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# Development of cellular instability of liquid film under gas-dynamic stream

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The stability loss of a thin liquid shell, when taking a spheroid shape, has been first found experimentally. The shaping of the shell followed by its breakdown is developed under high-temperature gas stream consisting of combustion products. The stability loss of the thin shell leads to forming of staggered areas. The shell in these areas thin synchronously up to its rupture resulting to the formation of cellular structure. The obtained results can be used in developing the model of combustion of water-base foam resulting from the suppression of liquid fuel

**Keywords:** stability loss, thin liquid film, gas-dynamic stream, foam combustion.

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High-expansion foam is currently used to suppress fires associated with spills of liquefied hydrocarbon fuels [1]. However, the foam becomes flammable due to molecular diffusion of hydrocarbon vapors into air bubbles. This poses a risk of uncontrolled propagation of the combustion wave in certain regions of the gas-liquid medium. A mathematical model providing an adequate explanation for the physical processes accompanying the combustion of foams was proposed in [2]. However, the predictive ability of this model is limited (specifically, due to the use of such a difficult-to-determine parameter as the range of dimensions of droplets formed in the process of destruction of foam films). Thus, in-depth experimental studies of the mechanisms of destruction of foam films interacting with the flame front remain relevant.

In the present study, we report the results of physical modeling of destruction of a high-expansion foam film ($K > 200$, where $K$ is the ratio of the foam volume to the volume of the liquid phase) during its interaction with a high-temperature gas vortex.

The experimental setup is shown in Fig. 1. A high-temperature vortex was formed inside a plastic closed cylindrical chamber with a variable cross section (sections *3* and *4*) by burning a mixture of petroleum ether vapors ($40-70\,^{\circ}$C fraction, pure) with air. Length $l_3$ and inner diameter $d_3$ of section *3* were 55 and 5 mm, respectively. Section *4* had $l_4 = 16$ mm and $d_4 = 29$ mm. Section *3* was closed at one end with rubber plug *7*. A droplet of ether with volume $V \approx 0.011\,\text{cm}^3$ was placed on the inner wall of chamber *3*.

The chamber was then closed with soap water film *6* from the side of section *4* and rotated with frequency $f = 3.00 \pm 0.15$ Hz about axis of symmetry $Ox$. As the droplet evaporated, a vapor-air mixture was formed with a volume concentration of ether that was within the concentration limits of flame propagation (i.e., 0.7–8.0 %). The rotation of the chamber allowed one to mix ether vapors with air within $t \leqslant 4$ min without destroying the film. If the chamber was not rotated, the film got destroyed within approximately 15 s due to syneresis. The flammable mixture was ignited inside section *3* on the $Ox$ axis at point *2* with coordinate $x = 36$ by a high-voltage electric discharge. LED source *1* generated an adjustable (up to 720 lm) constant luminous flux. The process of deformation and destruction of the liquid film was recorded on video using a NANOGATE 22/16 high-speed monochrome 16-frame electron-optical camera (exposure time $\tau = 0.1-20\,\mu$s; recording period $T = 63-600\,\mu$s) and a gas-discharge flash lamp (not shown in the figure) that was synchronized with the camera and formed a 1 ms pulsed light flux directed along the $Oz$ axis.

The solution for preparing the water film had the following main components: distilled water — 67 %, sodium laureth sulfate — 16 %, polypropylene glycol — 6 %, and glycerin — 11 %. These components were chosen empirically, primarily due to the need to obtain a liquid film that is as resistant as possible to intense thermomechanical effects. Hydrodynamic flows of liquid in the film were monitored via the interference pattern arising when light from source *1* was reflected from the surface of film *6*.

A new scenario of dispersion of a thin liquid film interacting with a gas-dynamic stream was discovered (Fig. 2). The scenario is based on the loss of stability of the liquid film precisely at that moment in time when it assumes the shape of an ellipsoid of revolution flattened along the $Ox$ axis with semi-axes ratio $k = \Delta z/\Delta x = 1.55-1.6$. It should be noted that the film undergoes intense deformation and assumes many different shapes before the spheroid one. Other stochastically formed film shapes could be ruptured at any arbitrary section of the surface with subsequent destruction of the kind detailed, e. g., in [3]. At the last stage of formation of the spheroidal shape of the liquid shell, the value of coefficient $k$ decreases from 1.8 to 1.62–1.55. The loss of stability occurs within recording interval $T = 63\,\mu$s

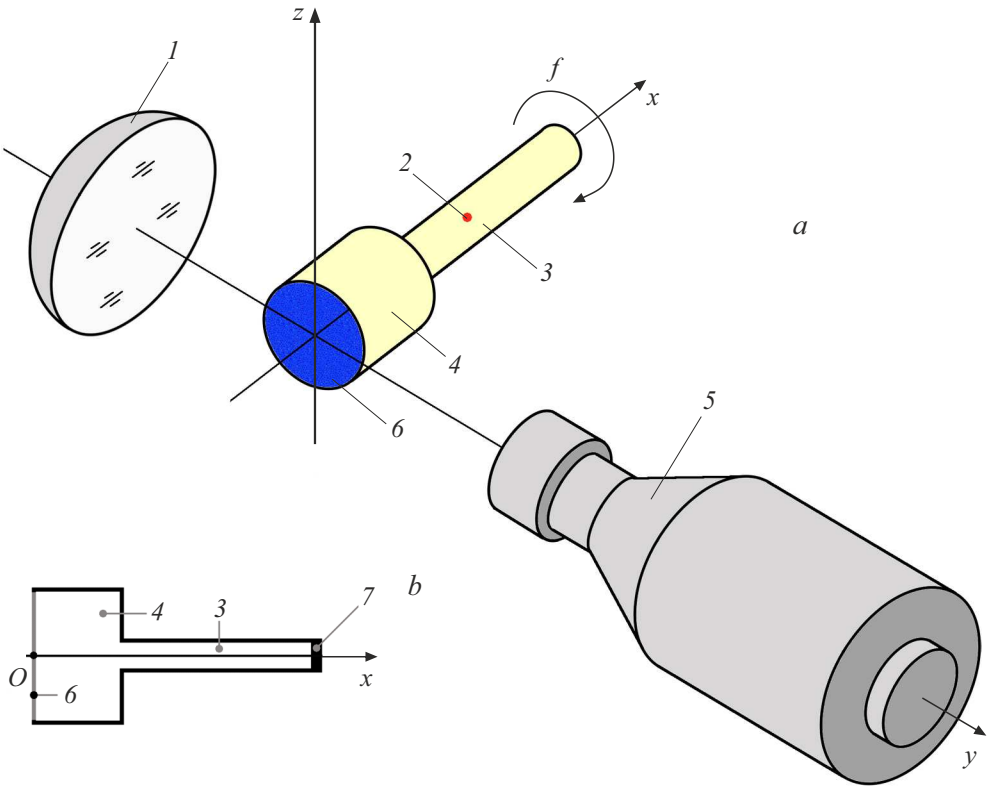


**Figure 1.** Schematic diagram of the experimental setup ($a$) and a section of the combustion chamber along the $Ox$ axis ($b$). *1* — Backlight lamp, *2* — spark discharge, *3* and *4* — combustion chamber sections, *5* — NANOGATE 22/16 high-speed camera, *6* — liquid film, and *7* — rubber plug.

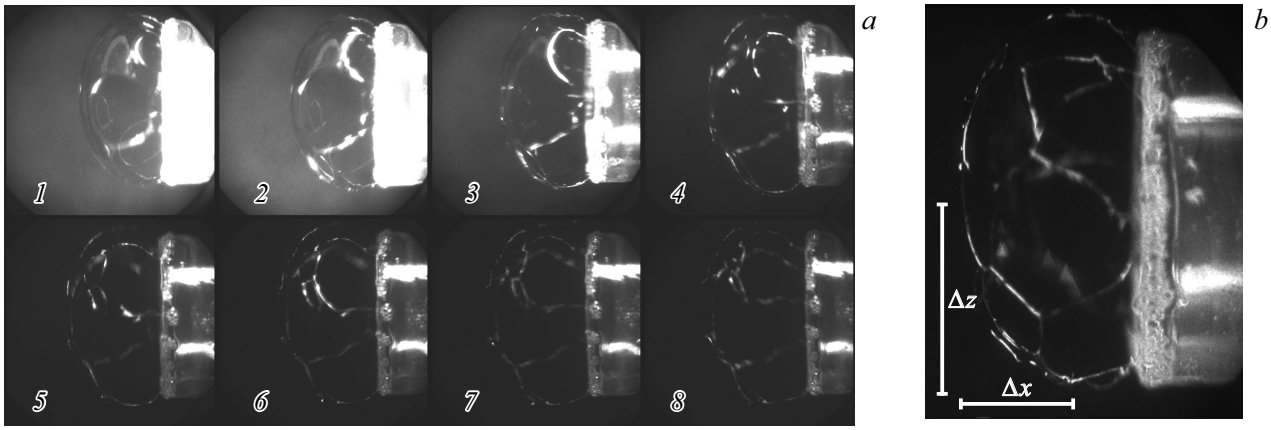


**Figure 2.** Formation of a cellular structure of a liquid film. $a$ — Dynamics of loss of stability of a film in the shape of a spheroid; $b$ — staggered arrangement of cells of a mesh structure after stability loss. The time interval between numbered frames is 63 $\mu$s. The frames in panels $a$ and $b$ correspond to different experiments. $\Delta x$ and $\Delta z$ are the spheroid semi-axes.

over time $t_b$ (i. e., $t_b < 63\,\mu$s) synchronously over the entire surface and is observed as the formation of individual cells in a staggered arrangement. Velocity $v_{Ox}$ of motion of the top of the spheroid film along axis $Ox$ at time $T$ before its destruction is 12 m/s. The number of forming cells is $K_s = 10-12$. The deformation of the liquid film in the form of an ellipsoid of revolution provides indirect indication of the formation of a gas stream in the form of a circular vortex inside section *4*.

The development of cellular instability in free flow of a flat water film from slot nozzles into the atmosphere has been examined in [4,5]. The cells, which were deformed by local vortex gas streams, took the form of convex sections of the liquid layer arranged in horizontal rows. Synchronous

destruction of film cells throughout the entire surface was not observed.

Self-illumination video data from the zone of combustion of a vapor-air mixture at low backlight lamp *1* intensity suggest that the process of combustion in the chamber may be divided tentatively into two stages. The first stage is the spread of flame inside the combustion chamber with an average visible velocity of 10.7 m/s. It ends at the moment when the camera sensitivity becomes insufficient to detect the glow. At the second stage, combustion is detected again, but in the form of individual diffuse sources with a transverse size no larger than a few millimeters. Notably, combustion sources do not form uniformly over the entire film surface; instead, they emerge randomly in the region between the outwardly deformed surface of the film and the end of section *4* of the chamber. Thus, the random nature of the non-uniform distribution of sources in the region of the liquid film indicates that they cannot cause synchronous destruction of the film, which leads to the development of a cellular mesh structure.

The soap film may be regarded as an elastic membrane with its own set of modes that depend on the geometric dimensions of the chamber and the film thickness. It can be assumed that the shock from electrical breakdown of the discharge gap leads to the excitation of transverse oscillations of the soap film; if the intensity of oscillations is sufficient, it may be ruptured at the antinodes of standing waves. The shape and geometric dimensions of the film and the distribution of its thickness change stochastically within the time interval of spheroid formation (i.e., over a period of approximately 10 ms), which leads to a continuous variation of the spectral composition of oscillation modes of the membrane film. It was demonstrated in [6,7] that liquid flows from nodes and nodal lines to the antinodes of waves under acoustic excitation of standing waves on the surface of a flat soap film. According to [6], the soap film thickness at the antinodes may be three orders of magnitude greater than the thickness at the nodal lines. Thus, with sufficient intensity of the source of oscillation excitation, the film is expected to be ruptured along the nodal lines with the formation of large droplets localized at the antinodes. This possible scenario of film destruction differs fundamentally from the one observed in experiments in the present study. Therefore, the detected instability cannot develop on the basis of any mechanisms of excitation of transverse oscillations of the soap film.

Having analyzed the interference pattern of hydrodynamic flows in the liquid layer of the film, we found no uniformly ordered vortex structures induced by its rotation. The film shape varied from flat to hemispherical with a minimum curvature radius of $d_4/2$. The analysis of literature data did also reveal no structures in a circular gas vortex that could drive the development of the detected liquid film instability.

A qualitative similarity is found only when one compares the obtained results with the development of instability of thin solid shells under supercritical deformations in the process of their uniform loading by external pressure [8]. Dents distributed uniformly over the surface of the shell may form synchronously, the material thickness becomes smaller at the poles of the dents, and the ratio of the surface area of the hard shell to the average area of dents is comparable to the value of coefficient $K_s$. In the case of a liquid film, the reduction of thickness of the shell at the poles indicates the possibility of formation of radially diverging flows directed away from the poles that lead to synchronous rupture with the formation of a mesh structure. However, two conditions must be satisfied for the theory of stability of solid shells to be applicable to the mechanism of loss of stability of a liquid shell: first, the film in the form of an oblate spheroid should be compressed uniformly; second, the film should feature shear elasticity, which is usually found in liquids at frequencies on the order of $10^{10}$ Hz [9]. The significantly stochastic nature of combustion of the vapor-air mixture made it difficult to obtain a video recording of film deformation immediately prior to the onset of instability. Since no separate study of the dynamics of vortex flow formation with account for two stages of combustion in the chamber discovered here was performed, the issue of the nature of deformation of the liquid film immediately prior to its destruction remains open.

The existence of low-frequency shear elasticity of liquids of complex composition at frequencies $f_{el} = 10^4 - 10^5$ Hz ($T_{el} = 1/f_{el} = 10 - 100\,\mu$s) was demonstrated experimentally in [10]. The rupture of the soap film is detected between two frames (i.e., within a time interval shorter than 63 $\mu$s, which is comparable with $T_{el}$). Thus, it is fair to assume that the low-frequency elasticity of a thin liquid layer manifests itself in the examined new experimental setup and the second condition necessary for application of the theory of stability of solid shells is fulfilled. Additional experimental work is needed to confirm the fulfillment of the first condition.

The number of finely dispersed droplets into which the film breaks down as a result of development of the detected instability is greater than the one characteristic of a rupture localized at a single random site. The heat exchange is intensified as a result, since the total area of contact between the flame and the liquid finely dispersed phase increases, and the combustion process is inhibited more actively by droplets up to 100 $\mu$m in size (Fig. 2). High-expansion foams consist of bubbles separated by liquid films in the form of flat polyhedra. Further study of the mechanism of dispersion of foam films of various shapes in the process of interaction with gas-dynamic streams should allow us to elaborate the model of combustion of water-based foam for the purpose of predicting the rate of its burnout.

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### Conflict of interest

The author declares that he has no conflict of interest.

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