# SURFACE GEOMETRY OF A LIQUID EXPLOSIVE BURNING BEYOND THE STABILITY LIMIT

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ABSTRACT: After L. D. Landau's work [1] on the stability of normal burning of liquid explosives, many experimental studies of this phenomenon, e. g., [2, 3], were published. In this paper, on the basis of Landau's theory, we investigate the geometry of the perturbations which develop on the surface of the liquid explosive in a vessel of circular cross section and consider the influence of vessel diameter on burning stability. Results of an experimental observation of the geometry of the liquid surface are also presented for developed turbulent combustion in a circular cylindrical tube. The calculation was based on the usual assumptions that the chemical reaction of combustion proceeds in a thin layer of vapor over the plane (meniscus neglected) surface of the inviscid liquid explosive.

In combustion in a cylindrical tube, apart from the conditions at the burning surface, it is necessary to satisfy the boundary conditions

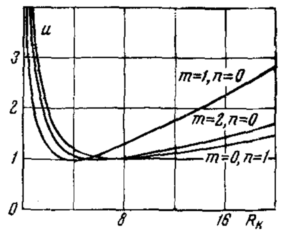


Fig. 1

at the wall of the tube, where the radial component of velocity is zero. This condition determines the permissible values of the wave number of the surface perturbation k:

$$k = k_{mn} = \alpha_{mn} / R\,, \tag{1}$$

where $\alpha_{mn}$ are the roots of the first derivative of a Bessel function $I_m$ of the first kind and order m, while n is the number of the root and R the radius of the tube. The shape of the elementary perturbations of the surface $\xi$ (r, $\varphi$),

$$\xi \sim I_m (\alpha_{mn} r / R) \cos m\varphi\,,$$

is determined by the values of the integers m (number of nodal diameters) and n (number of nodal circumferences). The critical burning rate $W_*(R)$ is related to the diameter of the tube 2R [4] by

$$\frac{W^2_*(R)}{W^2_*} = \frac{1}{2}\left(\frac{k_*}{k} + \frac{k}{k_*}\right), \quad (\rho_1 W_*)^4 = \frac{4\sigma\rho_1^2\rho_2 g}{\rho_1 - \rho_2}. \tag{2}$$

Here $W_*$ is the critical burning rate in a tube of infinite radius [1].

Substituting in (2) relation (1) for burning in a cylindrical tube, we have

$$u^2 = \frac{W^2_*(R)}{W^2_*} = \frac{1}{2}\left(\frac{\alpha_{nm}}{Rk_*} + \frac{Rk_*}{\alpha_{mn}}\right), \quad k_*^2 = \frac{g\rho_1}{\sigma}. \tag{3}$$

In the case of a plane-parallel vessel in (3), instead of $\alpha_{mn}$, it is necessary to substitute $i\pi/2$ (i = 1, 2, . . . ) [4]; R is half the long side of the rectangle formed by the cross section of the vessel.

The dependence of burning rate on tube radius (Fig. 1) for $Rk_* > 1$ (wide tubes) has low maxima. If these are disregarded, then $W_*(R)$ will be important only in narrow tubes, i. e.,

$$u = 1 \quad \text{when } Rk_* > 1\,,$$

$$u^2 = \frac{1}{2}\left(\frac{R_1}{R} + \frac{R}{R_1}\right) \quad \text{when } Rk_* < 1\,, \tag{4}$$

where $R_1 = \alpha_{10} k_* \approx 1.84\, k_*$ (for burning in a circular tube) and $R_1 = \pi k_*/2 = 1.57\, k_*$ (for a plane vessel). Formula (4) describes quite well the data on the relation between the critical burning rate of nitroglycol and tube diameter presented in Fig. 2 (points—experiment, curve—theoretical). In Fig. 2 of [4] the relation between the burning rate of nitroglycol and tube diameter is also described by a curve constructed from formula (4), however, $R_1$ was selected empirically, whereas in this study $R_1$ was calculated.

The geometry of the surface of a liquid explosive burning beyond the stability limit was observed experimentally by high-speed (2000 frames per second) motion-picture photography from the end face through the layer of burning liquid. Two substances were investigated: nitroglycol and diglycoldinitrate, for which the critical pressures for unstable burning are equal, respectively, to 15 and 54 atm (in a test tube 6 mm in diameter). Since the self-illumination was utilized in taking the photographs, the refraction of light at the surface of the liquid revealed its structure. Figures 3a-h show typical frames depicting unstable combustion. These photos were obtained for combustion at the following pressures: a) 14, b) 24, c) 20, d) 30, e) 17, f) 26, g) 22, and h) 16 atm. Inspection of the frames shows that Fig. 3a can be correlated with the mode m = 1, n = 0 (one nodal diameter) and Fig. 3b with the mode m = 2, n = 0 (two nodal diameters). The other frames correspond to more complex combination modes. Figure 3a is the most common picture; perturbations of this form are encountered in almost all the films made for both substances. In external appearance the photos obtained for burning diglycoldinitrate do not differ from the photos for nitroglycol. However, an examination of the films reveals that in this substance there is a rotational movement of the flame due to a wave on the surface of the liquid traveling along the periphery of the tube. In the developed regime of unstable combustion there is observed a unique process of complication of perturbation geometry: two semicircles are formed, each of which then splits in two, after which the process of division is accelerated and a complex picture in which various modes of motion combine is formed. Figure 3i shows the successive frames of such a process of division for diglycoldinitrate under a pressure of 62 atm in a tube 6 mm in diameter.

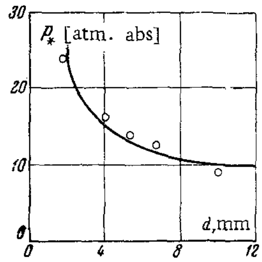


Fig. 2

Apart from the modes mentioned, radial pulsations of the liquid are also sometimes observed (Fig. 3e).

With increase in pressure (burning rate) the dimensions of the individual elements of the perturbations decrease, the large-scale inhomogeneities disappear, and there is formed a surface picture composed, as it were, of separate shreds. End-face motion-picture photography makes it possible to estimate the time taken by the perturbations to develop. Thus, in the case presented in Fig. 3i, it was about 15 $\mu$sec. Photos of the surface of a liquid burning in the disturbed regime were taken under conditions when the combustion propagation velocity exceeded the normal value by tens of times.

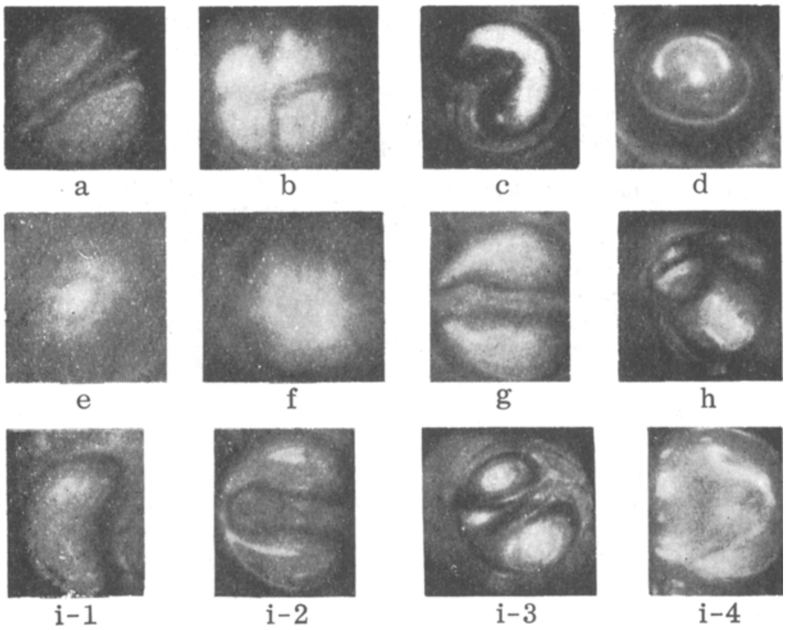


Fig. 3

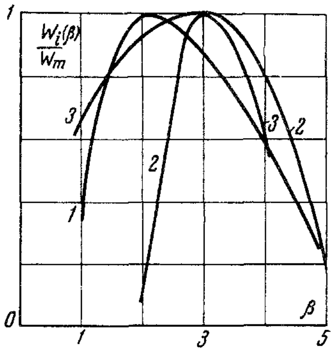


Fig. 4

However, the increase in the burning surface visible in the photos is small, not more than 2–3 times. Probably, the surface visible in certain photos is covered with shallow waves. However, an increase over the normal burning rate by tens of times cannot be accounted for by trivial geometric effects. It would be necessary to assume that the height of the individual waves was tens of times greater than the distance between waves. Therefore we may conclude that the perturbed burning of the liquid is turbulent. This is confirmed by the data of Fig. 4 which shows the ratio of burning rate $W_i(\beta)$ to the maximum at the given pressure $W_m$ as a function of the composition $\beta$ of a mixture of tetranitromethane (TNM) and ethanol expressed in fractions by volume of TNM per part ethanol. Curve 1 was obtained for $p = 2$ atm and corresponds to slow burning; curve 2 ($p = 8$ atm) and curve 3 ($p = 40$ atm) correspond to disturbed burning. The absolute values of $W_i(\beta)$ on curves 1, 2 and 3 differ by about $10^3$ times. It is clear that the maximum of the perturbed burning rate, as compared with normal burning, is shifted into the region of hotter mixtures. The same effect was obtained for a mixture of TNM and butanol. These data may be compared with the analogous results obtained for burning gas mixtures, where they are also treated as proof of the truly turbulent nature of the combustion [5]. However, taken as a whole, the perturbed burning of liquids is an even more complex phenomenon than the turbulent burning of gases.

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