THE COMBUSTION OF A SYSTEM OF LIQUID FUEL DROPS

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We examine the combustion of drops in a system of solitary drops. It is established that the rate of combustion for the system varies with a change in the distance between the drops.

Experimental investigations of a burning or evaporating air suspension [4-6] offer no possibility of rendering judgement as regards the processes occurring between the individual drops of that suspension.

The literature [2, 3] indicates that the nonagreement between the completeness of combustion for the air suspension and the individual drops can be explained by the fact that there is some interaction among the drops in the air suspension.

Laboratory model experiments to study a system consisting of a limited number of burning or vaporizing drops can therefore be of great significance in understanding the processes taking place in the interaction of drops during the combustion, and serve as an important linking element in the development of flame theory. Presently we know of one study along these lines [1].

Below we examine the change in the burning rate of a drop of T-1 kerosene, a drop of ethyl alcohol, and a drop of benzene, this change coming about as a function of the distance between the drops under conditions of natural and forced convection. The one-dimensional horizontal system consisted of two and three drops. The distance between the drops varied from 0.15 to 15 mm.

For burning under conditions of forced convection, the drops were placed into a flow with a U-shaped velocity profile; the flow was produced by means of a Vitoshinskii nozzle whose discharge orifice had a diameter of 10 cm. The flow velocity was set at 50 cm/sec to avoid flame separation from the drops. The initial drop dimensions for the system (equal to 1.95 mm in each of the tests) and the distance between the drops were measured by means of a microscope with a 15-fold magnification. The burning rate was determined by filming the burning drops with a Konvas motion-picture camera at a speed of 8 frames per second.

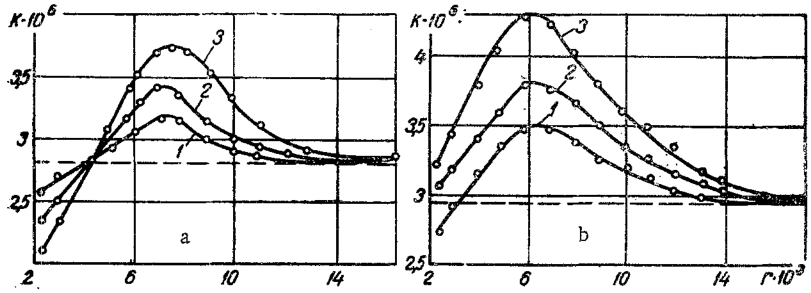

Fig. 1. Burning-rate constants K (m^2/sec) as a function of the distance r (m) between the drops of T-1 kerosene in the case of natural (a) and forced (b) convection: 1) a system of two drops; 2) a system of three drops (extreme); 3) a system of three drops (central).

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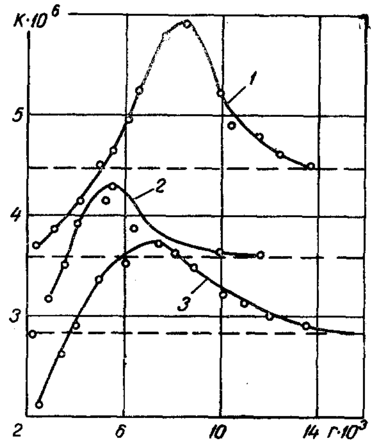

Fig. 2. Burning-rate constant K (m^2/sec) for the center drop in a system of three drops as a function of the distance r (m) between the drops in the case of natural convection: 1) benzene; 2) ethyl alcohol; 3) T-1 kerosene.

TABLE 1. Burning Efficiency for Drops in a System

Fuel	Number of drops	α	$K_{min} \cdot 10^6$	$K_{max} \cdot 10^6$	K_{min}/K_{max}
T-1	2	0,67	2,56	3,24	0,79
	3 extreme	0,67	2,40	3,42	0,70
	3 center	0,34	2,10	3,69	0,57
Benzene	2	0,65	4,00	5,75	0,69
	3 center	0,33	3,50	6,00	0,58
Alcohol	2	0,70	3,10	4,08	0,73
	3 center	0,40	2,40	4,24	0,57

For combustion under conditions of natural convection, the tests were carried out in a closed chamber, on the inside of which wires were positioned so as to permit the suspension of the drops.

The drops were ignited either by means of a spark, using a Ruhmkorff coil, or by means of a pilot light.

The drop diameters were measured on the film. A curve was then plotted in S–t coordinates, where S denotes the drop surface and t is the time. Since the law of linear time variation for the square of the drop diameter was observed in each case, the burning-rate constant $K = dS/dt$.

Under conditions of natural convection, in the burning of a solitary drop, the height of the bottom portion and the flame diameter across the horizontal section, passing through the center of the drop, remain constant throughout the burning process [2]. As demonstrated by measurements of the flame photographs, these relationships are preserved in our experiments for the combustion of a system of drops. Satisfaction of the law dS/dt = const in the combustion of a system of drops thus can be explained by the unchanging position of the flames relative to each other. The interaction of the burning drops in this case represents nothing other than the interaction of parts of their flames, directly encompassing the drops.

The relationships between the burning-rate constant and the distance between the drops of the system for various liquids is shown in Figs. 1-2, from which we can see that all of the curves describing these relationships are similar.

In altering the distance between the drops, we find that the burning-rate constant K does not change monotonically, but passes through a maximum at which it substantially exceeds K measured for a solitary drop. The height of the maximum and the distance corresponding to that maximum are functions of the combustion conditions (natural or forced convection), as well as a function of the number of drops in the system and of the chemical composition of the liquid.

For example, let us examine the combustion of a system of kerosene drops under conditions of natural convection (Fig. 1a). As we can see from the curve, the greatest magnitude of the maximum is achieved at the drop in the center, among three (curve 3), while the minimum is reached in a two-drop system (curve 1). Curve 2 describes the change in K for the extreme drop in a system of three drops. (The dashed line here, and in the subsequent graphs, denotes the K value of a solitary drop.) The maxima are attained at various distances between the drops..

While the first and second curves exhibit maxima attained at an identical distance, the maximum of the third curve is shifted to the right, in the direction of greater distances between the drops. With a further increase in distance the value of K diminishes, asymptotically approaching the burning-rate constant for a solitary drop. With a reduction in distance the value of K diminishes more sharply, reaching lower values than in the case of a solitary drop. With a minimum distance between the drops, the least burning rate is found in the central drop, in a system of three drops. We can assume that the change in K with distance for each drop in a given system is explained by the action of three factors: radiative heat exchange and convection heat transfer, these serving to increase the burning rate, while the factor of "oxygen starvation" serves to diminish this rate, i.e., there is less oxygen reaching the combustion zone because of flame coverage in the case of drops positioned near each other than is the case with a solitary drop.

With a minimum distance between the drops, the covering of the flames is at its maximum, and the effect of the third factor exceeds the effect of the first two to such an extent that the burning rate for the drop in the system becomes smaller than the burning rate of a solitary drop. As the distance is increased, the magnitude of the flame coverage diminishes to zero, which corresponds to flame contact. The phenomenon of "oxygen starvation" disappears entirely, and we are left exclusively with factors tending to increase the burning rate. With a further increase in distance, the effect of these factors also begins to diminish, and the burning-rate constant tends toward some limit value of K for a solitary drop.

As shown by photographs of burning drops, the point of contact between the bottom portions of the flames corresponds exactly to the burning-rate maximum.

If we assume that the reduction in the burning rate for the drop in a system (in comparison with a solitary drop) is proportional to the ratio of the area S_1 of the intersecting burning zones to the area S_2 of the drop-burning zone, we can introduce the concept of the efficiency α of the burning of the drop in the system. In this case $\alpha_1 = 1$ for the solitary drop; $\alpha_2 = 1 - S_1/S_2$ for two drops; and $\alpha_3 = 1 - 2\,S_1/S_2$ for the center drop among three drops.

As shown by elementary calculation,

$$\frac{S_1}{S_2} = \frac{1}{2}\left(1 - \frac{l + r_{\mathrm{d}}}{r_{\mathrm{b}}}\right).$$

The quantity S_1/S_2 is independent of time, since $2(l + r_{\mathrm{d}})$ is a fixed distance between the drop centers, and r_{b} does not change with time, as was demonstrated earlier.

Neglecting the change in the effect of the remaining factors in the interval of distances under consideration, we can write

$$K = K^*\alpha,$$

where K* is the value of the burning rate in the assumption that there is no "oxygen starvation."

With a change in $l + r_{\mathrm{d}}$ (drops touching) to r_{b} (flames touching) the burning efficiencies α_2 and α_3 are, respectively, equal to

$$\alpha_2 = \frac{1}{2}\left(1 + \frac{r_{\mathrm{d}}^0}{r_{\mathrm{b}}}\right), \quad \alpha_3 = \frac{r_{\mathrm{d}}^0}{r_{\mathrm{b}}}.$$

From the flame photographs and on the basis of these formulas, we have calculated the values of α. The burning efficiencies can also be defined as the corresponding ratios of the minimum value of K in the case of touching drops (K_{min}) to its maximum value when the flames are touching (K_{max}). The results of these calculations are given in Table 1.

We see from this table that satisfactory agreement exists between the theoretical magnitude of α and $K_{\mathrm{min}}/K_{\mathrm{max}}$.

When burning kerosene drops under conditions of forced convection (Fig. 1b), we find that the minimum burning rate for the drops in the system does not markedly differ from the burning rate of a solitary drop, while the maximum burning rate substantially exceeds the maximum value of K for the case of burning under conditions of natural convection. This is obvious, since the flow of air provides for an intensive influx of oxygen to the forward portion of the flame.

Experiments with drops of ethyl alcohol and benzene were undertaken to determine the effect of radiative heat exchange on the magnitude of K, since the emittances of the drops of these liquids differ markedly from the emittance of the kerosene flame. The tests showed (Fig. 2) that the maximum K for alcohol, the emittance of whose flame is smaller than for kerosene, is shifted to the left, while the maximum K in the case of benzene, exhibiting a greater flame emittance, is shifted to the right, relative to the maximum K for kerosene. Subsequently, radiative heat exchange is one of the decisive factors in a system of burning drops. It is precisely in this way that we can explain the divergence between the experimentally found and calculated values of K.

The increase in convection heat transfer in the burning of a system of drops – as compared to a solitary drop – can be estimated in approximate terms from the change in flame height h in a system of burning drops – as opposed to a solitary drop – since h is proportional to the velocity U of the ascending flows. Measurement showed that the flame height for drops burning in a system is greater by a factor of 1.5 than the flame height for a corresponding solitary drop. Consequently, the intensity of convection heat transfer is increased by 25% (in the assumption that $Nu \sim \sqrt{U}$).

It should be noted that the axes of the flames burning in a system of drops are not strictly vertical, as in the burning of a solitary drop, but they are shifted toward each other. This fact suggests the existence of a "force" interaction in a system of burning drops; however, a quantitative evaluation of this phenomenon has not yet been undertaken.

NOTATION

S is the drop surface;
t is the time;
K is the burning-rate constant;
α is the efficiency of burning for the drops in the system;
S_1 is the area of combustion-zone overlapping;
S_2 is the area of the burning zone for a solitary drop;
r_d is the drop radius;
r_b is the radius of the burning zone;
l is half the distance between the drops.

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