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Flame Spread over Thermally Thin Layer System "Metallic Substrate – Fuel Film"

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INTRODUCTION

Flame spread over the surface of a combustible material is complicated by the coupling of the gas-phase combustion process to the many physical and chemical processes related to the transformations of the combustible material, such as pyrolysis, gasification, phase transitions, heterogeneous reaction, and others. Variations of a single variable while keeping the others constant is practically impossible. With the aim of separately studying the influence of the thermophysical properties of the system and the reactivity of fuels recently, it has been proposed new heterogeneous thermally thin model layer system "liquid fuel film on a metallic substrate" [1]. This system is also a model one for studying flame propagation in an inert porous media wetted with fuel [2]. The present work deals with theoretical and experimental investigation of propagation of the diffusion flame above such thermally thin systems.

EXPERIMENTAL

The experiments were performed in air at atmospheric pressure and room temperature. We used films of various individual hydrocarbons and spirits with thickness of 7-8 μm as a fuel and aluminum, copper or steel foils 7-120 μm thick as substrates. For the experiment, a strip of a metal foil of width of more than 5 mm (for these dimensions, the steady-state velocity is independent of the width, and a foil 40 mm wide was usually used) and length of 0.2-6 m was fixed. The flame luminescence, substrate temperature and the flame velocity was measured. In some experiments, the fuel film was applied to both sides of the foil, and a two-sided flame was studied.

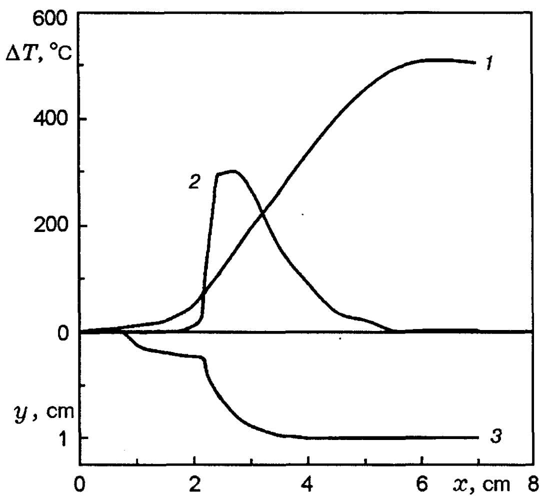
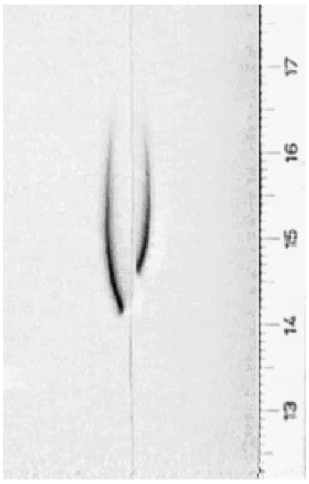


Figure 1 gives the distributions of the temperature of the substrate (1) and luminous intensity (2) of the one-side flame front along the n-undecane-copper system, (h_s = 45 μm), and the external boundary of the region of optical nonuniformity determined by schlieren technique (3). The temperature dependence and the position of the external boundary of optical nonuniformity indicates the presence of a rather extended (≈2 cm) heating zone ahead of the flame edge. Flame spread rate u=1.8 cm/sec.

Videotape recordings enabled flame spreading rates and oscillation frequencies to be obtained. By depositing additional combustible liquid on another (opposite) surface of the foil



a two-sided flame was obtained. For the same liquid fuel a flame steady-state spread from top to bottom over a strip of vertical foil in a two-sided symmetric flame (twin flames over opposite foil surfaces). With two different liquids there are possible various flame spread regimes: steady-state low combustion rate regime (Fig. 2), a nonsteady combustion regime with longitudinal oscillations and others.

On Fig. 2 there is video frame (negative) of steady-state flame spreading over copper foil of 45 μm thickness. Left - flame of n-nonane (C_9H_{20}), right – flame of n tridecane ($C_{13}H_{28}$), length in cm. There is a distance between the flames which is invariable in time. The flame spread rate remains constant (to within 2%) for specimens up to 6 m in length. This implies a time invariant combustion wave structure, in terms of phase, temperature, concentration and other profiles.

STEADY-STATE REGIMES OF FLAME SPREADING

Free Convection Regime. Figure 3 shows the dependence of the flame spreading rate, *u,* over thin and thick foils on the angle of inclination, α, of the foil plane relative to the horizon. Also shown in Fig. 3, to the right, in the scheme for identifying the angle α (counterclockwise), flame spreading direction (an arrow), and the foil surface over which the flame is spreading (position of the arrow). Here the foil is depicted as a dotted line. It is seen that in the range of α=0 to 90° the flame spreads upward along the upper surface at a rate that increases with increasing angle, α. The length of the luminous flame is a slightly wavy, but the mean length is constant. The flame spreading rate is constant to within 20%. There is no tendency of the flame to accelerate or decelerate in this quasi steady-state regime.

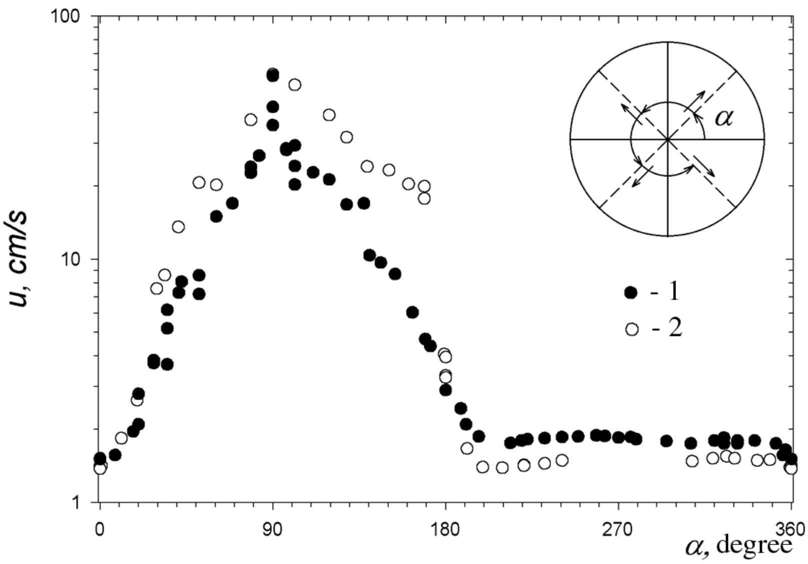


Figure 3. Dependence of flame spread rate u on inclination angle α of foil plane relative to horizontal. One-side flame. Systems: copper foil – n-undecane. 1-foil thickness 45 μm, width 4 cm; 2 – foil thickness 60 μm, width 17.5 cm.

In the range of α=90 to 180° flame spreads upward along the lower surface of the foil. This rate decreases with increasing α. In the case of the wide foil at $\alpha\approx$170° the flame spreading rate jumps to a value that is an order of magnitude lower. In the range of α=0 to 180° the maximal flame spreading rate is reached at α=90°. Over the whole range (excluding the region with α near to 0° and 180°) the flame spreads faster along the wide foil than along the narrow one.

Low Rate Regime (LR). For downward flame spread (α=180 to 360°) the spreading rates for the two foils are also steady both for flame spreading under (α=180 to 270°) and above the foil (α=270 to 360°). It is seen from the Fig. 3 flame spreading rate in the range of α=200 to 360° is independent of the angle of inclination of the foil plane, excluding the range α=240 to 307°. In this range the flame cannot spread downward along the thick foil. At downward spreading flame spreading rate over the wide (thick) foil is lower than over the narrow (thin) one. For various liquid fuels and foils the flame spreading rates are in the range of 1.5 to 5 cm/s. It was shown in [2] for flame spreading downward the dominant elemental process of heat propagation ahead of flame is conduction through the metallic substrate. The regime of flame spreading may be termed a low rate conductive one.

The experimental studies of combustion wave propagation allowed us to formulate a physical model of the phenomenon. The combustion wave propagates along the fuel surface due to the formation of a combustible mixture near the surface upon evaporation of the liquid fuel. Evaporation of the fuel results from its heating by the heat coming along the substrate from the combustion products. The substrate is heated due to the interphase heat exchange behind the flame edge. The flame edge is located above the point on the substrate, where the temperature of the substrate and fuel is equal to the temperature at which a stoichiometric mixture is formed under equilibrium conditions. After that, the fuel film completely evaporates at a certain distance from the flame edge, which is smaller than the flame-front length. Complete evaporation of the liquid may occur at temperatures below the boiling point.

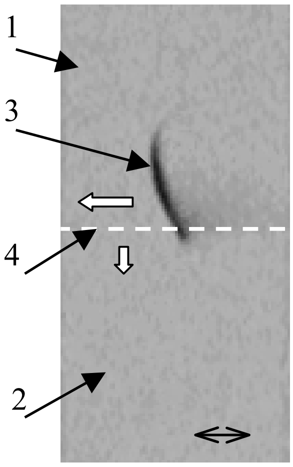
High Rate Regime (HR). Over the surface of a combustible liquid a flame can spread with a rate of the order of the laminar burning velocity of the homogeneous mixture of this liquid vapor and air. This occurs at temperatures above the "flash" temperature, namely, above the lower temperature limit [3]. This phenomenon is connected with the possibility of generating combustible mixture over the fuel surface before the flame spreading. This regime was observed in our experiments with an ethanol film on the upper surface of the horizontal copper foil of 60 μm thickness. The flame spreading rate in this case is about 70 cm/s. Since the mechanism of this flame spreading regime is analogous to laminar flame one it may be termed a high rate conductive regime.

OSCILLATION REGIMES OF FLAME SPREADING

The Longitudinal Oscillation Regime. Together with the steady-state regimes various oscillation regimes observed: transverse chaotic oscillation, spin combustion and a regime of longitudinal oscillations of the flame front. The longitudinal oscillation of the flame front means oscillations of the flame front along the foil strip in the direction of spreading of normally steady-state flames. If there are different fuels on the foil surfaces then that two cases are possible, as mentioned above, a steady-state low rate regime (Fig. 2) or a longitudinal oscillation regime. Last regime develops when on one surface of the substrate the fuel is able to burn without assistance, while on the other it is unable to do so. The flame oscillation frequency depends on the fuel, thickness and width of the foil. In experiments with various fuels the frequency lies in the range of 5 to 20 Hz. The front of the combustion spot travels forward at about 100 cm/s.

Transverse Chaotic Oscillation Regime (TCO). Transverse oscillations of the flame front occur when flames of restricted sizes (flame spots) run along the fuel edge normal to the direction of flame spreading of steady-state flames. Transverse oscillations of the flame front implement three combustion regimes: regimes of chaotic oscillations, regular oscillations and spin combustion. The first of these (TCO) is observed in flame spreading over a n-undecane film deposited on one surface of copper foil of 60 μm thickness at 180°<α<360°. The parameters of the system were selected such that steady-state spreading of flickering combustion strictly downward was impossible. By tilting the foil plane one could attain conditions in which steady-state longitudinal (along the foil strip with u=1.5 cm/s) spreading of an oscillating flame, which runs along the fuel edge across the strip, becomes possible. The oscillations are chaotic in character. Combustion spots can diverge, move towards one another, or follow each other.

Spin Regime. If the foil surface is made cylindrical then transverse oscillations can transform into spin combustion. One or several combustion spots will travel along the fuel film edge in the helical path on the cylindrical surface. For the existence of a spin regime it is necessary for the liquid fuel to have time to evaporate and generate a combustible mixture before the approach of the combustion spot. The spin regime was implemented on a steel cylinder of 66 mm diameter and a wall thickness of 120 μm with an n-butanol film on the outer surface. Experimental data show the rate at which the combustion spot travels along the fuel edge is about 100 cm/s.



It turns out that spin combustion is possible in the system without cylindrical symmetry on foil strip, if there is fuel on its two sides. Fig. 4 shows the video frame (negative) of the flame spot in spin regime over n-hexodecane on copper foil. Exposure interval - 1/2000 s. 1 – foil, 2 – fuel film, 3 – flame spot, 4 – fuel film edge.

DISCUSSION

A variety of steady-state and oscillatory regimes indicate a variety of flame spreading mechanisms. The mechanisms of flame spreading in high and low rate steady-state regimes are fundamentally different. The mechanism of flame spreading of HR is close to the mechanism of laminar premixed flame propagation that includes conductive and diffusive gas phase processes and chemical reaction. Therefore the spreading rate is of order of the laminar burning velocity, S_u, or flame speed $S=S_uE_i$, where E_i is the expansion ratio.

The mechanism of flame spreading of LR is connected with heat transfer through the metallic substrate. In this case the substrate has to be heated and great heat expenditure is required. The rate of propagation of the wave is determined by the thermal conductivity and heat capacity and the thickness of the foil and fuel parameters. Consequently the flame rate is small and about 1 cm/s. All oscillation regimes are close to the limit of LR. It is interesting in this respect that TCO is initiated near the limits α=240° and α=307° (see Fig. 3) on wide foil.

This suggests flame spreading occurs in HR. At the same time fragments of the main steady-state flame are spreading in a perpendicular direction, along the strip in LR. Thus, two different regimes are simultaneously implemented.

As far as the longitudinal oscillation regime is concerned its peculiarity consists in the oscillatory flame travel in the same direction as the leading flame. It is interesting to note that the whole flame does not oscillate, but only its leading part. The rear part travels slowly, without oscillation. Thus the mechanism of combustion spot spreading in all oscillation regimes are apparently the same, namely, HR with a characteristic rate of S_u to S_uE_i. The difference arises in the schemes of initiation of the oscillatory regimes. In oscillation regimes the conditions are usually outside of the LR regime limits.

It is seen from the Fig. 3 that when spreading "upward" ($0<\alpha<180°$) the flame spreading rate is by one to two orders of magnitude higher than when spreading "downward". This means that free convection must play an important accelerating role. The characteristic convection velocity at d=5 cm, $S_c \sim \sqrt{gd}$ =70 cm/s is by one to two orders of magnitude higher than one when spreading over a horizontal substrate. Such a high spreading rate in upward travel is due to heat recuperation in the combustion zone. At a vertical substrate hot combustion products rising upward, transfer heat to the cold substrate with the fuel film. Hence, ahead of the flame zone, the system "substrate-liquid fuel" prove to be well warmed up. As a result all elemental processes (heat exchange, evaporation, mixing, chemical reaction) are accelerated. Intensification of the heat exchange of combustion products and the system "substrate-liquid fuel" result finally in an increased rate of flame spreading does not mean LR changes in HR. The nature of the LR regime remains, namely, the need to heat the substrate. But the rate of this process substantially increases due to free convection.

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