

FIRE SAFETY ON FUEL CONTAINERS

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Fire safety on fuel containers can be improved at its initial stage if flame spreading can be controlled. Therefore, the understanding of the fundamental processes that control flame spreading will help us to determine a few control parameters that could be useful to improve security in fuel deposits. A series of experiments have been conducted in different fuel containers that helped to understand the basic mechanisms involved. A new phenomenon of convection ahead of the flame is observed in liquid fuels that do not appear in solid fuels. Finally, two control factors have been found useful to control fire spread: the initial fuel surface temperature and the convection zone observed in front of the flame. The first experimental results observed controlling these two factors led flame to spreading velocities of order 1 cm s^{-1} and, in some cases, flame extinguishes.

Keywords: *combustion, fire safety, flame spreading, liquid fuel*

Introduction

Fire safety on fuel containers depends on the control of the flame spreading in the very beginning of the fire progress right after ignition. The control of the flame progression at this initial stage is therefore the most important factor that can help us to prevent fire propagation in a fuel container, since it will provide time enough to activate the whole extinction system. Even more, the understanding of the basic mechanisms underlying flame spreading over liquid fuels will help us to control its advance. By understanding these mechanisms, we should be able to create technical conditions that will make difficult, even impossible, the ignition process. The purpose of our work is to contribute to this understanding of this phenomenon, and to find the basic control parameters of flame propagation in the initial period as well.

Flame spreading over liquid fuels is a combustion problem [1]. It is a complex system, where many interrelated factors are involved. The complete set of equations involved in the process is too intricate to help us in our research. Even though some numerical codes have been developed they correspond to simplified situations. In any case, they do not provide information of the basic mechanisms involved. Furthermore, it has been found that there is a coupling between the gas phase (where combustion occurs) and the liquid phase, where complex thermocapillary convection near the flame is observed. This coupling of these two factors is unsteady and highly non linear, that lead our system to a chaotic behaviour. It has also

been observed that flame is not located on the surface of the liquid, but at some quenching distance (d_q) above it. Some qualitative results indicate that (d_q) is inversely proportional to the flame velocity (v_f): instead of a two-layer problem (liquid-phase-gas phase) we really should have three layers to be taken in account in our analysis (gas phase-quenching zone-liquid phase). Even the flame structure (known as a ‘triple flame’) is still now the object of some discussion and controversy.

Experimental results in a long channel

In order to understand the basic mechanisms involved in the process, a series of experiments have been performed in our laboratories, that give a general overview of flame spreading, considered as a one dimensional problem (more details of the experimental setup can be found in [2]). A long, wide channel is filled with liquid fuel; it is ignited at one side, and flame propagates through the channel to the other side. The temperature evolution at the liquid surface is registered. Also, during the ignition process a camera records the flame front evolution (x_f), that can be plotted as a function of the initial fuel surface temperature (T_∞). By a simple numerical derivation, flame velocity profile (v_f) can be obtained. For a given value of (T_∞) we can record the minimum flame spreading velocity (v_{fmin}) and the maximum spreading velocity (v_{fmax}). Finally, by plotting (v_{fmin} , v_{fmax}) as a function of (T_∞) bifurcation diagram is obtained. The principal results are shown in Figs 1 and 2. They correspond to propanol in a 40 cm long, 2.5 cm

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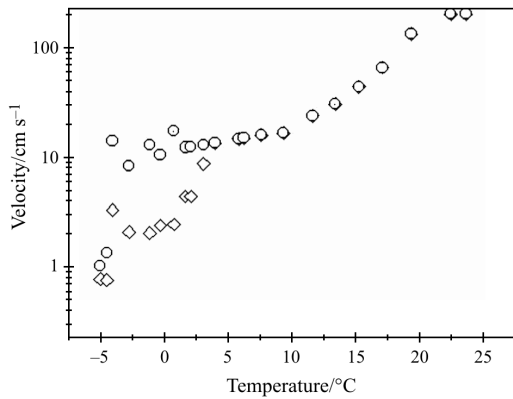


Fig. 1 Bifurcation diagram (propanol, in a 40 cm long channel)

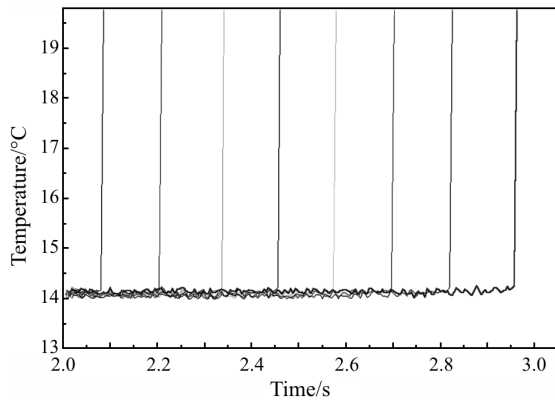


Fig. 2 Temperature evolution corresponding to region II (propanol, 40 cm channel). The eight curves are obtained at eight different surface points

wide and 3 cm deep channel. Similar results have been found for different fuels and channel configurations. Five different regions can be observed:

- For $T_\infty \geq T_1$, flame spreading is uniform and nearly constant, with flame velocities of order 100 cm s^{-1} (uniform regime-I).
- For $T_1 \leq T_\infty \leq T_2$, flame spreading is uniform, but the slope of the $(T_\infty - v_f)$ diagram is of order $10.0 \text{ cm s}^{-1} \text{ }^\circ\text{C}^{-1}$ (uniform regime-II).
- For $T_2 \leq T_\infty \leq T_3$, flame spreading is uniform, but in this case the slope of the $(T_\infty - v_f)$ diagram is of order $1.0 \text{ cm}^{-1} \text{ s}^{-1} \text{ }^\circ\text{C}^{-1}$ (uniform regime-III).
- For $T_4 \leq T_\infty \leq T_3$, flame spreading velocity is pulsating; the oscillation characteristic period of (v_f) diverges for $T_\infty = T_4$ (pulsating regime-IV).
- For $(T_\infty \leq T_4)$, flame spreading is uniform, but in this case flame velocity is almost constant, of order 1.0 cm s^{-1} (pseudo uniform regime-V).

The critical temperatures T_1 , T_2 , T_3 and T_4 have been characterized considering flame spreading as a non-linear system: T_1 corresponds to a steady bifurcation, T_2 is a transcritical bifurcation, while T_3 is a Hopf bifurcation (sub-critical) and T_4 fits with a homoclinic connection.

Preheated region

Flame front is located above the liquid surface at some characteristic distance (d_q). Due to the presence of this heat source, temperature gradients are induced, both in the liquid fuel and in the gas phase. The temperature gradients in the gas phase are of order $(T_f - T_\infty)$ being (T_f) the local flame temperature, and (T_∞) the initial fuel surface temperature. On the other side, the gradients are of order $(T_b - T_\infty)$ in the liquid phase, where (T_b) corresponds to the fuel boiling temperature. As a consequence of this phenomenon, surface tension gradients are produced, that move hot liquid beneath the flame front at some characteristic velocity u_s ; when $u_s \geq v_f$, the preheated region surpasses the flame front position and a vortex is observed; when $u_s \leq v_f$, no vortex is observed, and flame spreads as if in the solid case. An approximated value of the horizontal dimension (L) of the vortex can be done using our thermocouple records. Three different plots are shown here.

Figure 2 shows the temporal evolution of the surface temperature in region II recorded for 8 surface points equally spaced, where no preheated region is observed (that is, when $(u_s \leq v_f)$). Figure 3 corresponds to the pulsating region, where a well developed vortex appears. Finally, Fig. 4 depicts the corresponding profile in the pseudouniform region. As we can see, the preheating of the liquid starts approximately 14 s before the flame arrival. In this case, flame velocity is of order 1.0 cm s^{-1} (or even lower) so the approximated horizontal length of the vortex should be close to 14 cm. The vertical dimension of the thermocapillary induced region is of order 1.0 cm, it has been observed that it never exceeds 1.5 cm.

In spite of the limited accuracy of the thermocouples technique, we can affirm that no preheating region has been observed in regions I or II. A small preheating region has been detected in region III that never exceeds 1 cm: for $T_\infty \approx T_3$ L is close to 1 cm, and it vanishes for $T_\infty \approx T_2$.

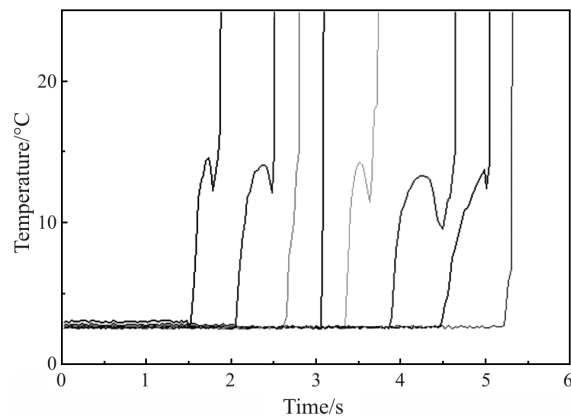


Fig. 3 Temperature evolution corresponding to region IV (propanol, 40 cm long channel)

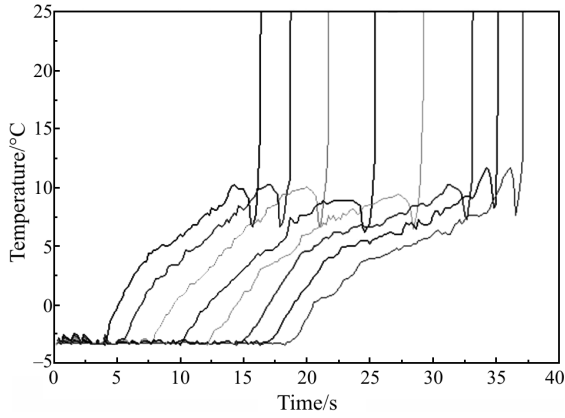


Fig. 4 Temperature evolution corresponding to region V (propanol, 40 cm long channel)

A bigger vortex (of order 10 cm) is observed in region IV while, in region V, the characteristic size L is almost constant, close to 15.0 cm. The assistance effect of the preheated region, which starts for $T_\infty \approx T_2$ (where $u_s \approx v_f$) provides an extra amount of fuel to the gas phase, that accelerates flame spreading. This assistance effect becomes unsteady for $T_\infty \approx T_3$, where an oscillatory mechanism of characteristic period P is observed. A first approximation to this mechanism has been proposed in [3] that correlate really well with our experimental data. Finally, the oscillation period diverges for $T_\infty \approx T_4$, the oscillation mechanism can not occur anymore, and a slow motion is then observed.

Solid like regime

For values of T_∞ corresponding to regions I–II a solid-like model of propagation can be applied. If we do a heat and momentum balance between the gas phase and the liquid but considered as a solid-like fuel, we find that the following relation between the flame velocity (v_f) and the initial fuel surface temperature is obtained:

$$v_f \propto \frac{T_\infty^{1/6}}{T_\infty^{1/2}} \frac{1}{(T_b - T_\infty)^2} = \frac{1}{T_\infty^{1/3} (T_b - T_\infty)^2}$$

This relation fits well with our experimental data as it can be seen in Fig. 5 (for a more detailed explanation see for instance [4, 5]). The results correspond to four different alcohols. The experimental results are plotted using dimensionless variables in order to include all our data in the same graphic. The variables used in this case are

$$\left(v_f \cdot \frac{1}{T_\infty^{1/3} (T_b - T_\infty)^2} \right)$$

The perfect linear relation between the variables should correspond to the dashed line. As it can be easily seen, the correlation coefficient is very high, close

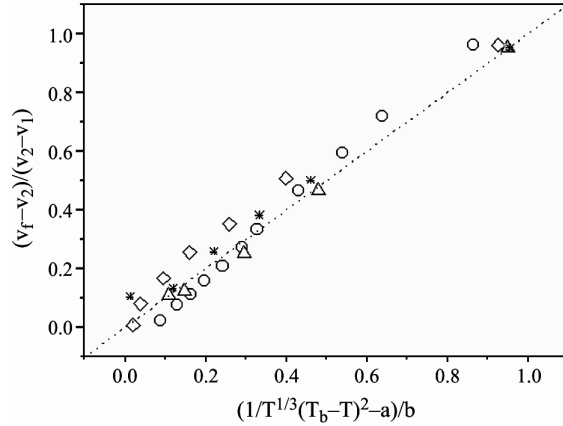


Fig. 5 Experimental results in region II for four different alcohols (o – methanol, \diamond – ethanol, Δ – propanol and * – butanol)

to 0.96. Therefore, we can assume that, for $T_\infty \geq T_2$ flame behaves like a solid, even though it is a liquid: in this range of temperatures, no difference is observed between a liquid fuel and a solid fuel with the same thermodynamic parameters. But, for lower values of T_∞ (that is, for $T_\infty \leq T_2$), a preheated region is experimentally observed, that modifies dramatically heat and momentum transfer. This fact is experimentally observed for $T_\infty \approx T_2$ where the derivative of the $(T_\infty - v_f)$ diagram varies from 10.0 to 1.0 $\text{cm s}^{-1} \text{ } ^\circ\text{C}^{-1}$, that is, an abrupt variation in the $(T_\infty - v_f)$ diagram is observed. The assistance effect of the preheated vortex gives an extra amount of fuel and, by increasing the fuel vapour pressure the flame velocity is augmented, compared to the solid case.

The control of this assistance mechanism that is observed in the liquid case for $T_\infty \leq T_2$ is fully applicable to fire safety, and it will play a major role in flame spreading control as we will see. For a wide range of fuel containers, the ignition process usually starts at some temperature located in region II, where flame velocities are (for propanol) of order 20 cm s^{-1} . This magnitude of flame velocity does not provide time enough to any security system to activate extinction systems effectively; a lower value of (v_f) is required. In order to slow down flame velocity, two control factors can be applied.

The first control parameter is the initial fuel surface temperature (T_∞); by simply reducing this value with an appropriate cooling system, we can drive flame front to region IV or V, where flame velocities are close to 1 cm s^{-1} . In the case of propanol, this temperature gap will correspond to approximately 10°C. By cooling the system we can obtain flame velocities of order 1–2 cm s^{-1} that will enable us to activate any fire extinction system in a reasonable amount of time. We can even think in reducing periodically the fuel surface temperature, so that we only need a smaller temperature decrease in the case of a fire formation. This tech-

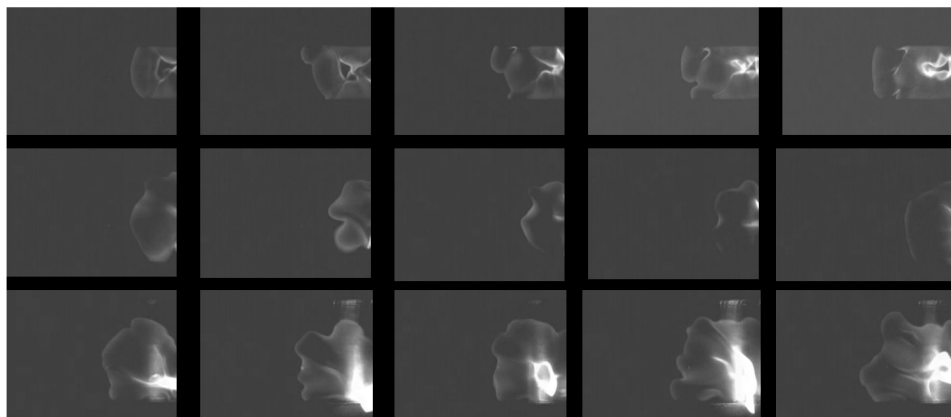


Fig. 6 Flame front evolution for 3 different fuels (first row: ethanol, second row: propanol, third row: butanol)

nique will simultaneously reduce the temperature gap and probability of fire inflammation. Fire can be easily produced for $T_{\infty} \geq T_2$ by almost any kind of heat source. It is much more difficult to produce a fire below T_2 which is a temperature close to the well known flash-point temperature of the liquid T_f .

The second factor that will contribute to reduce flame velocity is the control of the formation of the preheated convection zone. By controlling the formation of the convection zone, flame spreading will follow the solid-like model instead of the liquid profile in the $(T_{\infty}-v_f)$ diagram. The formation of the thermo-capillary vortex is restricted to a very thin zone, close to the liquid surface. The extent of this vertical zone never exceeds 1.5 cm, so it will be relatively easy in the future to create a mechanical system that will prevent the vortex formation. In this hypothesis a lower temperature decrease gap of the temperature is required. In the case of propanol we can estimate that a surface temperature decrease lower than 5°C is necessary to obtain similar results. With the simultaneous action of these two factors (reducing liquid surface temperature and preventing the vortex formation) we obtain a temperature interval that should be relatively easy to obtain with some kind of cooling system, as we also reduce the probability of fire formation.

In order to verify this hypothesis, a preliminary experiment has been done. A small fuel container (30 cm long, 10 cm wide and 3 cm deep) has been filled with three different fuels (ethanol, propanol and butanol). A cooling system has been constructed under the container, so we can control its surface temperature that can be kept uniform at the horizontal. By installing equally spaced metallic walls we can prevent the vortex formation. The first results are shown in Fig. 6. They correspond to ethanol (first line), propanol (second line), and butanol (third line). The time interval between two images is $\Delta t = 0.133$ s. As we can see clearly, even though flame spreads, it does very slowly; flame velocities are of order $1\text{--}2$ cm s^{-1} .

Flame front exhibits a complex pulsating behaviour; a complete description of its structure should be the subject of future work. Even though these experimental results are a preliminary test, they confirm that the simultaneous control of these two factors can be successfully applied to increase fire safety.

Conclusions

The role of the preheating region observed ahead of the flame front has been shown here, and a solid-like model has been presented for liquid fuels, that correlate very well with our experimental data. Two different factors have been found to be useful to control fire spreading, and the first experimental results indicate that any security system will have to take them in account. Even though a complete flame spreading description is available in long (one-dimensional) channels, a complete description of the flame behaviour in a normal container must be done in the future. The technical design of safety systems that could reduce surface temperature and the vortex formation in a short period of time can also be the subject of future research.

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