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# THERMALLY THIN SYSTEM FOR INVESTIGATING SURFACE DIFFUSION FLAMES

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*A thermally thin layered system representing a liquid fuel on a metal substrate was investigated. The characteristic parameters of such a system are the thickness of the fuel layer and the thickness of the substrate, equal to 3–12 and 10–100* μm *respectively. Hydrocarbons were used as a fuel. It has been established that in this system a number of stationary and nonstationary combustion regimes with conductive and convective mechanisms of chemical-reaction transfer and non-one-dimensional combustion waves with an unusual structure and an "excess of energy" can take place.*

***Keywords:*** *flame, combustion, thermally thin system, excess of energy.*

**Introduction.** The process of propagation of a flame over the surface of a liquid fuel deposited on a metal substrate is of interest from several viewpoints. First, this heterogeneous multiphase system has wide use in the technogenic sphere and can be used for the provision of fire and explosion safety as well as for solving problems of power generation and different production processes. At the same time, the indicated system is relatively simple and can be effectively used for investigating surface combustion — the propagation of a flame over the surface of a fuel, in particular, a flame in an inert porous medium. This system allows one to separately investigate both the parameters of the fuel itself (its composition, reactivity, heat capacity, etc.) and the physicochemical parameters of the inert substrate. Moreover, the high thermal diffusivity of the substrate used in the indicated system provides good conditions for the application of the approximation of a thermally thin system to it, which has been impossible to do sufficiently well in the case of usual fuels such as paper, plastic materials, and wood [1]. The system being considered is also of interest from the combustion-theory standpoint, because, in it, many combustion regimes can be realized, e.g., a spin conduction, flames with two heat sources, and so on. Finally, this system is characterized by the self-concentration of energy in the region of the flame edge, which leads to the appearance of nontraditional effects, namely, to an increase in the velocity of the flame or to a widening of the range of its propagation not through an increase in the temperature of the flame and in the rate of the chemical reaction but through an increase in the rate of evaporation of the fuel and the formation of a combustible mixture over the surface of the liquid fuel. The latter aspect of the problem is the object of analysis in the present work. Since it is associated with different combustion regimes and mechanisms of flame propagation, they are also considered and discussed here.

Note that the flames investigated in the present work are analogous in certain characteristics to the detonation spin effects, to the understanding of which R. I. Soloukhin has made a large contribution.

**Experimental.** The experiments were carried out in air at atmospheric pressure and room temperature. Copper foil strips of two types were mainly used — those of thickness 46 μm and width 4 cm and of thickness 60 μm and width 17.5 cm. Films of the following liquid fuels were deposited on the substrates: *n*-undecane, *n*-tridecane, *n*-dodecane, *n*-hexadecane, ethanol, a transformer oil, and *n*-butanol, of thickness 7–12 μm. Certain physicochemical properties of these fuels are presented in Table 1. Here, $T_{\text{low}}$ is the temperature at which a vapor of a fuel of stoichiometric concentration is formed near the fuel surface.

Video records of propagation of a flame allowed us to calculate its velocity and vibration frequency. The scheme of a stationary propagation of a flame in the downward direction over a fuel film deposited on one surface of a foil (a one-sided flame) is shown in Fig. 1a. A two-sided flame (Fig. 1b) was obtained in the case where a different combustion liquid was deposited on the other (opposite) surface of the foil. In the case where one and the same fuel

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TABLE 1. Properties of Fuels

| Fuel | $Q_{ev}$, kJ/kg | $T_{low}$, °C | $T_f$, °C | $T_b$, °C | Stoichiometric ratio, vol. % |
|---|---|---|---|---|---|
| $C_9H_{20}$ | 353.6 | 31 | 39.6 | 150.8 | 1.49 |
| $C_{10}H_{22}$ | 339.9 | 46 | 58.0 | 174.1 | 1.34 |
| $C_{11}H_{24}$ | 360.7 | 62 | 73.5 | 196.0 | 1.22 |
| $C_{12}H_{26}$ | 360.2 | 76 | 88.0 | 216.3 | 1.12 |
| $C_{13}H_{28}$ | 359.5 | 90 | 101.9 | 235.5 | 1.04 |
| $C_{16}H_{34}$ | 358.3 | 126 | 135.4 | 287.1 | 0.85 |
| $C_4H_9OH$ | 590.4 | 34 | 45.0 | 117.5 | 3.38 |

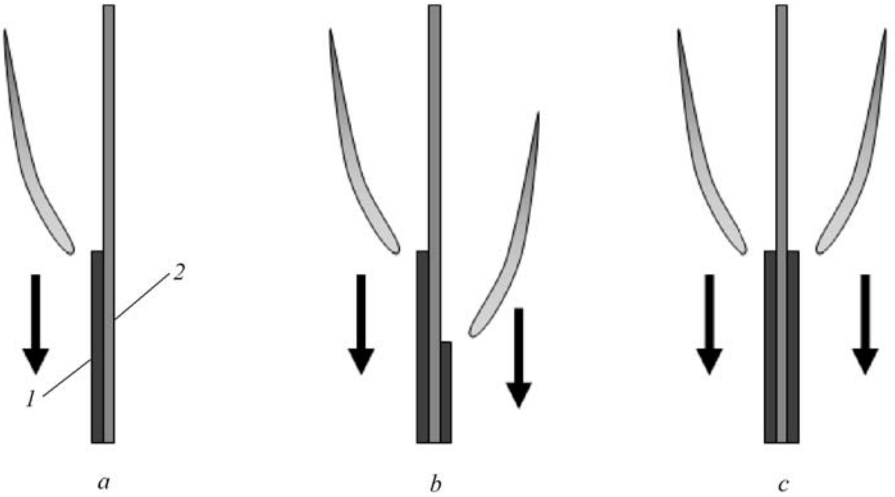

Fig. 1. Structure of the combustion wave in the cases of a one-sided flame (a), a two-sided flame (b), and a symmetric two-sided flame (c). The flame propagates in the downward direction.

was deposited on the vertical foil strip, a two-sided symmetric flame (Fig. 1c) propagated in the downward direction. In the case of two different fuels, two combustion regimes can be realized: a stationary low-rate combustion and a nonstationary combustion with longitudinal vibrations.

Experiments carried out with a flame propagating over a foil strip in the downward direction have shown that a stationary combustion regime is established after a short initial period. Then the velocity of propagation of the flame above the foils of length 6 m remained constant (within 2%). This points to the fact that the structure of a combustion wave, i.e., its phase, temperature, concentration, and other profiles, do not change with time. The structure, velocity, and other critical characteristics of flames were experimentally investigated in detail in [1–6].

**Influence of the Orientation of the Liquid-Fuel–Metal-Substrate System on the Flame Characteristics.** Figure 2 presents the dependence of the velocity of propagation of a flame *u* over a thin foil on the angle of inclination $\alpha$ of the foil. In this figure, at its upper right corner, the scheme of measuring the angle $\alpha$ (in the counterclockwise direction), the direction of the flame propagation, and the foil surface on which a fuel is deposited (the position of the arrows) are also shown. Here, the foil is denoted by the dashed lines and the foil plane is perpendicular to the plane of the figure. It is seen that, in the range of angles $\alpha$ from 0 to $90^o$, the flame propagates in the upward direction over the fuel film deposited on the upper surface of the foil and its velocity increases with increasing $\alpha$. The length of the glowing flame changes insignificantly; however, its average length remains unchanged. The velocity of the flame varies within 20%. It does not accelerate or decelerate in this quasi-stationary regime.

In the range of change in $\alpha$ from 90 to $180^o$, a flame propagates in the upward direction over the fuel film deposited on the lower surface of the foil. In this case, the velocity of propagation of the flame decreases with increasing $\alpha$. In the range of change in $\alpha$ from 0 to $180^o$, the velocity of the flame propagation reaches a maximum at $\alpha = 90^o$ for all the fuels being investigated.

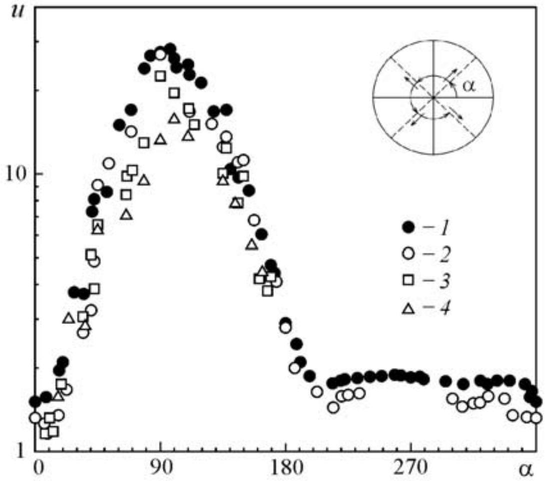

Fig. 2. Dependence of the velocity of the flame of saturated-hydrocarbons propagating over one side of a substrate on the angle of its inclination α: 1) undecane; 2) dodecane; 3) tridecane; 4) hexadecane [the inset shows the scheme of measuring the angle α, the direction of flame propagations (the arrows), and the foil surface on which a fuel is deposited (the position of the arrows)]. *u*, cm/s; α, deg.

When a flame propagates in the downward direction ($180 < \alpha < 360^{\text{o}}$), its velocity remains unchanged in both the case where the flame propagates over the fuel film deposited on the upper side of the substrate ($180 < \alpha < 270^{\text{o}}$) and the case where it propagates over the fuel film deposited on the lower side of the substrate ($270 < \alpha < 360^{\text{o}}$). It is seen from Fig. 2 that, for *n*-undecane, the velocity of a flame in the range $200 < \alpha < 300^{\text{o}}$ is independent of the angle of inclination of the foil. For dodecane, the flame velocity is also independent of the angle α; however, in the range $233 < \alpha < 300^{\text{o}}$, a flame does not propagate. For more heavy fuels, the range of flame-propagation angles is even narrower. A flame does not propagate at $\alpha < 7^{\text{o}}$ and $\alpha > 170^{\text{o}}$ for tridecane and at $\alpha < 16^{\text{o}}$ and $\alpha > 164^{\text{o}}$ for hexadecane. The experimental data obtained allow the conclusion that, for the fuels and foils being investigated, the velocity of propagation of a flame in the downward direction falls within the range 1.5–5 cm/s.

**Stationary Regimes of Flame Propagation.** ***Regime of high velocities.*** A flame can propagate over the surface of a combustion liquid with a velocity of the order of the normal velocity of a laminar flame of a homogeneous mixture of the vapor of this liquid with air. This regime is realized at a temperature higher than the "flash" temperature, namely, at a temperature higher than the limiting lower temperature [7]. This effect is explained by the possibility of formation of a combustion mixture over the surface of a fuel even before a flame begins to propagate. The regime of high flame velocities (high-velocity regime) was detected in experiments with an ethanol film deposited on the upper side of a horizontal foil of width 17.5 cm and thickness 60 μm. In this case, the velocity of the flame was about 70 cm/s. Since the mechanism of flame propagation in this combustion mixture formed is analogous to the mechanism of a laminar flame, the regime of flame propagation in this case can be considered as a high-velocity conductive regime.

***Evaporation-diffusion regime.*** When a flame propagates in the downward direction (Fig. 2, $180 < \alpha < 360^{\text{o}}$), a typical stationary evaporation-diffusion regime of combustion with a flame-propagation velocity $u \approx 2$ cm/s is realized. This regime was investigated in detail in [1–6]. In these works, the parametric dependences of the velocity of propagation of a flame as well as its structure, stability, and propagation limits were investigated. Physical and mathematical models of the process have been developed and the mechanism of transfer of a reaction has been determined [1–6]. It was shown that part of the heat released by the combustion products is transferred to the metal substrate and then, through it, due to its high heat conductivity, to the region of the flame edge where the fuel is evaporated. The flame edge is located above the region of the substrate where its temperature is close to the temperature at which, under the equilibrium conditions, a stoichiometric mixture of the fuel vapor with air is formed.

***Free-convective regime.*** It is seen from Fig. 2 that, in the case where a flame propagates in the upward direction ($0 < \alpha < 180^{\text{o}}$), the velocity of the flame is one or two orders of magnitude larger than that in the case where it propagates in the downward direction. This means that the free convection plays an important accelerating role. For a vertical substrate of width 5 cm, the characteristic velocity of convection $S_c \sim \sqrt{gd} = 70$ cm/s is one or two orders of magnitude larger than that in the case of propagation of a flame over the horizontal substrate. Such a high velocity of convection in the case where a flame propagates in the upward direction is explained by the recuperation of heat in the combustion zone. The hot combustion products propagating over the vertical substrate in the upward direction transfer heat to the cold substrate with a fuel film. Consequently, the region of the substrate–fuel-film system located upstream of the flame zone is heated well. As a result, all elementary processes (heat exchange, evaporation, mixing, chemical reaction) are accelerated. An intensification of the heat and mass exchange in the substrate–fuel-film system leads to an increase in the velocity of the flame propagation. This does not mean that the evaporation-diffusion regime changes to the high-velocity regime. The nature of the evaporation-diffusion regime is retained, namely, the substrate should be heated; however, the rate of this process increases substantially because of the free convection. We call this combustion regime the free-convection regime [8].

We now consider some general characteristics of the filtration combustion of gases [9] and of the propagation of a flame over the surface of a fuel deposited on a metal substrate. In both cases, the movement of the gas relative to the condensed phase plays a determining role. In the evaporation-diffusion regime, in the case where a flame propagates in the downward direction, a scheme of combustion to ward the free-convective flow of a fresh mixture having a relatively weak influence on the process is realized. In the case where a flame propagates in the upward direction in the free-convective regime, a scheme of a backwash combustion is realized under the strong positive action of the free convective flow of the combustion products. In the system being considered, the heat recuperation occurring with the participation of the free convective motion of the combustion products over the surface of the liquid fuel leads to an increase in the velocity of propagation of the flame. It is likely that the temperature of the flame does not increase in this case because the recuperative heat of the combustion products, transferred through the substrate from the region of combustion products to the edge of the flame, causes not an increase in the temperature of the flame, as in the filtration combustion of gases, but an intensive heating and evaporation of the fuel, the formation of a combustion mixture, and, as a consequence, an increase in the velocity of the flame propagation. To put it differently, an increase in the heat flow due to the high heat conductivity of the substrate leads not an increase in the rate of the chemical reaction and in its heat action in the gas phase but to an increase in the rate of evaporation of the fuel. This makes it possible to gradually change the velocity of a flame, by changing the orientation of the system, from the minimum values in the case of propagation of the flame in the downward direction to the maximum ones of the order of the velocity of a flame in the high-velocity-regime propagation in the case of propagation of the flame in the upward direction (Fig. 2). In the case where the heat conditions in a flame and the velocity of its propagation change substantially, it is difficult to separate the high-velocity regime from the evaporation-diffusion one.

**Oscillation Regimes of Flame Propagation.** In the case of propagation of a flame over a substrate, along with the stationary regimes, four oscillation regimes corresponding to oscillation processes of two types — transverse and longitudinal pulsations of the flame front — can be realized. They are the combustion regimes with chaotic transverse oscillations, regular transverse oscillations, and longitudinal oscillations of a flame as well as the spin combustion.

***Regime of longitudinal oscillations.*** The combustion regime with longitudinal oscillations represents a combustion with a periodic motion of the front of a stationary flame along the direction of its propagation. In the case where different fuels are deposited on the opposite surfaces of a foil, two regimes of propagation of a flame — the stationary evaporation-diffusion regime and the regime of longitudinal oscillations — can be realized. In the first case, the flame propagates over the fuel with a higher boiling temperature with a velocity equal to the velocity of the flame of a highly volatile fuel; however, its leading edge is downstream of the leading flame. For example, in the system *n*-nonane–*n*-tridecane on a copper substrate of thickness 45 μm, a combustion wave propagates in the stationary evaporation-diffusion regime with a velocity of 3 cm/s and the flame of *n*-tridecane is 5 mm downstream of the leading flame.

A combustion with longitudinal oscillations arises in the case where a fuel capable of burning without a heat supply is deposited on one side of a substrate and the fuel deposited on the other side of the substrate is not capable of such burning. Figure 3 presents video frames of the flame propagation in this regime. The experiments were carried out with a copper foil, on the surface of which *n*-undecane and a transformer oil were deposited. The average velocity of propagation of a flame was 2 cm/s and the frequency of the flame pulsations measured by a photodiode was 10

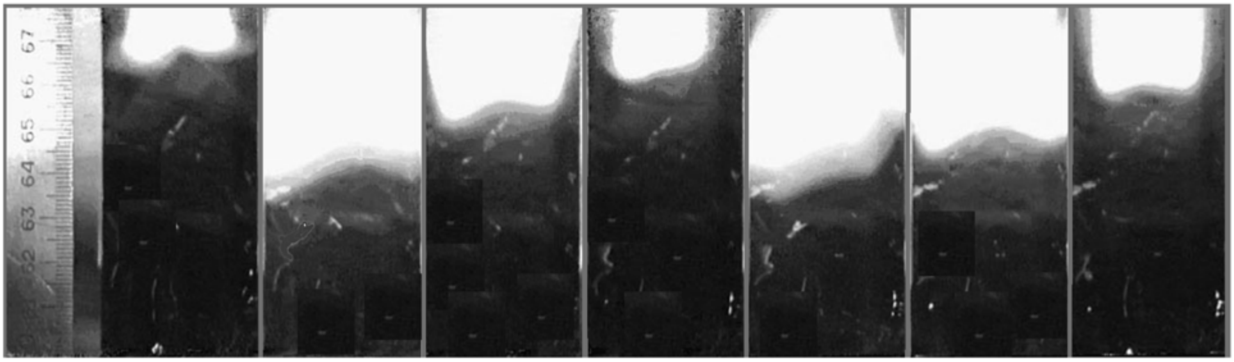

Fig. 3. Frame-by-frame photography of the longitudinal oscillations of a flame on an ice substrate of thickness 45 μm covered by a fuel layer of *n*-undecane and a transformer oil. The frame frequency is 25 Hz.

Hz. The two oscillation periods are shown in this figure. The frame frequency was close to the frequency of the flame oscillations but not a multiple of it. The flame on the transformer-oil side was photographed. In the figure, the flame is shown by the white color, and it propagates downward from left to right.

The leading flame of *n*-undecane heats the foil and, in doing so, causes the film of the poorly volatile fuel to evaporate with the formation of a combustion mixture that burns out rapidly in the high-velocity regime. Then the intensity of combustion becomes lower, a fresh combustion mixture is formed once again, and the process is repeated. The first frame in Fig. 3 is the final stage of the passive phase (the afterburning). Between the first and second frames, a flame shock propagated along the foil in the high-velocity regime. Frames 2–4 show the afterburning of the mixture and the cooling of the combustion products. Then the process is repeated. The frequency of the flame oscillations depends on the type of fuel as well as on the thickness and width of the foil strip. In the experiments with different fuels, the frequency of the flame oscillations ranged from 5 to 20 Hz. The combustion front moved with a velocity of about 100 cm/s. In this part of the oscillation period, the mixture of the transformer oil with air burns out in the high-velocity regime. Then the intensity of the combustion decreases and, after a new portion of a mixture is produced, the process is repeated.

***Spin regimes.*** The combustion regime with transverse oscillations of the flame front represents a combustion in which a flame (a combustion site) of limiting size propagates along the edge of a fuel. Transverse oscillations of the flame front were detected in three combustion regimes — the spin combustion, the combustion with chaotic oscillations, and the combustion with regular oscillations. The first of these regimes was realized on the surface of a cylindrical foil. One or several combustion sites moved along the spiral edge of the fuel film deposited on the surface of the cylinder. In order that the spin regime be realized, a liquid fuel must have time to evaporate and form a combustion mixture before the combustion site approaches.

A spin combustion site is localized in a comparatively small region and has a narrow crescent-like shape with a convexity on the unburnt-fuel side. The characteristic velocity of movement of this site along the fuel edge is of the order of 100 cm/s, and the velocity of its movement perpendicularly to this edge is of the order of 1 cm/s. The spin regime of combustion was realized in several variants on different substrates near the layered-combustion limits.

*Spin regimes of combustion over a cylinder.* Cylinders of diameter 66 mm made from aluminum and steel foils of thickness 115 μm were used. A fuel film of thickness 7–9 μm was deposited on the outer side of a cylinder. As fuels, *n*-butyl alcohol and saturated hydrocarbons were used. After the *n*-nonane vapor formed at the outer surface of the cylinder was ignited, a combustion site began to propagate along the spiral (see Fig. 4a).

The average velocity of the wave propagating in the transverse direction $v$ is about 120 cm/s, and the average velocity of the wave propagating in the longitudinal direction along the cylinder element (the velocity of movement of the fuel edge) $u = 1$ cm/s. The frequency of rotation of the combustion site is stable and equal to 5.5 Hz. Analogous data were obtained for the combustion of an *n*-decane film over the same cylinder. The frequency of rotation of the cylinder was 5.2 Hz for the one-headed spin and 8.2 Hz for the two-headed one. The velocity of movement of the spin along the fuel edge depends insignificantly on the fuel type and is substantially dependent on the number of spin heads. For example, a one-headed spin moves along this trajectory with a velocity $v = 120$ cm/s, and a two-headed

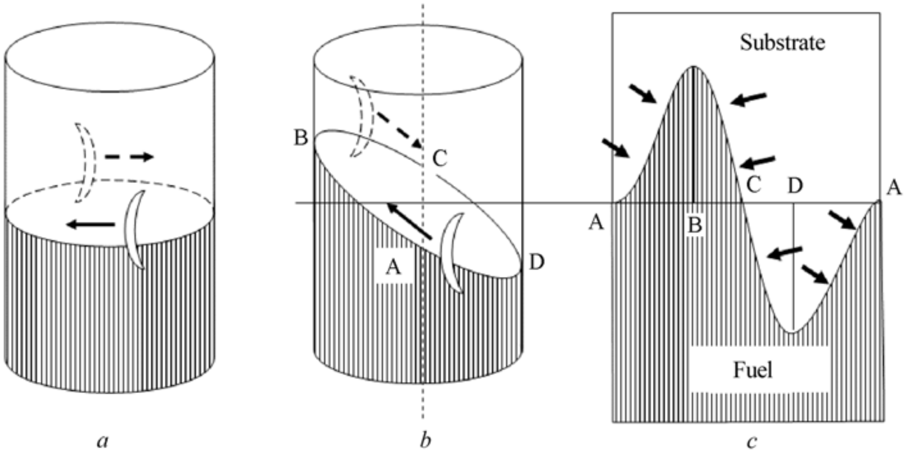

Fig. 4. Scheme of combustion of a fuel over a cylinder with circular (a) and elliptic spins (b); fuel edge and direction of heat flows (c).

spin moves with a velocity $v = 90$ cm/s. The corresponding longitudinal velocities are equal to $u = 0.7$ cm/s for the one-headed spin and $u = 1.9$ cm/s for the two-headed one. The regime of spin combustion over the steel cylinder with a film of *n*-butanol was also realized. In this case, the characteristic velocities were equal to $v = 100$ cm/s and $u = 1$ cm/s, and both the right-sided and left-sided rotations of the combustion site were detected.

Under definite conditions, a spin with an elliptic trajectory of movement can be initiated on the surface of a cylindrical foil (Fig. 4b). Unlike the spin with a circular spiral trajectory, the spin with an elliptic trajectory is nonstable. A maximum velocity of movement of a combustion site was detected at the upper point of the trajectory of this spin (Fig. 4b), and the velocity of this site was minimum at the lower point of the spin path (Fig. 4b). Figure 4c shows the development of the cylinder surface on the plane. It is seen that the flame edge at the upper point is concave relative to the liquid film, and it is convex at the lower point. It is known that the heat conductivity of a curved flame in the concave regions of its front favors the combustion and, in the convex regions, it decelerates the combustion.

Since, after a flame is initiated, the length and curvature of the elliptic trajectory of the combustion site changes with time in the process of its transformation into the circular one, the propagation of the combustion site in this stage is nonstationary and its propagation along the circular spiral trajectory is stationary.

A spin combustion can also arise in a system that does not possess a cylindrical symmetry, e.g., on a plane foil strip, on both sides of which a fuel film is deposited (a shuttle spin). Experiments conducted with a vertical copper foil of thickness 45 μm and width $w = 4$ cm with an *n*-hexadecane film at the initial values of $p = 749$ mm Hg and $T = 292$ K have shown that, in the case where a flame propagates over this foil in the downward direction, one of the above-indicated two combustion regimes is realized. They are the two-sided layer-by-layer propagation of a flame with a velocity $u = 2.2$ cm/s and a spin propagation of a flame along the fuel-film edge — a one-headed spin (Fig. 5). In this case, the spin combustion can arise spontaneously from a stationary layer-by-layer combustion or as a result of the ignition of an open flame. The frequency of rotation of the combustion site $f = 11.2$ Hz, i.e., it moves with an average velocity $v = 2wf \approx 90$ cm/s; its longitudinal velocity $u = 1.6$ cm/s.

A difference between the combustion processes in the cylindrical and plane systems is that in the plane system there are two singular points at which the flame passes from one surface of the foil to the other. Moreover, these processes are differentiated by the fact that the heat conditions along the trajectory of movement of a flame over a plane foil are not equivalent to those for a cylindrical foil. This is explained by the fact that the system is thermally thin and the flame propagating over one of its sides changes, in a complex way, the heat conditions at the other side. Under these conditions, a nonstationary propagation of a flame along the fuel edge is realized. However, the average velocity of the flame propagation $u$ remains constant, which points to the reproduction of the conditions of flame propagation along the fuel edge in each turn of the spiral.

The evaporation-diffusion and spin combustion regimes differ most markedly by the vector velocities of a flame in them. The vectors of the velocities $u$ and $v$ are orthogonal, and their values differ by two orders of magnitude. A flame propagating layer-by-layer in the longitudinal direction over a foil has a diffusion structure, and a flame

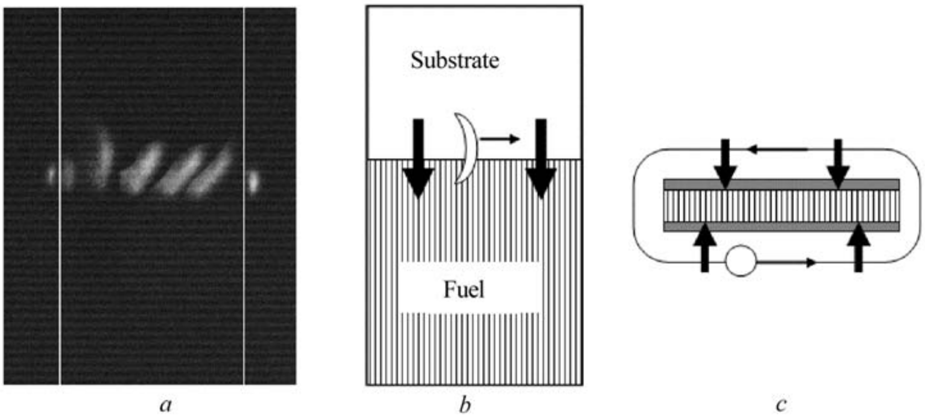

Fig. 5. Stroboscopic photograph of a shuttle spin on a plane substrate (a); scheme of the heat flows (denoted by the arrows), the front view (b); scheme of the spin trajectory and of the heat flows, the top view (c).

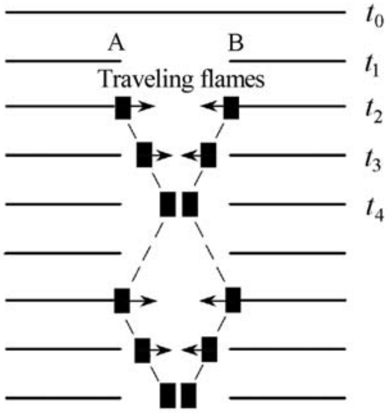

Fig. 6. Formation of chaotic oscillations: the lines $t_0$–$t_4$ denote the flame-evolution stages; a flame is absent in the region AB.

in the spin-combustion regime has a structure like the structure of a mixed-compound flame. Correspondingly, the velocity $v$ in the second case falls within the range $S_u$–$S_uF_i$.

Since the conditions of the spin regime are beyond the limits of the evaporation-diffusion regime, it is necessary to additionally increase the reactivity of a combustion mixture or improve the local conditions of its combustion. In the spin regime, this is apparently attained due to the more effective use of the heat of the products of the fuel burned earlier. A combustion site in the spin regime uses the heat accumulated in the substrate from the combustion in the previous turns. The possibility of realization of the spin regimes on different substrates covered with different substances points to the fact that these combustion regimes can have a wide application.

***Regime of chaotic transverse oscillations***. A combustion with chaotic transverse oscillations was realized on an *n*-undecane film deposited on one side of a copper substrate of thickness 60 μm and width 175 mm in the range of angles $\alpha$ from 180 to 360$^{\circ}$. The parameters of the system being investigated were selected such that the stationary propagation of a flame only in the downward direction was impossible. The conditions necessary for a stationary longitudinal propagation of a flame oscillating transversally relative to the fuel edge over a foil strip (with a velocity of 1.5 cm/s) can be attained by inclination of the plane of the foil. The regime of chaotic transverse oscillations was initiated under the near-limiting conditions with $\alpha = 240^{\circ}$ and $\alpha = 307^{\circ}$ (Fig. 2). The flame pulsations were chaotic in character, and the combustion sites moved in opposite directions, or to meet each other, or one after the other.

The indicated regime is realized in the following way. For initiation of a flame, it is necessary that the substrate be locally heated to some extent. In this case, the conditions necessary for a stationary longitudinal propagation of a flame are locally attained, and a continuous flame front moves along the substrate for a short time. Then the

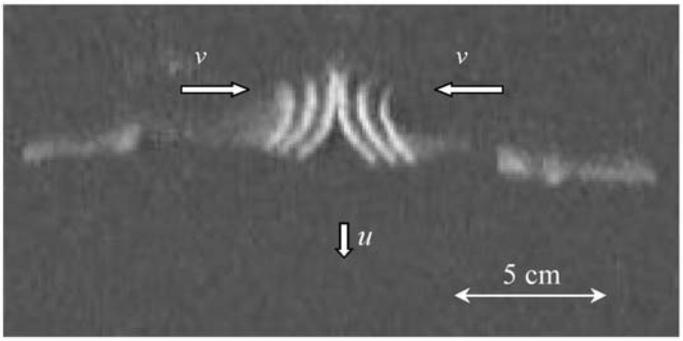

Fig. 7. Video frame of the chaotic transverse oscillations of a flame during the time period from $t_2$ to $t_4$. The arrows show the direction of propagation of a flame with a velocity $v = 96$ cm/s and the general direction of burn-out of the fuel with a velocity $u = 1.54$ cm/s.

flame front separates into several parts. The mechanism of this combustion can be represented in the following way (Fig. 6). Because of the fluctuations of the parameters of the system (the local thickness of the fuel film and others), at the instant of time $t_1$ the combustion in the region AB is terminated; initially, at the instant of time $t_0$, a continuous flame front propagates. Since the metal substrate is heated, within a certain time, in this region a mixture capable of sustaining the combustion is formed near the substrate as a result of the evaporation of the liquid and the mixing of the vapor with air. The mixture at the positions A and B at the edges of a flame begins to burn at the instant of time $t_2$. The combustion sites formed move toward each other during the period of time from $t_2$ to $t_4$. Then the process is repeated.

Figure 7 shows a video frame representing three images (the time of exposure of the frame is 1/50 s, the time of exposure of one image is 0.65 s, and the time between the exposures is 7.2 μs). To this stroboscopic video recording corresponds the time interval from $t_2$ to $t_4$ in Fig. 6. The indicated frame was obtained in the process of propagation of a flame over a two-sided *n*-dodecane film on an aluminum substrate of thickness 115 μm. The velocity of propagation of the flame along the edge of the fuel was 96 cm/s. The average velocity of the flame propagation along the substrate in the downward direction was $u = 1.54$ cm/s.

Thus, the velocity of movement of a combustion site along the region AB comprises 100 cm/s. This allows the suggestion that, in this case, a flame propagates in the high-velocity regime. At the same time, fragments of the main stationary flame propagate in the perpendicular direction in the low-velocity regime. Thus, the two different combustion regimes are realized simultaneously. The above-described scheme of oscillations of a flame with two combustion sites is one in many such schemes. The combustion sites at the points A and B can start at one time or at different times. Other schemes with one combustion site can be also realized. The multiplicity and variety of these schemes forms a randomless pattern.

***Regime of regular transverse oscillations.*** A combustion with regular transverse oscillations was realized on a vertical copper foil of thickness 60 μm and width 175 mm with an *n*-undecane film at $\alpha = 270^{\circ}$. These experimental conditions are beyond the conditions necessary for the longitudinal propagation (in the downward direction) and the strictly transverse propagation of a stationary flame. However, a nonstationary combustion is possible under the indicated conditions. To realize this combustion, it is necessary to form, with the use of an additional heat source, a heated linear region inclined at an acute angle $\beta$ to one of the foil edges. Then the fuel vapor above this heated slanting region of the foil was ignited. At the initial instant after the ignition, a rectilinear flame front was formed along the heated slanting region. Then this front disappeared in the larger part of the boundary between the film and the substrate because the conditions were beyond the conditions necessary for its existence. However, in the region where the flame front forms an acute angle with the foil edge, a flame continued to exist locally (Fig. 8, position 4). From this point acting as a source of ignition, combustion sites separated periodically and moved along the edge of the fuel to the opposite edge of the foil strip. Since a heat is released when a combustion site moves over a foil with a fuel film and the foil is heated, a vapor–air mixture capable of sustaining the combustion is formed once again above the fuel surface.

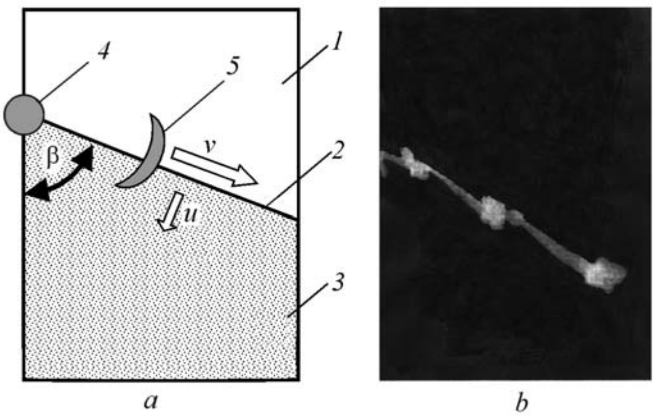

Fig. 8. Scheme of regular oscillations of a flame (a): 1) substrate; 2) fuel edge; 3) fuel; 4) pilot flame (combustion site); 5) moving combustion site (the arrows $u$ and $v$ show the directions of the burn-out and of the transverse oscillations); video frames of a flame with regular oscillations (b).

The specific nonstationarity taking place in this case is determined by the fact that the film near the acute angle burns out more rapidly than the film in the other regions along the fuel edge [2]. Consequently, the angle between the front of a flame and the foil edge will increase constantly as long as the flame dies out at a certain value of this angle. The value of the angle $\beta$ at which the flame dies out depends on the degree of remoteness of the combustion conditions from the limiting ones. For the foil being considered of thickness 60 μm with an *n*-undecane film, the limiting angle is $66^{\mathrm{o}}$ and the average velocity of longitudinal movement of a combustion site is 1.5 cm/s. The velocity of movement of a combustion site along the edge of the film reaches 100 cm/s. The movement of the combustion site is apparently nonstationary, and its velocity should decrease with time; however, this decrease is insignificant, and the conditions at a large distance from the indicated point can be considered as stationary during the larger part of the flame-evolution period. This provides a relative regularity of the combustion regime. If the conditions are far beyond the limiting ones, a flame turns as long as the line of the flame front is perpendicular to the edges of the film strip; the pulsation regime is not realized under these conditions. If a foil strip is fairly wide, several combustion sites can move simultaneously as a train. In Fig. 8b, three combustion sites propagating concurrently are seen. The combustion sites move one after another at close intervals from the vertex of the acute angle. This figure presents a video frame with an exposure of 0.02 s.

The mechanism of flame propagation in the regime of regular transverse oscillations does not differ radically from that of the regime of chaotic transverse oscillations. The indicated regimes differ by the method of initiation of the propagation of a flame. If a large number of combustion sites arise accidentally in the regime of chaotic transverse oscillations, one combustion site is formed in the regime of regular transverse oscillations, and this site is fairly specific: it is stable and nonstationary. In the case where the indicated site is formed artificially at the vertex of an acute angle of contact, the stabilizing property of the thermal diffusivity at the front of a bent flame is used. The velocity of the flame propagation in the region convex in the propagation direction is smaller than that in the concave region. Analogously, the velocity of the flame at an acute angle of contact is higher than that at a right or obtuse angle of contact [2]. Since a steady-state flame is impossible because the conditions are beyond the limiting ones, a combustion with regular pulsations ceases at a certain angle of inclination of the flame trajectory. It should be noted that the front of a flame equalizes slowly as compared to the time of movement of a combustion site. Therefore, the oscillations of a flame in this combustion regime are considered as regular. Even though we investigated the regime of regular transverse oscillations with an artificial combustion site, this regime is certain to be realized spontaneously under definite conditions.

**Discussion of Results.** The large number of combustion regimes with flames having different characteristics and velocities falling within a wide range that were detected in the system being considered points to the fact that a variety of flames differing in structure and propagating by different mechanisms can be realized in this system. However, these radically different combustion regimes are characterized by certain general mechanisms. It should be noted that the two mechanisms of flame propagation corresponding to the stationary high-velocity and low-velocity evaporation-diffusion combustion regimes differ fundamentally from each other. The first mechanism of flame propagation is close to the mechanism of propagation of laminar flames, i.e., it includes conductive-diffusion gas-phase processes of transfer of chemical reactions with a weak heat interaction of a flame with the condensed phase. Therefore, the velocity of the flame propagation is of the order of the normal velocity component $S_u$ or $S = S_uE_i$. In the second case, the mechanism of flame propagation in the evaporation-diffusion regime is related to the heat transfer through the metal substrate, which leads to a large heat loss. The velocity of the wave is determined not only by the heat conductivity of the substrate, but also by its capacity and thickness. Because of this, the velocity of the flame is small and is of the order of 1 cm/s. The properties of all the main regimes represent a combination of the properties of the high-velocity regime and the evaporation-diffusion regime. For example, in the regime of regular transverse oscillations, the regime of chaotic transverse oscillations, and the regime of longitudinal oscillations, the mechanism of propagation of a flame includes elements of the mechanisms of the high-velocity and evaporation-diffusion regimes. In the regime of longitudinal oscillations, the evaporation-diffusion part of the flame participates in the production of the mixture for the high-velocity part of the flame. In the regimes with chaotic and regular oscillations, the evaporation-diffusion flame acts as a "pilot flame" that initiates a high-velocity flame. In the spin regimes, the traveling heat wave is related to the wave in the previous turn and acts as a heat support of the evaporation and production of the mixture for the flame in the next turn.

Thus, combustion sites in all the oscillation regimes propagate, apparently, by one and the same mechanism corresponding to the mechanism of flame propagation in the high-velocity regime. The indicated regimes differ in the conditions of their initiation and the methods of production of the mixture above the substrate. Since in all the cases of initiation of oscillation regimes the conditions are beyond the limiting ones. i.e., the stationary evaporation-diffusion regime is impossible, to realize of these regimes, it is necessary to increase the reactivity of the combustion mixture and improve the local conditions of the combustion. This is attained by using the heat of the products of the fuel burned earlier in the combustion at the next stages with a prolonged ignition delay, i.e., the heat recuperation. A combustion site uses, in the oscillation movement in the regimes of chaotic transverse oscillations and regular transverse oscillations, the heat of the previous oscillations. A combustion site in the spin combustion uses the heat accumulated in the substrate from the combustion in the previous turns. In the combustion with longitudinal oscillations, the bodies of flames use the heat from the leading flame of the previous oscillation combustion.

One of the most important consequences of the phase heterogeneity of the system being considered is the relative movement of the phases. This movement can be natural or forced, and it is determined by the velocity of the moving phase (a gas or a liquid), representing an important controlling parameter. The moving phase in a reacting medium can act not only as a physical heat-transfer agent, but also as a chemical one. This property is common for the surface and filtration combustion, in particular for the combustion of a liquid fuel on a metal substrate and the combustion in an inert porous medium wetted with a fuel [10–12]. The analogy between these regimes can be demonstrated by the example of the free convective combustion corresponding to the cocurrent filtration combustion. Finally, as is known, the superadiabaticity effect can give rise to both a combustion with superequilibrium temperatures and a combustion with rapid chemical transformations. It may be suggested that combustion regimes analogous to the above-indicated regimes in other parameters can be realized.

One of the most interesting effects detected in the system being investigated is the spin and spin-like combustion. From the experimental data described above, it follows that the spin and spin-like processes can be realized at the sites of a flame or in its frontal structures; and they can be stationary or nonstationary in character. Combustion sites can move along finite or infinite trajectories. A spin combustion as well as a combustion of any other type can be initiated under definite conditions. We consider a spin (rotation) as a special case of the more general phenomenon having certain important features.

The properties of the spin combustion differ substantially from the properties of the usual, so-called layer-by-layer combustion. The velocity vectors of the usual and spin flames are perpendicular to each other, and the values of these velocities differ by two orders of magnitude. A spin combustion usually arises beyond the limits of the usual layer-by-layer combustion or under conditions close to the conditions of this combustion. The experimental data obtained allow the conclusion that, when this limit approaches, the reactivity of the combustion mixture and the heat released by it decrease. The flame loses the ability to propagate in the longitudinal direction and dies out. However, the flame can exist and propagate outside the range of the layer-by-layer combustion in the case where an additional energy is supplied to the combustion site from the specific processes of heat and mass transfer.

The energy supply to the zone of chemical transformation is due to the recuperation of heat from the region of the combustion products, the selective diffusion of the deficient component to the leading points of the flame front, the filtration of the deficient reagent, the heat released as a result of the interaction of two flames, and other processes. Flames with an energy support are called "flames with an excess of enthalpy" [13] or "flames with an energy concentration" [14].

The peculiar properties of the spin combustion with transverse waves allow one to consider it as a special type of combustion with its own stationary and nonstationary regimes, parametric regions of existence, mechanisms of reaction transfer, and other characteristics. The most important feature of this combustion is the autoconcentration of energy through the transverse heat and mass transfer and the propagation of a flame along the fresh mixture–combustion products interface.

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## NOTATION

$E_i$, coefficient of expansion of the combustion products; $f$, rotation frequency of a combustion site; $p$, pressure; $Q_{\text{ev}}$, heat of evaporation; $S_u$, normal component of the flame velocity; $S$, visible velocity of the flame; $T_{\text{low}}$, lower limiting temperature; $T_{\text{b}}$, boiling temperature; $T_{\text{f}}$, temperature of the flame; $t$, time; $u$, velocity of the flame propagation in the longitudinal direction; $v$, velocity of the flame propagation in the transverse direction; $w$, width of a foil. Subscripts: ev, evaporation; low, lower; b, boiling; f, flame; c, convection.

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