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CONTROL PARAMETERS OF FLAME SPREADING IN A FUEL CONTAINER

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The processes involved in flame spreading over liquid fuels are subject of this work. A heat and momentum transfer analysis has been undertaken for fuel temperatures below the flash-point that confirms (within this range of temperatures studied in this work) that flame spreading is assisted by a convection pattern ahead of the flame. This assistance mechanism, which is not observed for solid fuels, is the origin (for lower temperatures) of a pulsating behaviour of the flame. A first experimental determination of the characteristic horizontal length of this assistance zone will be given. The analysis of our data lead us to conclude that flame spreading can be reduced by simultaneously preventing the formation of the convection zone and reducing the fuel surface temperature.

Keywords: *convection pattern, fire safety, flame spreading, liquid fuels*

Introduction

Even though flame propagation over liquid fuel is a well known phenomenon, the basic mechanisms involved are still now subject of some controversy. It is well known that, for initial fuel surface temperatures above the flash-point, flame spreading is similar to the solid case. But, for values below the flashpoint temperature, an assistance effect, due to the appearance of a preheating zone ahead of the flame is observed. This vortex modifies the fuel vapor pressure in the gas phase and, therefore, modifies its spreading velocity. Using a thermocouple technique, we can estimate the characteristic length of this vortex. The purpose of this work is to shed some light to the problem. Section 2 will describe very briefly some experimental results obtained in our laboratories. Section 3 will analyse flame propagation velocity dependence for fuel temperatures below the flash point temperature of the fuel. Section 4 will show how the characteristic length of the vortex can be estimated using a thermocouple technique. Finally, a brief conclusion will be given.

Experimental

In order to measure the flame velocity over liquid fuels, a series of experiments have been conducted in different channel sizes, for four different fuels (more details can be found in [1–3]). A typical result is shown in Fig. 1. It corresponds to the plot of the flame spreading velocity as a function of the initial fuel surface temperature. For every value of the initial fuel surface temperature (T_∞) the minimum spreading velocity (represented by diamonds) and the maximum spreading velocity (represented by circles) are plotted. The liquid fuel used in this experiment corresponds to isopropanol, burning in a 40 cm long channel. Five different spreading zones can be found, separated by four critical temperatures T_1, T_2, T_3, T_4. For $T_\infty > T_1$ (region I) flame spreading is almost constant, of order 200 cm s^{-1}. For $T_2 < T_\infty < T_1$ (region II) flame velocity is uniform, and the slope of the $T_\infty - \nu_f$ diagram is of order 100 cm s^{-1} K^{-1}. For $T_3 < T_\infty < T_2$ (region III) flame spreading is still uniform, but in this case we found that the slope of the graphic is of order 1 cm s^{-1} K^{-1}. For lower temperatures $T_4 < T_\infty < T_3$ (region IV) a pulsating behaviour is observed. Finally, for very low temperatures $T_\infty < T_4$ (region V) flame spreading is again uniform and almost constant, with $\nu_f \approx 1$ cm s^{-1}.

Results and discussion

Our discussion will be centred for $T_3 < T_\infty < T_2$. The temperature T_2 is, for a given fuel, almost independent from the channel geometry. The value of this transition temperature is very close to the flash-point temperature of the fuel that corresponds to the limit value of T_∞ above which instantaneous combustion occurs if we approach a heat source to the fuel. Although the definition of this temperature corresponds to static conditions and the values of T_2 obtained in

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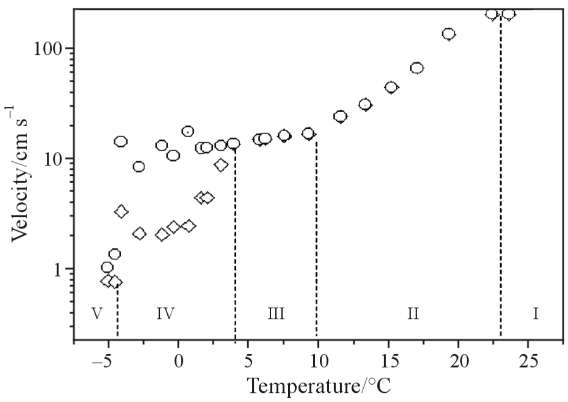

Fig. 1 Bifurcation diagram of propanol in a 40 cm long channel

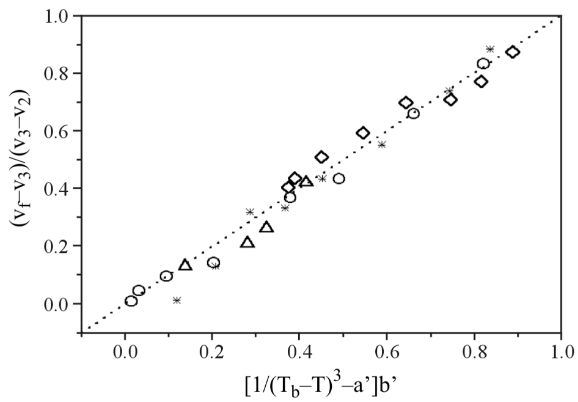

Fig. 2 Experimental results in the assisted region

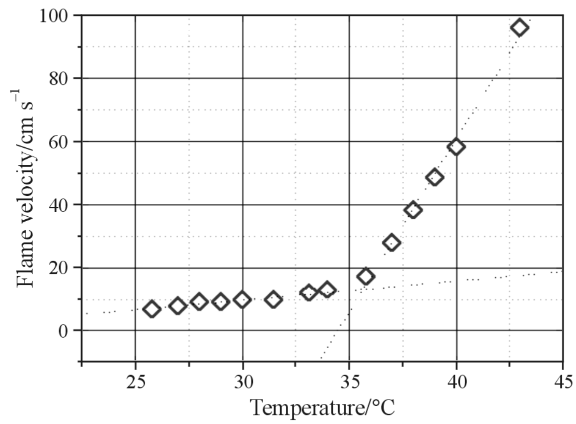

Fig. 3 Flame spreading velocity for $T_\infty \approx T_2$

our experiments correspond to a dynamic situation (a flame spreading over a liquid fuel), both have a similar meaning, they represent the temperature above which instantaneous combustion occurs when a heat source is close enough.

If we consider our system as a non linear system, we can characterize the critical temperatures T_1, T_2, T_3, T_4. T_1 corresponds to a stationary bifurcation, T_2 is a transcritical bifurcation, T_3 is a Hopf bifurcation and T_4 is a homoclinic connection. All fuels presented the same behaviour in all the geometries used in our experiments.

For $T_\infty > T_2$ (regions I–II) flame spreading exhibits a solid-like behaviour; if we consider a solid fuel with similar characteristics than those presented by our liquid fuel, we find that the T_∞–v_f dependence is identical to the experimental results obtained with liquid fuels. If we undertake a heat and momentum transfer between the gas phase and the solid-like fuel, we find [4, 5] that the theoretical T_∞–v_f dependency obtained in this region is:

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

Being T_b the fuel boiling temperature. But, for $T_\infty < T_2$ (region III) flame spreading over liquid fuels does not follow the solid-like model. As we will see later, a convective pattern ahead of the flame is observed, that modifies heat and momentum transfer conditions and the T_∞–v_f profile. If we take into account the vortex ahead of the flame, we find that the T_∞–v_f dependency should be of the following type:

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

This relation correlates very well with our experimental results in this region, as Fig. 2 shows. Figure 2 corresponds to the data obtained for four different alcohols, plotted using dimensionless variables, in order to include all the data in the same graphic between 0 and 1. The dotted line represents the ideal relation, given by the previous equation.

Two different slopes are found in the vicinity of T_2. As we can also see in Fig. 3, the slope of the graphic changes abruptly for $T_\infty \approx T_2$. For values above this critical value, the slope of the T_∞–v_f curve is of order 10 cm s^{-1} K^{-1}. But, for values below T_2, the order of magnitude of the slope turns to be of order 1 cm s^{-1} K^{-1}. Therefore $T_\infty = T_2$ is a transcritical bifurcation.

A preheated region ahead of the flame is observed in region III. Strong temperature gradients between the flame and the gas phase are observed, of order T_f–T_∞, being T_f the flame temperature. Similar gradients are observed in the liquid phase, of order T_b–T_∞. For that reason, a surface tension gradient appears in the liquid phase in the vicinity of the flame front. This gradient tends to move hot liquid ahead of the flame, producing an increasing of the fuel vapour pressure that finally leads to a higher flame velocity. Compared with the solid fuel case, flame spreading velocity is higher.

A characteristic velocity for the fuel moving in front of the flame has been evaluated with the following formula:

$$u_s = \frac{d\sigma}{dT_\infty} \frac{T_b - T_\infty}{2\sqrt{\rho\mu L}}$$

where σ is the surface tension, ρ the fuel density, μ its viscosity, and L the characteristic horizontal size of the preheated region. The characteristic value u_s can be evaluated experimentally. It has been found that:

- For $T_\infty < T_2$, $u_s < \nu_f$: the convection zone cannot advance flame front. No preheated region is observed ahead of the flame.
- For $T_\infty \approx T_2$, $u_s \approx \nu_f$, no preheated region is observed ahead of the flame.
- For $T_3 < T_\infty < T_2$, $u_s > \nu_f$: the convection zone advances flame front, being L its characteristic horizontal size.
- For $T_\infty < T_3$ this assistance effect through the liquid phase becomes unstable, producing a pulsating behaviour.

By using a thermocouple located close to the liquid surface, we can obtain a first estimate of the characteristic horizontal length L of the vortex. If a detectable increase in the fuel surface temperature is detected (compared to the initial fuel surface temperature) at some instant t_1, and the flame arrival at the thermocouple location occurs at some instant t_2, then the approximate value of L is given by:

$$L \approx \nu_f (t_2 - t_1)$$

A characteristic value of L is shown in Fig. 4. This case corresponds to the results obtained for ethanol in a 100 cm long channel using a thermocouple technique. No preheated region is observed in regions I–II, while, for $T_3 < T_\infty < T_2$ a small preheating region is observed. The characteristic size of the vortex is a decreasing function of T_∞, being L of the order of the flame thermal thickness ($L \approx 0.01$ cm) for $T_\infty \approx T_2$ and $L \approx 1$ cm for $T_\infty \approx T_3$. For $T_4 < T_\infty < T_3$ a bigger vortex is observed, whose characteristic size varies from 1 cm (for $T_\infty \approx T_3$) to 11 cm (for $T_\infty \approx T_4$). Finally, for $T_\infty > T_4$, L is almost constant, of order 15 cm.

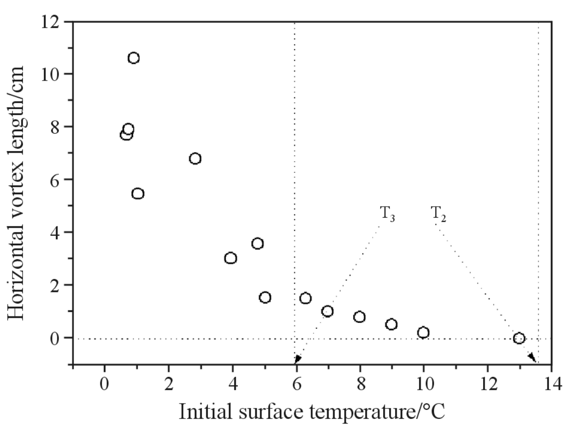

Fig. 4 Characteristic horizontal size of the preheated region ahead of the flame

The assistance effect increases flame spreading. If this convection pattern could be eliminated, flame spreading would be much smaller than the value ν_f observed experimentally. If, by preventing the vortex formation, we could additionally decrease the surface temperature to $T_\infty \approx T_2 - T_3$, then flame spreading velocity could be reduced to values of order 1 cm s^{-1}. This is an important point that can be applied in fire safety, since the time needed to activate the extinction system is of order 20–30 s, and the flame velocities observed initially during fire spread are of order 100–200 cm s^{-1}. In most of the cases, there is no practical time to detect a fire and proceed to its extinction. Additionally, by reducing T_∞ two or three degrees below T_2, the probability of a fire formation while approaching a heat source to the fuel surface is dramatically reduced and, simultaneously, the probability of extinction is increased.

Conclusions

An assisted model has been presented for liquid fuels (region III) that correlate very well with our experimental data for values of the temperature below the flash-point. The differences with the solid-like case (region IV) have been cleared, and the relevance of the transition temperature T_2 has been pointed out. Some factors that can be useful in fire safety have been noted. A future subject of research could be the technical design of safety systems that will take into account the factors mentioned.

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