Comparison of flame spread and blow-off extinction over vertical and horizontal PMMA samples

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Abstract
Flame spread in the kinetic regime and eventual extinction have been studied for more than four decades for the implications on fire safety and flame instabilities. It is well known that the ratio between the residence time and the combustion time at the leading edge, the so called Damköhler number, plays a fundamental role in the blow-off extinction of a spreading flame. However, the role of the boundary layer, which may significantly affect the residence time at the flame leading edge, on the blow-off extinction has not been thoroughly studied. In this work we present new experimental data on blow-off extinction of PMMA (polymethyl methacrylate) fuels and establish an empirical relation between the boundary layer development length and the extinction flow velocity. Using a vertical wind tunnel it has been possible to carry on a large number of experiments over thin PMMA samples, for an opposed flow velocity range from 0 cm/s up to 100 cm/s. Furthermore, it was possible to rotate the wind tunnel to obtain results with a horizontal configuration, reducing the effect of buoyancy on the flame spread. The experimental data reveal that the extinction length, the distance from the sample leading edge at which the blow-off extinction occurs, is directly related to the opposing flow velocity. Using a simplified scale analysis previously proved to be reliable, the blow-off extinction appeared to occur at a constant effective velocity (defined inside of the boundary layer). This conclusion can have important implications in the definition of the kinetic regime and the quantification of an extinction limit for thin fuels.

Key words: Flame spread, Flame extinction, Solid fuel, PMMA experiments

1. Introduction

Flame-spread in opposed-flow configuration has been studied by researchers all over the world for the last four decades for its importance in fire safety, ignition transients in solid propellants, and a basic understanding of combustion phenomena (Williams, 1976) (Wichman, 1992).

The opposed-flow approaching the flame is characterized by a component due to buoyancy and a possible forced flow. Buoyancy helps create a flow of oxidizer in the region close to the flame, helping the mixing of the reactants and therefore the combustion process. Because buoyancy is driven by gravity, a flame burning vertically from the top to the bottom is significantly affected by natural convection. When a flame is burning along a horizontal surface, however, buoyancy has a much smaller effect in the propagation direction. These considerations are particularly valid when natural convection is the main component of the oxidizer flow; introducing a forced flow, in fact, the relative importance of buoyancy gradually diminishes (Altenkirch, et al., 1980) (Fernandez-Pello, et al., 1981).

The opposing flow velocity is a fundamental aspect to define the flame behavior, because it is inversely proportional to the residence time, defined as the time spent by the oxidizer in the reacting region. Therefore, the ratio between the residence time and the combustion time varies accordingly with the flow velocity, since the combustion time can be considered constant in first approximation (Fernandez-Pello, et al., 1981). Even though in literature many definitions of the Damköhler number can be found, it usually represents the ratio of two different time scales, and in this work we refer to the ratio between the residence and combustion times.

Intuitively, extinction will occur when the residence time becomes comparable to the combustion time; in other words, for a critical value of the Damköhler number the flame will extinguish. We can thus define different regimes to
characterize the flame behavior: kinetic regime, typical of flames near extinction, where the residence time decreases and approaches the combustion time (so reaction kinetics becomes important) (Bhattacharjee, et al., 2015). In the kinetic regime, the flame is subject of local or eventually complete extinction. When the Damköhler number is much larger than one, variations in the free stream velocity do not really affect the flame propagation, that remains quite stationary; this is the case of the thermal regime (Bhattacharjee, et al., 2016).

Critical values of the Damköhler number vary significantly in the literature (Fernandez-Pello, et al., 1981) (Frey, et al., 1979) (Duh, et al., 1991), due to the different definitions and the large number of applications. Extinction criteria using Damköhler number (Williams, 1985), have been very important to define flammability maps, like the work of Lecoustre et al. (Lecoustre, et al., 2010), that takes into account different extinction limits associated to aerodynamic, thermal and dilution quenching. On the other side, Liñán et al. use the Damköhler number as a parameter to determine the structure and stability of diffusion jet flames (Liñán, et al., 2015), also on the basis of the previous work of Williams (Williams, 1971).

Many efforts have been spent to get accurate predictions of the spread rate in the kinetic regimes, and different ways to consider the opposing flow velocity in the problem were developed. In the thermal regime, Wichman introduced the effect of the velocity gradient seen by the flame leading edge for thick fuels (Wichman, 1983), and more recently West et al. (West, 1998) proposed an effective velocity inside the boundary layer to investigate the boundary layer effect on the spread rate. An effective velocity was described also by Bhattacharjee et al. using a scaling approach (Bhattacharjee, et al., 2014) and an empirical law (Carmignani et al., 2016), considering the gas phase length above the fuel surface introduced by Etoh et al. (Etoh, et al., 2003). Other models, i.e. simple slug-flows or Oseen approximation were used to describe the opposing flow velocity, but did not agree universally with the experimental results (Wichman, 1992). Since the boundary layer has been proven to be important in the flame propagation, at least in the kinetic regime (Bhattacharjee, et al., 2015) (Fernandez-Pello, et al., 1981), it is reasonable to believe that it plays a role also in the extinction phenomenon. The development length (distance of the flame leading edge from the beginning of the sample) and the oxidizer velocity then become fundamental for the problem description, and accurate experimental studies on the extinction velocities and the related extinction lengths can help improving the computational models of the phenomenon (Wichman, 1992) (Frey, et al., 1979). Even though a dependence of the flow velocity at extinction and the distance between the flame and the sample leading edge was noticed few decades ago by Fernandez-Pello (Fernandez-Pello, et al., 1981), it is hard to find experimental data in literature mentioning that.

The experimental results presented in this work were carried on with a wind tunnel built following the original design of Hirano (Hirano, 1978), which is particularly useful for low flow velocities (in the range of 0-100 cm/s). To investigate the importance of boundary layer and natural flow on flame extinction, we consider two experimental configurations: vertical and horizontal (indicated in the graphs with A90 and A0 respectively).

Flames burning vertically are symmetrical with respect to the fuel, while in the horizontal configuration it is necessary a forced flow to cancel the effect of natural convection, the latter being on the order of 30 cm/s for flames long about 2-3 cm (Liñán, et al., 2015).

Using thin sheets of PMMA as fuel, we were able to neglect the flame propagation in the direction orthogonal to the fuel surface and consider just the spread along that.

Extinction lengths (development lengths at which extinction occurred) were obtained by processing pictures of the unburnt samples, while with a Matlab code it is possible to get the spread rates processing the experiment videos (Carmignani, 2015). The extinction lengths were shown to be experimentally repeatable and with a clear proportionality to the flow velocity at extinction. A correlation between the two is established from experimental results, following our previous work for cellulose (Bhattacharjee, et al., 2015).

2. Experimental set-up: the Flame Tunnel

The vertical-flow tunnel or Flame Tunnel creates a controlled laminar flow over a sample thanks to four computer fans placed at the bottom. The bottom of the tunnel is squared base (20x20 cm) and blends down to a square duct of 10x10 cm at the top, where the sample will burn. The total height is about 70 cm, as shown on the left of Fig. 1. Since the fans generate a non-uniform flow a double layer of honeycomb (with a total thickness of about 35 mm), so called laminarizer, was put inside the bottom part and supported by four T-shape holders very close to the tunnel walls (Carmignani, 2015). Obviously, this device does not make the flow completely laminar, but since the interaction between
The fans velocity is regulated by the MCU connected to a computer running the Matlab code. Thanks to a Graphical User Interface (GUI), the tunnel is controlled in a very simple way, where the user can decide the fans speed and monitor the flow velocity (and the RTD readings). MCU controls each fan separately using the pulse width modulation (PWM) method, where one PWM pin was assigned to each fan. The working principle of PWM is based on turning on and off the pin (either 0 or 5 V) very quickly with an adjustable duty cycle. With 256 settings total, starting from 0 (always off) up to 255 (always on), it is possible to obtain intermediate duty cycles, determining how long the pin stays on each state. Each pin is powered by a 12 V external power source since the MCU would not produce enough power.

The RTDs output is amplified and then collected by the MCU, which converts the voltage in a number between 0 and 1023 (ten bit resolution), and the value corresponds to a velocity through the equation obtained with the calibration. This velocity was obtained through the calibration of the Flame Tunnel using a calibrated anemometer at the sample holder leading edge and taking RTD output reading (Carmignani, et al., 2015). In this way, an equation related to a best-fit line between the RTD readings and anemometer values was plugged into the Matlab code controlling the MCU. The calibration is very accurate in the range between 0 and 100 cm/s, particularly useful to study low flow interactions of the flame with the free stream.

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An important feature of the Flame Tunnel is the possibility to rotate it with the help of a steel structure. This allow us to carry on experiments with different angles respect to the vertical direction, as shown in Fig. 2.

The flow interactions inside the tunnel were also modeled in the flow and the sample (placed in the upper part) occurs at very low velocity, the boundary layer over the sample will be laminar (the maximum Reynolds number is on the order of 12000). The magnitude of the flow velocity is computed in Matlab thanks to the conversion of a voltage signal coming from two Resistance Temperature Detectors (RTD) flow sensors. In fact, the two RTD sensors (configuration 4, 100 Ω, platinum) are located right below the sample holder, and just one is actively heated. Connecting the RTDs in a Wheatstone bridge it was possible to compute the unknown resistance varying because of the convection associated with the flow. The voltage difference obtained in this way is amplified and sent to a microcontroller unit (MCU) to get a velocity as output. Thanks to the configuration with the Wheatstone bridge, the velocity inside the tunnel can be determined regardless of small changes in the room temperature. This velocity was obtained through the calibration of the Flame Tunnel using a calibrated anemometer at the sample holder leading edge and taking RTD output reading (Carmignani, et al., 2015). In this way, an equation related to a best-fit line between the RTD readings and anemometer values was plugged into the Matlab code controlling the MCU. The calibration is very accurate in the range between 0 and 100 cm/s, particularly useful to study low flow interactions of the flame with the free stream.

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SolidWorks and then imported in ANSYS fluent, where 2D flow simulations with second-order pressure and third-order momentum were performed using the SIMPLE algorithm. The result for the whole tunnel considering a bottom velocity of 40 cm/s is shown on the right of Fig.1.

The experiments are video-recorded and then analyzed with an image processor built for this purpose in Matlab and called Flame Analyzer. The spread rate of the flame is obtained by looking at the intensity values in the frames of the video that is being analyzed. After deciding an appropriate threshold for the intensity of the flame leading edge, the code tracks it on a frame-by-frame basis. The value of the flame spread rate is obtained as the slope of the location vs time curve of the flame. The uncertainty in the spread rate calculations through this method depends on the sample size, but five consecutive locations have been found to be a good compromise between noise and temporal precision and the error in spread rate has been found to be always within 5%.

After the instantaneous flame spread is obtained from the Flame Analyzer as a function of time, the spread rate can be plotted against the boundary layer development length as shown in Fig. 3 for the two orientations for an opposing flow of 70 cm/s for flame spread over 50 µm samples. The solid circles indicate blow off extinction in this figure. The spread rate can be seen to increase with an increase in the development length. The orientation does not seem to affect this trend much, except the flame extinguishes at a development distance of about 30 mm in the vertical case and 20 mm in the horizontal orientation. Clearly, boundary layer has an important effect on the flame spread. It should be noted that in literature only the average spread rate is reported.

3. Experimental data and discussion

In this work, data were obtained for samples of PMMA with a thickness of 50 µm. Samples have width of 20 mm and length of about 200 mm, and they burn in atmospheric air (oxygen concentration 20.9%) at ambient pressure (101 kPa) and room temperature (295 K). The opposing flow velocity range considered is from 0 cm/s (completely buoyancy controlled flow) up to 100 cm/s (forced flow controlled). While for the downward configuration it is possible to study the flame propagation for very low opposing velocities (in the range 0-20 cm/s), in the horizontal configuration the experiments start at relatively higher velocities, which are necessary to overpower buoyancy induced flow; in this way the flame is symmetric on the two sides of the sample. The angle of the configuration in considered to grow in anticlockwise direction starting from the horizontal axis in a laboratory reference frame, therefore it is zero for the horizontal configuration (A0) and 90º for the vertical configuration (A90).

It is helpful at this point to consider the vertical and horizontal configuration separately before making any comparison. For the purely downward configuration (zero forced flow), indicated as vertical in Fig. 3, the spread rate is...
The spread rate recorded to remain constant at about 4.7 mm/s. In this configuration, there is no dependence of spread rate on the flame location since the only flow affecting the flame is buoyancy induced, which is not affected by the length of the fuel sample. However, in the presence of a high forced flow, the spread rate is found to decrease monotonically when the flame moves toward the sample leading edge.

As shown in the sketch of Fig. 4, we expect the flame to encounter a stronger effective flow as the boundary layer created by the fuel sample becomes thinner during the spread of the flame. In experiment after experiment, we do observe this behavior. Moreover, the flame size also decreases and in some cases, the flame extinguishes before it reaches the end of the sample.

A large number of experiments are analyzed to explore the spread rate behavior with respect to opposing flow velocity $V_f$ and the development length of the boundary layer $x_d$ in the vertical and horizontal configuration. The spread rate typically changes with the development length as shown in Fig. 3, and an average spread rate can be calculated from the instantaneous velocity profile. The spread rate averaged over five repeated tests for each flow velocity are presented in Fig. 5 along with the uncertainties (standard deviation in the measured spread rate). The red symbols represent the horizontal orientation of the tunnel and the black symbols stand for the vertical configuration. Tests with opposed flow velocities less than 20 cm/s in the horizontal configuration are excluded from the plot because the flame turns asymmetric below this threshold. In the vertical configuration, we can see that the spread rate is not affected much by the forced flow for $V_f < 30$ cm/s. As the flow velocity is increased beyond this value, the average spread rate starts decreasing and at $V_f = 70$ cm/s the flame undergoes blow-off extinction before it reaches the end of the sample. Any flow velocity beyond this value results in blow-off extinction at progressively larger value of $x_d$. The filled symbols in Fig. 5 represents extinction somewhere along the boundary layer even though the average spread rate is finite.

The average spread rate exhibits quite similar behavior in the horizontal configuration, even though the numerical values are slightly different. The spread rate in the horizontal configuration is slightly lower than that in the vertical configuration at relatively low $V_f$ (less than 50 cm/s). However, at high opposing flow velocity the average spread rate is found to be higher in the horizontal configuration. Maybe the molten PMMA flow, which is different in the two orientations, is responsible for this behavior.

To establish that boundary layer has a similar effect on the spreading flame as does the opposing flow velocity, flame images from different locations along the boundary layer for a given flow velocity (75 cm/s) are compared with those at

![Fig. 4. Velocity gradient at different locations for same opposing velocity; the embedded flame will encounter a higher velocity close to the leading edge (considering the same height).](image)

![Fig. 5. Average spread rate over the entire distance of developing boundary layer for vertical (black) and horizontal (red) configurations.](image)
different flow velocities, but at a fixed value of \( x_f \) in Fig. 6 and 7 respectively. Although these images are from the vertical configuration, the images are quite similar in the horizontal orientation. As \( x_f \) decreases from about 15 cm to 4 cm, the flame front can be seen to become progressively thinner. The decreasing separation distance between the flames (over the same time interval) clearly indicates a flame that is slowing down. The visible color of the flame also turns blue as the flame nears blow-off extinction at \( x_f = 35 \text{ mm} \). When the flow velocity \( V_f \) is varying such as in Fig. 7, we see
similar behavior with the flame close to blow-off extinction at \( V = 100 \text{ cm/s}. \)

To explore the effect of orientation, flame images at the verge of blow-off extinction are compared for the two configurations in Fig. 8. As already stated, blow-off extinction can occur at different flow velocities based on the extend of the boundary layer ahead of the flame. At four different velocities for a given configuration, the flame shapes can be seen to be almost identical. The size of the flame, which should scale with the diffusion length and therefore vary inversely with the flow velocity, does not seem to depend on \( V \). This indicates that perhaps the flame sees an effective flow velocity \( V_{\text{eff}} \) near blow-off extinction that is constant. Different combinations of \( V \) and \( x_d \) must be responsible for producing this critical velocity resulting in a universal shape of the flame near blow-off extinction for a given configuration. It is also interesting to note the separation of the flame front from the pyrolysis front in the vertical orientation. This may be due to the molten PMMA being influenced by gravity in the vertical orientation. More experiments with non-melting fuel such as filter paper are necessary before this behavior can be attributed to melting alone.

4. Extinction velocity correlation

To explore the effect of the flame location on blow-off extinction, we define the extinction development length \( x_{d, \text{ext}} \) as the development length at which blow-off extinction is observed for a given flow velocity, which is called extinction flow velocity \( V_{g, \text{ext}} \). Extinction data usually carry large uncertainties, but the plot of \( x_{d, \text{ext}} \) against \( V_{g, \text{ext}} \) for both orientations in Fig. 9 clearly shows that as the flow velocity is increased, blow-off extinction occurs deeper into the boundary layer, that is, at higher values of \( x_{d, \text{ext}} \). Also, it is clear from Fig. 9 that for a given development length, extinction occurs at a lower flow velocity for the vertical orientation.

To build an empirical correlation between \( V_{g, \text{ext}} \) and \( x_{d, \text{ext}} \), the combination of which results in the experimentally observed blow-off extinction, we propose a power relation as follows:

\[
x_{d, \text{ext}} + a = b \cdot V_{g, \text{ext}}^m
\]  

For a purely flow induced extinction where the boundary layer is absent, that is, \( x_{d, \text{ext}} = 0 \), Eq. (1), simplifies to:

\[
V_{g, \text{ext}}^* = \sqrt[1-m]{\frac{a}{b}}
\]  

The value of \( V_{g, \text{ext}}^* \) represents a fundamental extinction flow velocity responsible for making the residence time small enough in comparison to chemical time to cause blow off extinction. If a critical Damköhler number is to be evaluated, it is this velocity, called the critical extinction velocity, which must be evaluated first.

To calculate the extinction lengths in each experiment, we isolated the unburnt area with ImageJ (Abramoff, et al., 2004), and divided it by the sample width. Using the experimental data gathered for PMMA, we obtain the values of the parameters \( a \), \( b \) and \( m \) in both vertical and horizontal configurations, which are listed in Table 1. The critical extinction velocity \( V_{g, \text{ext}}^* \) is estimated directly from the data as 55 cm/s for the horizontal configuration and 45 cm/s for the vertical orientation, while \( a \), \( b \) and \( m \) follow from simple algebra. The data points in the vertical configuration exhibit higher standard deviation, especially at high flow velocities, because of melting and “dripping” phenomena. The fact that the critical extinction velocity is slightly lower for the vertical orientation suggests that this dripping acts as a cooling mechanism (taking heat away from the leading edge). In other words, the dripping observed in the vertical orientation (see the second picture on the top of Fig. 8) makes the flame weaker. However, sometimes the molten PMMA can form little droplets that “help” the flame propagating in the downward direction, while in the horizontal configuration the droplets just fall on the Flame Tunnel wall. It is hard to determine the global effect of these small droplets.

### Table 1. Values of parameters found in eq. 1, obtained from the experimental data, expressing the velocity in m/s and the extinction length in m.

<table>
<thead>
<tr>
<th></th>
<th>A0</th>
<th>A90</th>
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<tbody>
<tr>
<td>( a )</td>
<td>1.27E-3</td>
<td>8.23E-4</td>
</tr>
<tr>
<td>( b )</td>
<td>0.116</td>
<td>0.388</td>
</tr>
<tr>
<td>( m )</td>
<td>7.547</td>
<td>7.712</td>
</tr>
<tr>
<td>( V_{g, \text{ext}}^* ) [m/s]</td>
<td>0.55</td>
<td>0.45</td>
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</table>
Using the values from Table 1, Eq. (1) is used to predict the behavior of $x_{d,ext}$ as a function of $V_{ext}$, as shown by the black and red lines in Fig. 9. Obviously, more data is required before a more generalized correlation can be found. However, the finding of a critical extinction flow velocity of about 50 cm/s should help develop better Damköhler number correlations for blow-off extinction.

From Fig. 9 we can see that Eq. (1) describes better the data points in the horizontal configuration rather than in the vertical one. As said before, the PMMA dripping causes uncertainty in the data points, which affects the parameters in Table 1. However, omitting the values of $x_{d,ext}$ for $V_{ext} = 70 \pm 100$ cm/s the values of $a$, $b$ and $m$ do not change significantly; we can then interpret the curve in Fig. 9 obtained from Eq. (1) as more accurate for the low velocities than the higher.

5. Conclusion

Using a wind tunnel that produces flow of air with velocities in the range of 0-100 cm/s, it was possible to study the flame propagation, and in particular the blow-off extinction, over thin PMMA samples. Data were collected using two configurations of the Flame Tunnel, vertical and horizontal, to isolate the influence of buoyancy.

It is established in this work that the flow velocity at which blow-off extinction occurs is not unique and is strongly influenced by the boundary layer development length. Comparison of flame images near extinction, which look remarkably similar, suggest that there is a critical effective flow velocity at which the flame extinguishes regardless of the development length and free stream velocity. Extinction flow velocity, which is shown to be a function of the boundary layer development length, is correlated to the development length resulting in a value of the critical extinction flow velocity of about 55 cm/s in the horizontal configuration and about 45 cm/s in the vertical orientation. The difference in these values for the two configurations is attributed to the dripping of PMMA in a vertical configuration, possibly acting as a heat loss mechanism. More work is necessary, especially at different oxygen level, to improve the Damköhler number correlations available in literature. Due to the less sensitivity of the results on the dripping phenomena, the horizontal configuration seems to be more reliable to calculate the Damköhler number. However, the results presented can serve as good benchmark to improve the kinetics model in computational modeling of opposed-flow flame spread.

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