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COMBUSTION REGIMES OF LIQUID FUEL FILM ON THERMALLY THIN METALLIC SUBSTRATE

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ABSTRACT

The process of flame spread over a liquid fuel film (n-undecane, ethanol, dibutylphtalate, or a dielectric oil) on a foil of copper or aluminium has been examined for a linear thermally thin layer system. The flame spread depends on the direction of propagation relative to the gravitational force. In the flame spread mechanism heat transfer from the products to the preflame zone plays an important role. This heat transfer can proceed due to conductivity through the metallic substrate or to free convection. Accordingly, one may identify two flame spread regimes: thermal conductive and convective. When environmental temperatures are higher than the lower temperature flammability limit, there can be either rapid (~ 100 cm/s) flame spread through the gas phase without substantial heat exchange with the metallic substrate or slow spread (~5 cm/s) with a key mechanism of forward heat transfer through the substrate. Together with steady-state regimes four oscillation combustion regimes were obtained, namely, combustion with transverse chaotic oscillations, combustion with transverse regular oscillations, spin combustion and combustion with regular longitudinal oscillations.

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, a thermally thin model system of 'liquid fuel film on a metallic substrate' is considered. This system is also a model for studying flame propagation in an inert porous media wetted with fuel [1-3]. The goal of this investigation is to reveal flame spread regimes in the above system for various spatial orientations.

EXPERIMENTAL

The experiments were performed in air at atmospheric pressure and room temperature. Two types of metallic substrates were employed. These comprised two copper foil strips, one of 45

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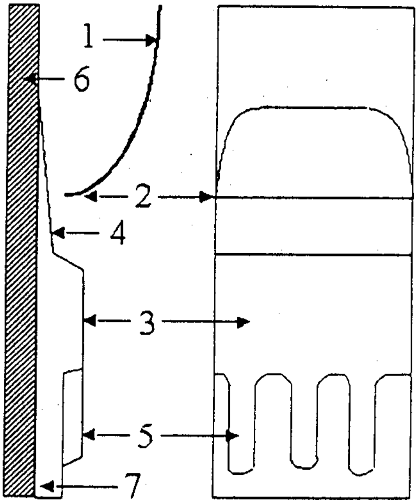
µm thickness and 4 cm width and another of 60 µm thickness and 17.5 cm width, termed thin (narrow) and thick (wide) foils. Liquid fuel films n-undecane, ethanol, dielectric oil, n-butanol, and dibutilphtalate of 7, 6, 12, 7, 12 µm thickness, respectively, were formed on the substrates. Videotape recordings enabled flame spreading rates and oscillation frequencies to be obtained. A sketch of the steady-state flame spread process is shown in Fig. 1, for the case of flame spreading from the top down over the fuel film on one surface of the foil (one-sided flame). 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 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 two conditions emerge: a steady-state low combustion rate regime and a non-steady combustion regime with longitudinal oscillations.



(a) (b)

Figure 1. Combustion wave structure. a) side view, b) front view, 1 – flame front, 2 – front edge, 3 – boss of fuel film, 4 – vanishing fuel region, 5 – fuel "fingers", 6 – substrate, 7 – fuel film.

The experiments with downward flame propagation showed that a steady-state regime formed after an initial non-steady period. The further flame spreading 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. The characteristic features of the flame structure (Fig. 1) are: flame front (1) with an edge (2), a "boss" of liquid fuel ahead of the flame edge (3), a vanishing fuel region (4) and "fingers" of fuel ahead of the boss. The flame edge is a straight line normal to the parallel sides of the substrate. Ahead of the edge there is a bulge of fuel film, the "boss" (3) of 10 to 15 mm length. Ahead of the boss is a zone of streaming with an uneven forward edge in the form of "fingers" of ~50 mm length and of ~5 to 7 mm width (5). Behind the flame edge under the luminescence zone there is a vanishing fuel region (4) of 1 to 10 mm in length.

STEADY-STATE REGIMES OF FLAME SPREADING

Free Convection Regime

Fig. 2 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. 2, 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.

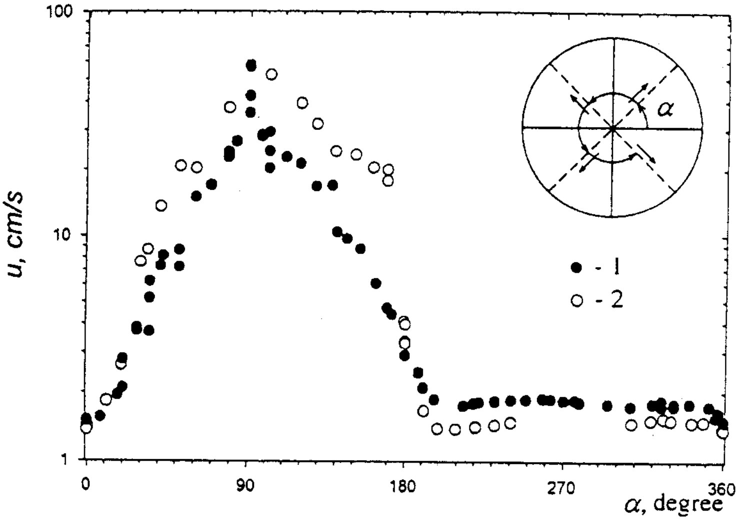


Figure 2. Dependence of flame spread rate *u* on inclination angle *α* of foil plane relative to horizontal. One-side flame. Systems: copper foil – n-undecane. 1-foil thickness 45 μm, width 4 cm; 2 – foil thickness 60 μm, width 17.5 cm.

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 Fig. 2 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. When spreading downwards, the rate of flame spread 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 [4] 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.

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 vapour and air. This occurs at temperatures above the "flash" temperature, namely, above the lower temperature limit [5]. This phenomenon is connected with the possibility of generating combustible mixture over the fuel surface before the flame spreading. The generation of combustible mixture depends only on the temperature and pressure of the ambient gas and it is independent of the thermo-physical properties of the liquid and the substrate. One can expect such a combustion regime can also exist in the "liquid on metallic substrate" system. Indeed this regime was observed in 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 that of a laminar flame it may be termed a high rate conductive regime. At the same conditions, but at a vertical foil, the low rate conductive regime is implemented with flame spreading downward at a rate of 4.5 cm/s.

Thus three regimes exist of steady-state flame spreading over a liquid fuel film on metallic substrates. They are low rate, high rate and free convective regimes.

OSCILLATION REGIMES OF FLAME SPREADING

Together with the steady-state regimes four oscillation regimes observed corresponding to two oscillation processes for flame spreading over a fuel film on a metallic substrate, namely, the transverse and longitudinal oscillations of the flame front. These combustion regimes are transverse chaotic oscillation, transverse regular oscillation, spin combustion and a regime of longitudinal oscillations of the flame front.

The Longitudinal Oscillation Regime

The longitudinal oscillation of the flame front occurs when oscillations of the flame front occur along the foil strip in the direction of spread of normally steady-state flames. If there are different fuels on the foil surfaces then two cases are possible, namely, a steady low rate regime or a longitudinal oscillation regime. In the first case the flame spreading over high-boiling fuel is behind the flame of volatile fuel. For example, in the system of n-undecane-dibutilphtalate on copper substrate of 45 μm thickness, the combustion wave spreads in the low steady-state rate regime with the steady rate, 2 cm/s, and dibutilphtalat flame is 5 mm behind the leading flame.

The longitudinal oscillation 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. Fig. 3 shows serial frames of the videotape recording (frequency 25 Hz) in this regime. The tests were on copper foil with surfaces deposits of n-undecane and dielectric oil. The average combustion wave spreading rate was 2 cm/s and the frequency of oscillations measured by a photodiode was 10 Hz. Two periods of oscillations are presented in Fig. 3. The frame frequency is close to an oscillation one but it is not a multiple one. Recordings are of the dielectric oil side. The flame is represented by the white colour and spreads downward, with increase in time from left to right.

The leading n-undecane flame, by heating the foil, gives rise to evaporation of the low volatile fuel film (dielectric oil) and of combustible mixture which burns out rapidly in the high rate regime. Thereafter the intensity of combustion becomes weaker until, after formation of a fresh combustible mixture the process is repeated. The first frame in Fig. 3 records the last stage of the passive phase (afterburning). Between the first and second frames a high rate of flame spread occurs along the foil. Frames 2-4 record afterburning of the mixture or afterglow and cooling of the products. Thereafter the process is repeated. 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. This is the part of flame oscillation when the prepared vapour-air mixture of dielectric oil – air is burning out in the high rate regime. Then extinction of the front of the flame occurs and preparation of a new combustible mixture begins.

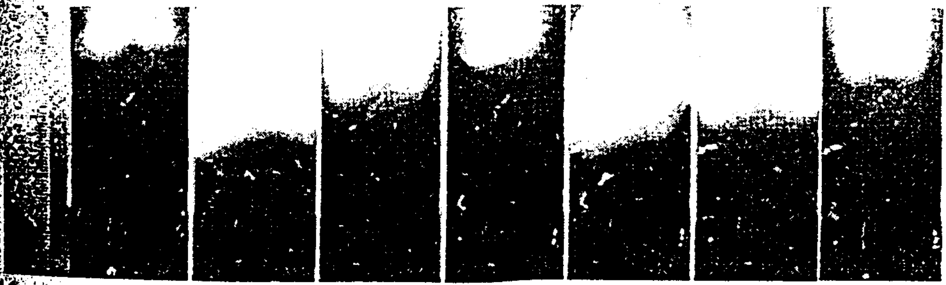


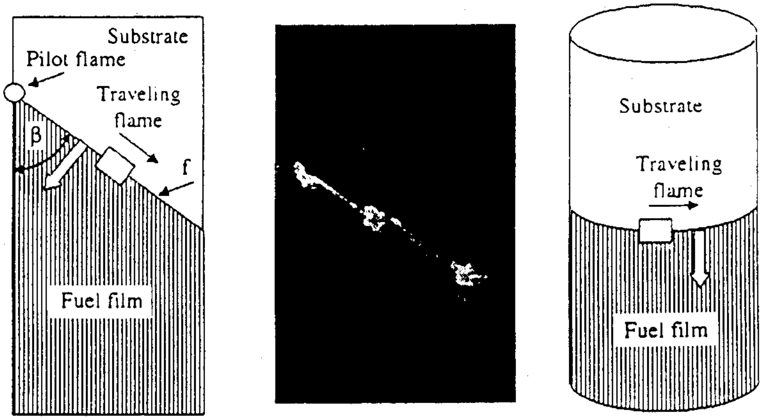
Figure 3. Frame by frame longitudinal flame oscillation. Frame frequency 25 Hz, substrate – copper of 45 μm thickness, fuels – n-undecane and dielectric oil.

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 oscillating combustion strictly downward was impossible. By tilting the foil plane one could attain conditions in which steady-state longitudinal (along the foil strip with a spreading rate of 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.

Transverse Regular Oscillation Regime (TRO)

This regime is observed on thick copper foil at α=270°. It is seen from Fig. 2 that these experimental conditions lie beyond the flammability limits. Steady-state flame spreading is impossible here. However, nonsteady combustion is possible under these conditions when the ignition takes place along the line *f* and the angle β is acute (Fig.4a). Over the greater part of the line *f* condition lay outside the flammability limits. However, in the region where the flame front forms an acute angle with the strip edge, the flame continues to exist locally. From this point, that acts as an ignition source, the flame spots segregate periodically and move away along the line *f* (Fig.4b). During the flame spot movement heat is released and the foil and fuel are warmed up. Thereafter a mixture of vapour with air is generated which is able to support flame spreading. At the same time several flame spots, moving in tandem, are observed. Fig. 4b shows three moving flame spots.



(a) (b) (c)

Figure 4. a, c – Schemes of regular oscillations and spin flame spread regimes, b – video-frame of regular oscillations flame, copper foil of 60 μm thickness and 17.5 cm width, n-undecane film.

Irregularities in this case arise from the fact that at an acute angle the film is burning out sooner than in the rest of the region along the line *f*. Therefore the angle β will permanently increase until the flame quenches at some its value. The value of β (Fig. 4a) at which the flame quenches depends on how far the conditions are the limiting ones. For the copper foil of 60 μm thickness and n-undecane film the limiting angle β is 66°. An average rate of longitudinal propagation of the ignition point is 1.5 cm/s. The rate of combustion spot travel along the line *f* is about 100 cm/s. Along with the fact that propagation of the ignition point was nonsteady, because its rate have gradually to decrease, a magnitude of this rate of descent is negligible. For conditions which are far from the ignition point most of the time, one can consider them to be steady-state. This ensures regularity of the regime. If the conditions are not limiting ones, then the flame propagates until the flame front line becomes perpendicular to the foil strip edges. Far from the limiting conditions the oscillation regime cannot be established. When the foil strip is wide enough then several combustion spots can simultaneously spread. This is clearly seen in the video frame shown in Fig. 4b. Combustion spots follow each other from the vertex of an acute angle with close interval between them.

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 160 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.

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 flame propagation, that includes conductive and diffusive gas phase processes of 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. 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. 2) on thick foil. The mechanism of its onset may be conceived as the next (Fig. 5). Due to fluctuations of the system parameters (changing of foil curvature, fuel film thickness etc.) there is failure of combustion at the site (ab) of the element (1) of the flame. Since the metallic substrate is heated some time later close to this site combustible mixture will be generated as a result of evaporation and mixing of vapour with air. At the flame edges at the points (a) and (b), ignition of the mixture occurs. Flame spots travel towards each other (3)-(4). After the stage of afterburning, cooling and generation of new mixture (4)-(5) the process is repeated (5)-(6). The rate of travel of combustion spots along the site (ab) is about 70 cm/s. 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. Combustion spots in points (a) and (b) can start either simultaneously or non-simultaneously. The multiplicity and variety of these schemes can create a picture of a chaotic character.

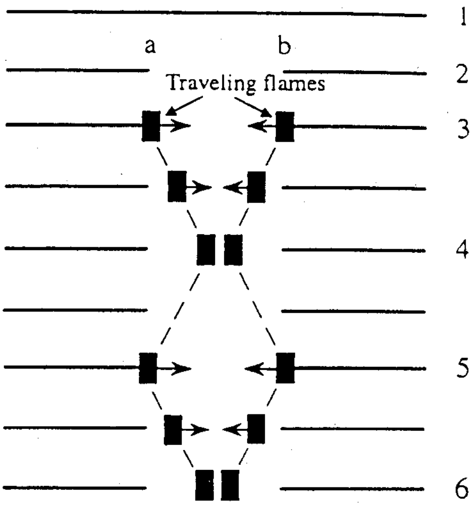


Figure 5. Formation of chaotic oscillations. Lines 1-6 – stages of the flame evolution. The site (a – b) – failure of combustion.

The transverse regular oscillations regime (TRO), in terms of the mechanism of flame spreading, is not in principle different from the TCO one. The difference was only in the ignition point. In the TCO regime there are many ignition points and they appear randomly; in the TRO regime the single ignition point has specific properties. It was relatively stable and nonsteady. At its artificial creation as vertex of angle we use the stabilising property of thermal diffusivity at the front of curved flame. The flame velocity at a convex (towards the spreading direction) site lower than in concave one. Analogously the flame spreading rate at an acute border angle (the angle between substrate strip edge and flame front edge) is higher than that at right or obtuse angles [4]. As a result of this effect the initially curved or indirect flame in due course becomes straight and occupies a position perpendicular to the substrate strip edges. Since the steady-state flame is impossible as the conditions are out of the limit ones the transverse regular oscillations regime at a certain angle ceases to exist. The flame smoothing process occurs slowly in comparison with the time of flame spot travel. Therefore oscillations in this combustion regime are regular. Though TRO is investigated with an artificial ignition point, there is no doubt such a regime can be spontaneously implemented at some conditions.

On the mechanism of combustion spot spreading, spin combustion is no different from the above described oscillation processes of spot travel in HR. The difference lies only in the uninterrupted trajectory at which the combustible mixture is able to support a combustion spot. One or several combustion spots travel along a circular helix by burning some fuel in each revolution. At each turn combustion is uninterrupted and hence an external source of ignition is not required.

As far as the longitudinal oscillation regime (LO) is concerned its peculiarity consists in the oscillatory flame travel in the same direction as the leading flame of n-undecane. It is interesting to note that the whole flame does not oscillate, but only its leading part. The rear part travels slowly, without oscillation. Tongues of flame of dielectric oil are thrown out from the main flame and then die out (Fig. 3). Based on the order of the value of the rate of flame tongue forward travel it may be assumed that the mechanism of oscillatory spreading corresponds to HR. The rear part of the flame acts as an incessant ignition source. On the same grounds one may assume that this sustained flame part spreads in LR. In other words in one flame two of its parts spread into different regimes. The leading part spreads into HR, the rear one into LR.

Thus the mechanisms 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 all oscillation regimes the conditions are outside the LR regime limits. For TCO and TRO regimes there are ways of improving of local combustion conditions for a flame spreading in the LR regime, and for spin regime there are conditions for HR ahead of the combustion spot. In all these regimes the heat of previously burnt fuel uses in combustion on following stages with a delay. Combustion spot at oscillation travel in TCO and TRO utilises the heat of previous oscillations. The combustion spot in the spin regime utilises the heat accumulated in the substrate of combustion spots at previous pitches (at one-head spin). Flame tongues at longitudinal oscillations utilise the heat of the leading flame of n-undecane and previous oscillations of dielectric oil flame.

It is seen from the Fig. 2 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 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 via 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", resulting ultimately 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.

In spite of the great variety of steady and nonsteady-state combustion regimes, flame structures and limit phenomena there are seemingly two mechanisms of flame spreading. The low rate regime mechanism is determined mainly by the heat conductivity through the substrate. The mechanism of high rate regime is closed to the mechanism of propagation of premixed flames. These regimes can exist either separately or simultaneously creating different oscillation modes of combustion.

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