops of the sizes observed in the spray; and we shall examine whether these ligaments will collapse quickly enough to give the appearance observed, the appearance of drops being torn directly from the main mass of liquid (if the life of a ligament does not exceed about 10^{-4} sec., the appearance, when allowance is made for lag of the drops behind the air stream, would be similar to that shown in fig. 3.)

2. THEORY

(a) APPLICABILITY OF RAYLEIGH'S ANALYSIS

It is first necessary to consider whether Rayleigh's analysis, which was made for a different purpose, is applicable to this case. Four questions seem pertinent: (1) How far may we expect that these ligaments correspond to the cylindrical segments considered by Rayleigh? (2) Are conditions favorable for the existence of a velocity potential? (3) What extraneous forces may be expected to act and what should be their effect? (4) Is the contained volume sensibly constant during the collapse?

1. Rayleigh, it appears, was considering the case of at least two consecutive surface disturbances. Without going deeply into the matter, however, it appears that this same treatment should also apply to the growth of a single surface distrurbance in a cylinder already closed at one end. Hence, it should cover the present case.

2. For a velocity potential to exist, both rotation and viscosity must exert negligible influence on the motion. Little can be said of the former, except that there can be no consistent rotation before the ligament starts to be drawn from the main mass; hence, the only chance it will get to grow to harmful proportions is before the length of the ligament grows equal to its circumference, since the ligament collapses too soon after this. As to the viscosity effect, the mean radial velocity, even in extreme cases, would seem to be too small for the viscosity to seriously affect the result.

3. The only external force is the friction of the air. How much effect this can have depends largely on the ligament's life period, which will appear to be very brief.

4. In the case considered the ligaments are so fine and consequently collapse so quickly that it seems improbable that a volume change of amount large enough to affect these conclusions can occur during this time.

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[8] It was, in fact, remarked some nine years ago by W. S. James, when a member of the staff of this bureau (J. Soc. Auto. Eng., 8, p. 549; 1921), that those interested in atomization problems would find "very suggestive reading in the article on Capillary Action, by Lord Rayleigh in the 11th ed. of the Encyclopedia Britannica."

(b) MEAN SIZE OF LIGAMENTS

As it seems impossible to make direct measurements of ligament size when atomization sets in, it is necessary to determine the relation between ligament size and drop size. Since a ligament of radius R and length $Z \cdot 2R$ becomes a drop of radius r, we have:

$$2ZR \cdot \pi R^2 = \frac{4}{3} \pi r^3$$

$$R = \left(\frac{2}{3Z}\right)^{1/3} \cdot r \tag{3}$$

so that, by equation (2), for the same final value of r

$$\frac{q_1}{q_2} = \frac{F_1 (Z_1)^{1/2}}{F_2 (Z_2)^{1/2}} \tag{2–a}$$

We shall limit our attention for the present to the maximum value of F, which is 0.343 and occurs at $Z = 4.5$. In this case $R = 0.53\ r$.

(c) THE LIFE PERIOD OF A LIGAMENT

Taking for r the value we deduced from Sauter's work, 5×10^{-4} cm, we have 2.65×10^{-4} cm for R, so that $q = 6.8 \times 10^5$ sec.$^{-1}$ for water at 20° C. Putting equation (1) in the form:

$$t = \frac{1}{q} \cdot ln\,(\alpha/\alpha_o) \tag{1a}$$

and noting that this ligament breaks when α grows to 2.65×10^{-4} cm, while α_o can not be much less than 10^{-8} cm, since the molecular diameter is around 10^{-7} cm, we have for an upper limit to the collapse time $t = 1.5 \times 10^{-5}$ sec. (If we take for α_o the more probable value of 10^{-5} cm, t will be only about one-third as great.) Thus the ligament life period, computed from Sauter's observations of drop size for water, assuming this to have been at around 20° C., and using the maximum value of F, corresponding to $Z = 4.5$, appears to be brief enough to account for such phenomena as are recorded in Figure 3.

(d) EFFECTIVE VALUE OF Z

As the above computations were based on the maximum value of F, it is necessary to inquire whether, and in how far, other cases need be considered. This we shall do by comparing, for a series of values of Z, the life periods of the corresponding ligaments, each starting with the same value of α_o and leading to the same final value [9] of r (5×10^{-4} cm). Remembering that α must grow to R for rupture to occur, we obtain from equations (1a), (2a), and (3)

$$\frac{t_Z}{t_{4.5}} = \frac{q_{4.5}}{q_Z} \cdot \frac{ln\,\frac{R_Z}{\alpha_o}}{ln\,\frac{R_{4.5}}{\alpha_o}} = \frac{0.055}{F_Z (Z)^{1/2}}\,(13.9 - \log_{10} Z) \tag{5a}$$

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[9] As this argument is based on observed values of r it seems proper to consider one value of r at a time, although a given sample of spray contains drops having quite a variety of these values.

for $\alpha_o = 10^{-8}$ cm; and

$$\frac{t_Z}{t_{4.5}} = \frac{0.170}{F(Z)^{1/2}} (4.92 - \log_{10} Z) \tag{5b}$$

for $\alpha_o = 10^{-5}$ cm.

From these equations, and data from Figure 5, we obtain Table 2.

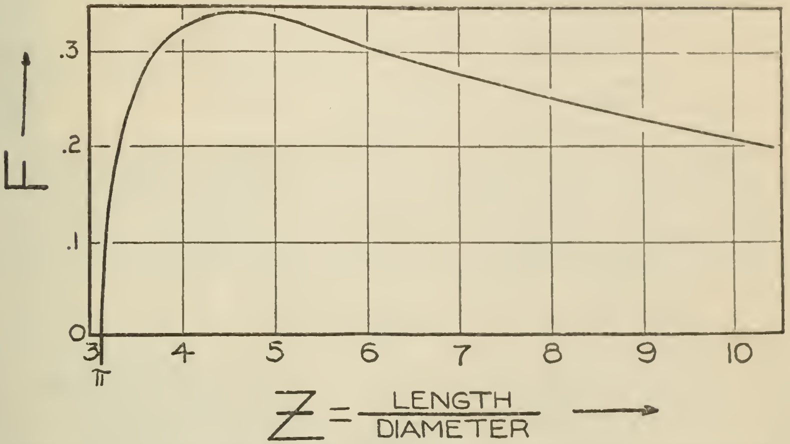

Figure 5.—*Dependence of degree of instability of a round liquid column upon ratio—$\frac{length}{diameter}$*

Table 2

Z	F	$t_z/t_{4.5}$	
		$\alpha_o = 10^{-8}$cm	$\alpha_o = 10^{-5}$cm
3.20	0.100	4.14	4.18
3.30	.180	2.23	2.28
3.50	.270	1.45	1.48
4.00	.325	1.13	1.13
4.50	.343	1.00	1.00
5.00	.338	.96	.95
7.00	.280	.97	.93
9.00	.230	1.03	.97

In words (remembering that Z increases from an initial value of zero, since the ligament is torn directly from the unatomized mass), it appears that a quicker disruption will result for $Z = 4.5$ than for any smaller value. As we have seen that this will result in a life period brief enough to account for observed phenomena, it follows that no larger values need be considered, and that we may take $F = 0.343$ at $Z = 4.5$ as the effective values.

3. COMPARISON WITH OBSERVATIONS

We have seen that, on the basis of Rayleigh's work and Sauter's drop-size observations, the kind of atomization described by Scheubel is to be expected. There remains to compare, on the basis of the present theory, some more observations by Sauter and by Scheubel, apparently independent of this theory and of each other.

Scheubel's pictures show that the ligaments vary much in size and length at the same air speed. On the above theory this agrees with Sauter's observations that there is a marked variety of drop sizes at a given air speed; for this implies a corresponding variety in the sizes and a much greater variety in the rates of collapse of the ligaments.

Scheubel also found that alcohol exhibited similar phenomena, but atomized at a much lower air speed than did water. Remembering that the surface tension of this liquid is only about one-third that of water, this result, in terms of the present theory, means that the ligaments are formed more readily with alcohol, the work required for a given extension of surface being less.

Sauter's observation of the manner of variation of drop size with air speed—that the mean size decreases rapidly to a practically constant value with increase in air speed—accords well with the present theory. For, as the air speed is increased, the sizes of the ligaments decrease, their life periods become much shorter, and much smaller drops result. However, this decrease in size soon reaches a limit at which the ligaments collapse practically as soon as formed. This is the point at which true "atomization" (in the etymological sense—that no smaller drops can be formed from this liquid by this method) may be regarded as setting in. It is further interesting to note that Sauter and Scheubel are in virtual,[10] and apparently independent, agreement as to the location of this point; for Sauter found that his curve of size of drop *v.* speed of air flattened at about 10,000 to 12,000 cm/sec., while Figure 3 of this paper indicates that Scheubel has not quite reached complete atomization at a mean air speed of 10,500 cm/sec.

IV. CONCLUSION

The actual process of atomization in an air stream seems rather simple: A portion of the large mass is caught up (say, at a point where its surface is ruffled) by the air stream and, being anchored at the other end, is drawn out into a fine ligament. This ligament is quickly cut off by the rapid growth of a dent in its surface, and the detached mass, being quite small, is swiftly drawn up into a spherical drop. (A quite similar phenomenon occurs when a large drop is detached from a tube. The chief difference is that the ligament connecting the small drop to the main mass is much finer than that connecting the large drop to the liquid in the tube, and, hence, the time of detachment is enormously less.) The higher the air speed, the finer the ligaments, the shorter their lives, and the smaller the drops formed, within the limits discussed above. The writer's aim has been to show how Rayleigh's work, done over 50 years ago apparently for an entirely different purpose, covers the more modern problem of atomization in an air stream.

Constructive criticism by Dr. N. E. Dorsey proved particularly helpful in the preparation of this paper.

WASHINGTON, December 27, 1930.

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[10] Sauter gave the volume of air flowing and the size of the carburetor throat, from which data the air speed in the throat was estimated. Scheubel gave the mean speed directly. In both cases, however, the carburetor would introduce peculiarities in the velocity distribution (see fig. 1) so that finer estimates on this point do not seem justified.