THE EFFECTS OF NON-UNIFORM SURFACE REGRESSION ON THE STABILITY AND SPREADING OF A PMMA BOUNDARY LAYER FLAME NEAR THE EXTINCTION LIMIT

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ABSTRACT

This paper focuses on the effects of moving boundary on the stability of a boundary layer flame over poly methylmethacrylate. Experiments were conducted with air (less than 19.4% oxygen (by volume)) and free stream velocity of 87 cm/s. At these conditions the flame retreated from the leading edge after ignition and stabilized downstream establishing a quenching distance. The results show that the flame could not sustain within the quenching distance when the surface was flat, molten and pyrolyzing but will sustain and spread upstream after the surface has solidified. This is possible because of the creation of a stabilizing valley on the solidified surface as a result of surface regression. It appears that the valley helped stabilize the flame, perhaps by creating a stagnation/re-circulating zone where the Damkholer number is increased. Thus, moving boundary effects could significantly enhance flame stability and spread and may make it difficult to extinguish the flame.

INTRODUCTION

Boundary layer-type flames are prevalent in wall fires, ceiling fires, and wind-driven fires on flat surfaces such as floors and roofs. The suppression and extinction of such fires present a challenge because of the proximity of the condensed fuel to the flame. The rate of burning depends on the heat feedback to the condensed fuel and in boundary layer flames this is highest in the leading section where the flame is closest to the surface and decreases with the stream-wise distance from the leading edge. In boundary layer combustion of non-charring solids like Polymethyl methacrylate (PMMA), the solid surface regresses as the sample burns and forms a valley near the flame leading edge.

Near the extinction limits, chemical kinetics effects dominate over transport effects and depending on the initial value of the Damkholer number, Da, the boundary layer flame can be anchored away from the fuel leading edge, creating a quenching distance (sometimes referred to as “extinction distance”), where combustion cannot be sustained. For a flat surface, it has been established [1-3] that the flame cannot spread upstream and the quenching distance remains constant with time.

This paper will present results of experiments that demonstrate the effects of moving boundary on the stability and upstream spreading of a boundary layer flame over PMMA. It will show that the flame could not sustain within the quenching distance when the surface was flat, molten and pyrolyzing but will spread upstream (decreasing the quenching distance) after the surface has solidified. The implication of this is that the moving boundary effects would enhance flame stability and make it more difficult to suppress the flame.

EXPERIMENTAL

The key components of the experimental setup consist of a 15-cm^2 cross-sectional wind tunnel, a PMMA sample holder mounted on a MiniTec ® sliding mechanism and a thermocouple mounted on computer controlled Velmex X-Y unislides (Fig.1). The wind tunnel has a 36 X 45 X 61 cm plenum at one end into which an Ametek RJ054 ® variable speed blower pumps air. Air from the blower is mixed with a known flow of nitrogen before the mixture flows into the plenum. Pressure build-up in the plenum drives the flow of the oxidizer through the wind tunnel and hence the effects of the blower on the flow are minimized. The flow velocity in the wind tunnel is selected by adjusting the speed of the blower. The oxygen concentration in the airflow is continuously measured by sampling gas from the wind tunnel and measuring the concentration of the sample in a Beckman ® Industrial oxygen analyzer Model 755. The burning sample is positioned outside the tunnel at the center of the tunnel exit. This makes it easier for the thermocouple to be moved freely in and out to measure temperatures.

The sample holder is made of a 1.5-mm-thick aluminum plate (18.5 cm x 19 cm) brazed onto a 10 cm x 8 cm x 2.1 cm deep cup, which holds the PMMA sample. This provides a 4-cm lip in the leading section and a 5-cm lip in the other three sides. At the measurement location, the holder is positioned with its leading edge against the tunnel exit at the center of the channel (Fig.1). A thin strip of quartz glass is placed between the PMMA sample and the walls of the holder on all the four sides to prevent molten PMMA from sticking on the walls of the sample holder. The sample and holder sit on a platform mounted on a slide mechanism such that the sample can be ignited under the radiant panel located about 50 cm downstream from the tunnel exit and quickly moved to the tunnel exit after ignition. The test samples are 7.7 X 9.5 cm and are made from Cyro Acrylite GP ® sheet nominally 2.54 cm thick. The incoming oxidizer velocity is measured at the exit of the tunnel (measurement location) using a hot wire anemometer. More details of the setup are described in [4].

Air with reduced oxygen (between 19.4 ± 0.1 % and 18.8 ± 0.1 % by volume) flows through the wind tunnel with an exit velocity of 87±1 cm/s at the center. With $U_\infty = 100$ cm/s, Kodama et al. [3] predicted a mass fraction of 18% at the lean extinction limit. Thus, these experiments were conducted near the flame extinction limits. The sample surface is ignited by uniform radiation from a radiant panel at the ignition location and the flame retreats downstream soon after it is moved to the exit of the tunnel (Fig.1). An R-type thermocouple, 75 μm in diameter, is quickly lowered into the molten layer as the flame retreats. The thermocouple continuously measures the temperature of a point on the molten/solidifying layer within the quenching distance as the flame stabilizes downstream and as the stable flame spreads upstream within the quenching distance. To reveal the sample surface

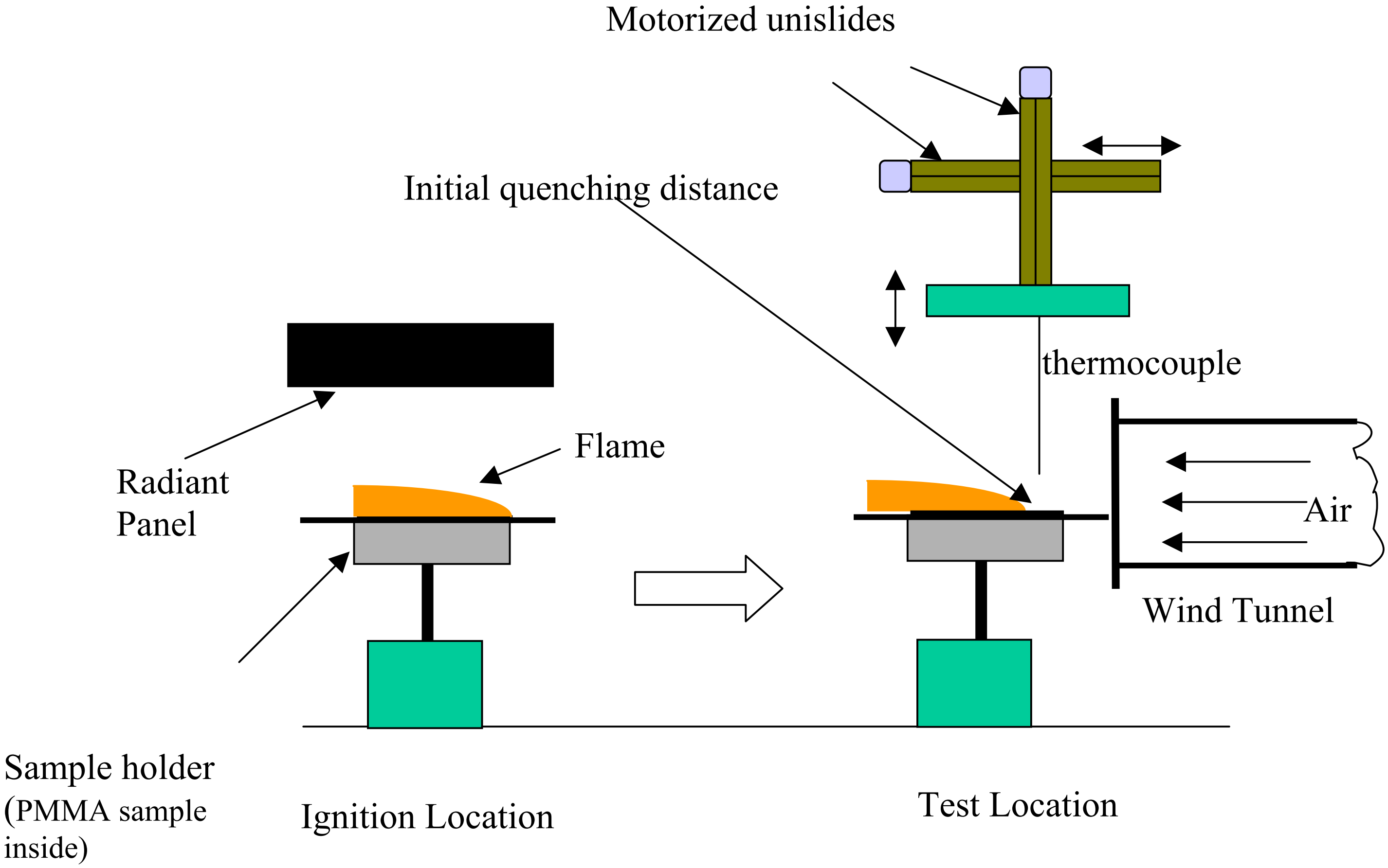

Figure 1: Schematic of the experimental setup illustrating the process of establishing the quenching distance on the PMMA sample surface

profile at the relevant times in the experiment, separate tests were conducted, where the flame was extinguished as it is retreating (stage 1), as it stabilizes (stage 2) and after it spreads upstream for some time (stage 3).

RESULTS AND DISCUSSIONS

To establish a boundary layer flame over the entire PMMA sample, the surface is heated under a radiant panel far downstream, where the air velocity is significantly smaller than at the exit of the tunnel, Fig.1. It is important to ensure that the entire surface is pyrolyzing as indicated by intense bubbling before the flame is ignited. After ignition, the sample is quickly moved to the exit of the tunnel.

Figure 2a shows the flame as the sample was being brought to the exit of the wind tunnel. It shows a relatively smooth flame near the leading edge region, which gets wrinkled and unsteady downstream. The wrinkling could be as a result of the movement or as a result of buoyancy effects, since the plate surrounding the sample was still very hot, having been heated by the radiant panel. The buoyancy effects die down as the metal lip cools to ambient within a short time. Figure 2a shows that the flame covers the entire sample, including the leading edge region, implying that this region is molten and pyrolyzing at this stage. The fuel surface sticks out of the sample holder by about 1 to 2 mm so that the surface does not regress below the metal lip during the test, preventing the formation of an artificial trough.

Shortly after the flame gets to the exit of the channel, where the velocity is significantly higher than at the ignition location, the boundary layer flame is dislodged from the sample leading edge and starts retreating downstream (Fig. 2b) The leading edge of the flame was observed to oscillate back and forth over the molten surface of PMMA as it retreats from the sample leading edge, similar to what Kodama et al. [3] observed. For the purposes of discussion we define this state where the flame was dislodged from the sample leading edge and was retreating downstream as stage 1. The thermocouple, which is about 15 mm downstream from the sample leading edge along the centerline, is quickly lowered into the molten surface at this stage. Figure 2b shows the thermocouple passing through the retreating bluish flame and one can see that the surface is still relatively flat at this stage. This will be shown more clearly later. Soon the leading edge of the flame stops oscillating and anchors at some distance (quenching distance) from the sample leading edge. Thereafter, a small step is formed at the location of the flame leading edge and the flame starts to spread upstream (stage 2). In this test, where the air has 19.4% oxygen the quenching distance was about 20 mm.

Figure 3a shows the flame in stage 2, anchored about 5 mm downstream from thermocouple. While the leading edge of the flame was retreating, the molten polymer was exposed to ambient air and was cooling down slowly. The melt has 1600 times smaller thermal diffusivity than the hot gas adjacent to the surface; therefore it takes a long time to cool down. Consequently, the surface could still put out a significant amount of fuel vapor during the transient stabilization process. In the present experiments the reaction rates ($\propto$ 1/time) are lowered by the presence of nitrogen and the flow rate is increased as the sample is brought to the exit of the channel. Therefore, the Damkholer number Da, which is flow time/reaction time**,** decreases as the flame is brought to the tunnel exit and this causes the flame to retreat and stabilize after a quenching distance.

In boundary layer flames, the heat feedback to the surface is largest near the leading edge of the flame where the boundary layer thickness is smallest and decreases with stream-wise distance. Since the surface regression rate is roughly proportional to the heat feedback, regression rate is non-uniform along the surface, being highest near the flame leading edge. Therefore, as time progresses, the shape of the surface changes as the depth and shape of the valley or a step formed near the flame leading edge increases and changes. The flame appears to anchor behind the step. With time, it was observed that the leading edge of the flame and valley move upstream decreasing the quenching

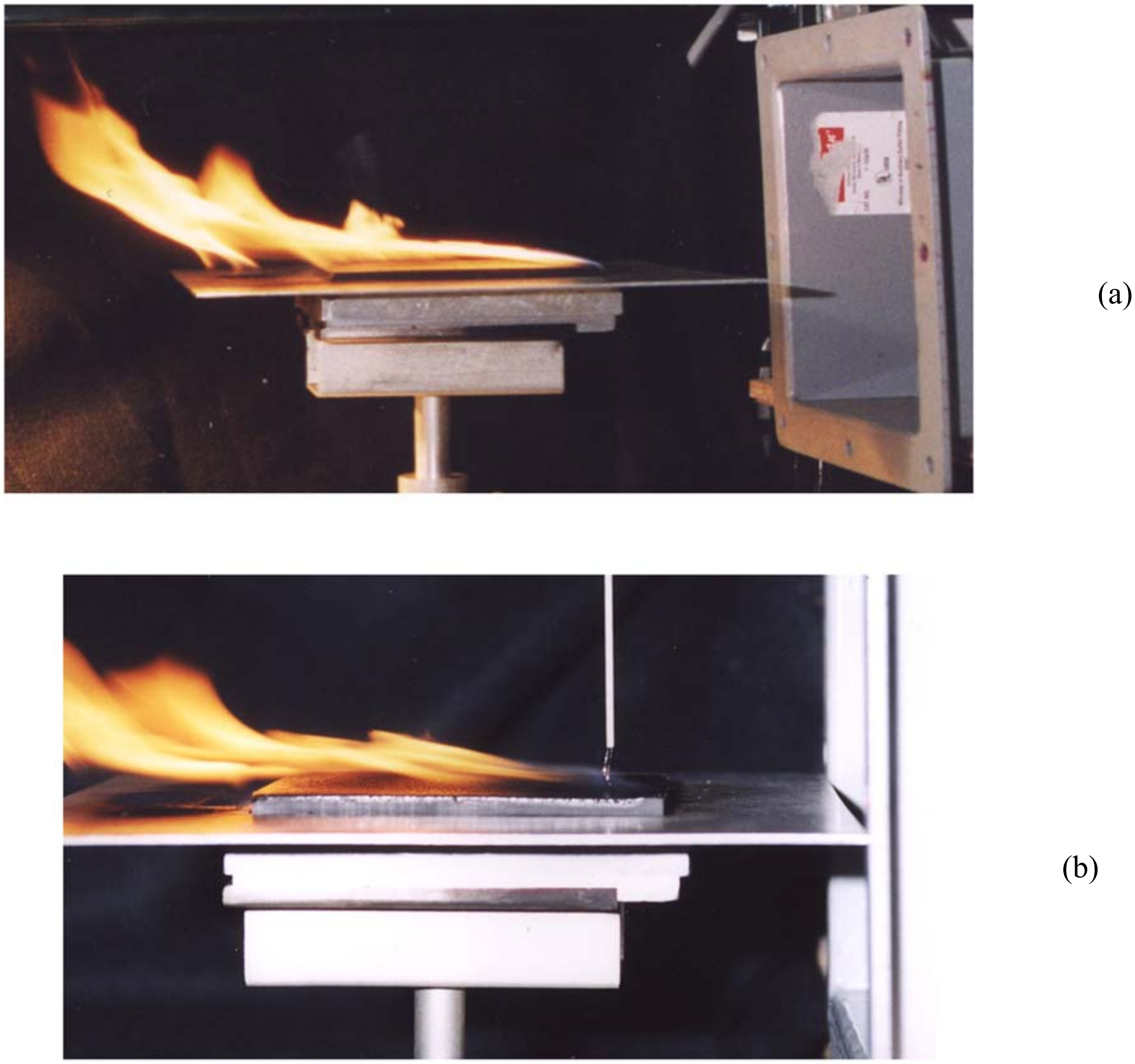

Figure 2: (a) Picture of the flame as it is being moved to the measurement location, flame anchored at the sample leading edge. (b): Flame dislodged and retreating downstream soon after it gets to the measurement location.

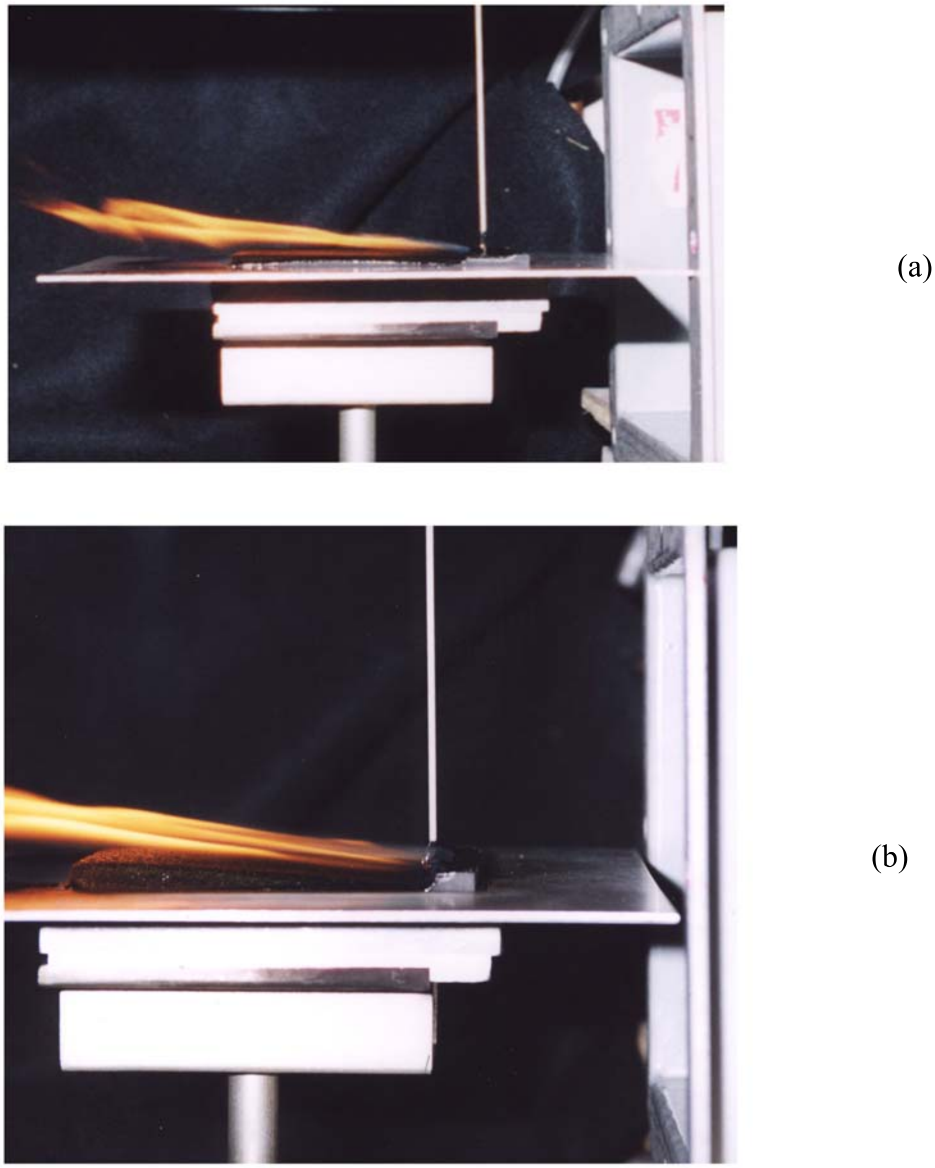

Figure 3: (a) Flame stabilized about 5mm downstream of the thermocouple location. (b): Flame spread upstream up to the location of the thermocouple

distance. Figure 3b shows a picture of the flame several minutes later (stage 3) as it approaches and engulfs the thermocouple, which was located 5 mm upstream from where the flame stabilized. It also shows that the surface is no longer flat and the edge of the valley has moved past the thermocouple toward the leading edge. The flame could now sustain behind the step at a location where it could not sustain before while the surface was flat (stage 1). The surface profile at the various stages will be shown more clearly later. The above observations suggest that the formation of a step stabilizes the flame and enables it to spread counter-currently as in Fig. 3b. It is well established in literature that flame is stabilized behind a step and this has been used extensively in burner design [5]. These experiments were repeated numerous times with various initial quenching distances established with various combinations of flow velocity and oxygen concentration and each time the flame was observed to spread upstream decreasing the quenching distance. Therefore, one can infer that the moving boundary effects lead to step formation, which was critical for the lean limit flame stabilization and spread. The flame could not sustain on the hot melt surface due to too low Da but was able to sustain on a cooler solid surface due to the moving boundary effect, which helped to increase the Da.

The time-dependent thermocouple data (uncorrected for radiation) measured as the flame retreats and then spreads upstream (Figures 2 and 3) are shown in Fig. 4. The first several data points on the left hand side of the curve were taken during stage 1 as the flame was retreating and the thermocouple was passing through it (Figure 2b). A fairly rigid thermocouple (75 μm diameter) was used to ensure that the bead goes into the melt/froth layer. The thermocouple was lowered into the melt until the bead, goes through the melt/froth layer and the thermocouple starts to bend. The thermocouple was moved slowly through the retreating flame to show that the surface was gasifying at this location, producing hot gases and yet the flame could not be sustained there. PMMA is known to pyrolyze at temperatures of the order of 650 to 700 K [6,7]. Furthermore, the pyrolysis rate drops by a factor of 100 as the temperature drops by about 60 K, since PMMA pyrolysis has high activation energy. Therefore for the purpose of this discussion we defined pyrolysis zone as 600 to 700 K-temperature range in Fig. 4. Therefore, the thermocouple is assumed to be in the PMMA condensed phase when it reads temperatures below 600 K. During this time the thermocouple readings represent real time changes in the temperature inside the condensed phase at the thermocouple location.

About 100 seconds into the test the thermocouple reads the lowest temperature (close to 400 K). This should correspond to stage 2, when the flame stabilized about 5 mm downstream from the thermocouple and it is farthest from the thermocouple. Meanwhile a step is formed where the flame stabilized and it starts spreading upstream. As the flame spreads, heat is transferred from the flame to the solid ahead of the flame front. This raises the temperature at the thermocouple location from about 400 K to the pyrolysis temperature in about 200 seconds as shown in Figure 4. As the flame creeps up to the thermocouple location, the polymer pyrolyzes exposing the thermocouple bead to the hot gases. Thereafter, the thermocouple measures the hot gas temperatures of the flame. The valley has now extended beyond the thermocouple location as seen in Fig. 3b (stage 3).

To examine the surface profiles more closely during each of the three stages described above, separate experiments were conducted, where the flame was extinguished during each stage. The sample was allowed to cool down and was cut stream-wise along the centerline to show the surface profile.

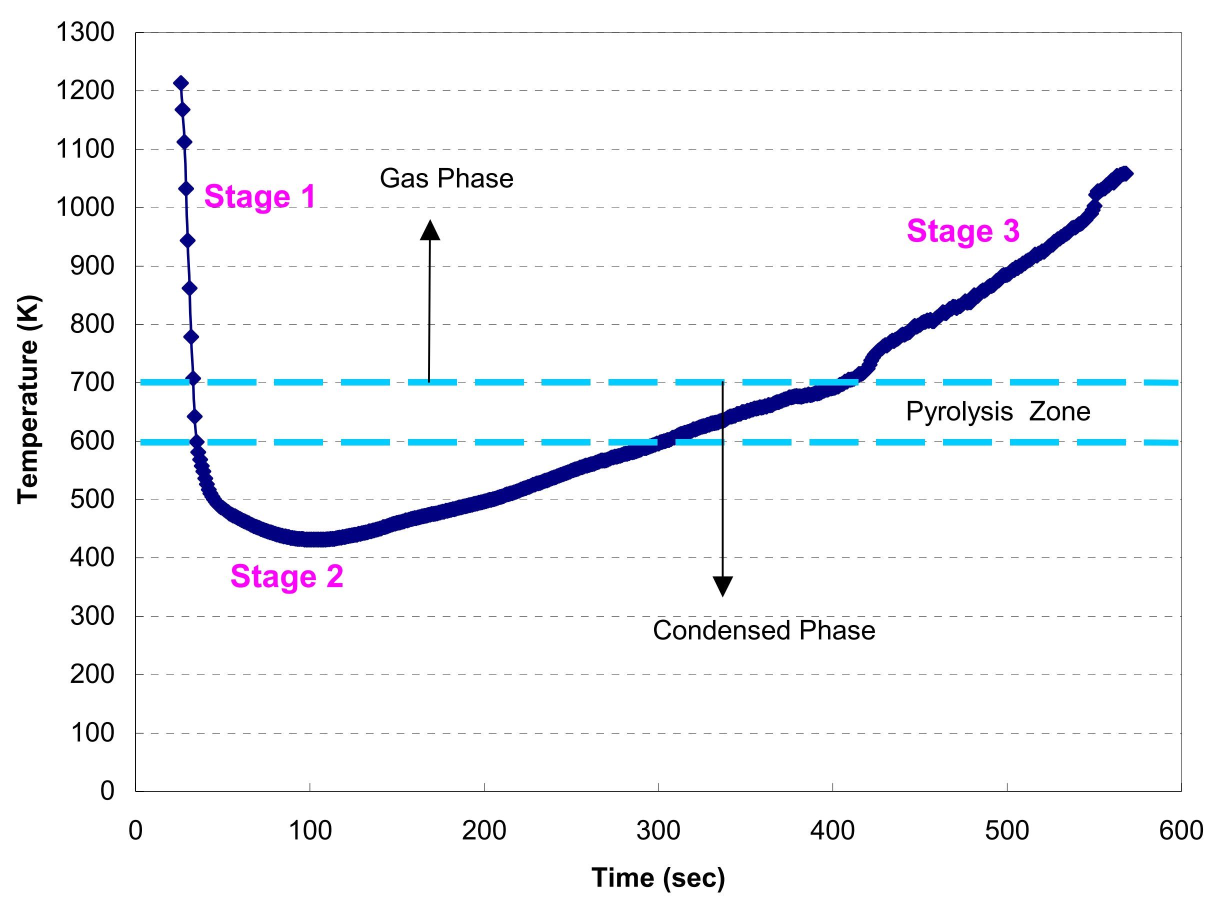

Figure 4: Time dependent temperature of a point within the quenching distance as the flame retreats (stage 1), stabilizes (stage 2) and spreads within the quenching distance (stage 3)

These experiments were performed with 18.8%± 0.1% oxygen concentration so as to obtain a significant quenching distance. Figure 5a shows the picture of the surface profile as the flame front retreats from the sample leading edge (stage 1). It shows that the entire surface is flat and that the degree of pyrolysis during the ignition process and the short burn time had negligible effect on the shape of the surface. Figure 5b shows the surface profile when the flame had just stabilized about 45 mm downstream from the sample leading edge. The surface was still nearly flat except for a tiny step at the location where the flame has just anchored. There, the reaction time is expected to be comparable to the flow time. The flame did not stay long enough at this location to create a deeper step before it was extinguished. Figure 5b also shows a tiny step formed at the leading edge of the sample before the flame was dislodged in this experiment. This tiny step was not adequate to stabilize the flame at the leading edge of the sample where the effective velocity was higher. At a fixed oxygen concentration and free stream velocity, the flame stability may depend both on the distance from the leading edge and on the size of the step for small size step. Therefore, a bigger step than seen in Figure 5b would be needed to stabilize the flame within the quenching distance. In Fig. 5c we show a picture of the surface profile in an experiment where the flame stabilized and was allowed to spread upstream for 5 minutes, before it was extinguished (stage 3). In this experiment, the flame initially stabilized nearer the sample leading edge than in Fig. 5b, creating an initial quenching distance less than 45 mm. This indicates that the length of the quenching distance can vary between experiments even when the oxygen concentrations are the same. Figure 5c shows a bigger valley than in Fig. 5b, indicating that a bigger valley is needed to sustain the flame as it spreads upstream closer to the leading edge. This is further illustrated in Figs. 6a, b and c.

Figures 6a, b and c show sample surface profiles in tests with 19.4% oxygen, where the flame was allowed to spread upstream for 5, 10 and 20 minutes, respectively. Like the flame described in Figs. 3 a and b, the flames in Figs. 6 a-c stabilized about 20 mm downstream from the sample leading edge and as the flames spread upstream the valleys get deeper and broader. The initial point of stabilization (X=20 mm) was exposed to the highest flux from the flame for the longest time than any other part of the surface during the flame spread process. Therefore, the deepest point (highest regression distance) in the valley is expected to occur approximately at the initial point of flame stabilization. As the flame gets closer to the leading edge, it encounters increasing air velocity. Therefore, a bigger valley is needed for the flame to be stable. The surface profiles in Figs. 6 a-c clearly show increased depth of valley with time that enables the flame to sustain and spread.

The results of these experiments have demonstrated that the formation of a valley (moving boundary) is critical for the stability and counter-current spreading of a lean limit boundary layer flame within the quenching distance. The effectiveness of steps and baffles as flame stabilizers have been recognized in the gas turbine industry, where burner designs exploit the enhanced stability associated with combustion in a re-circulation zone [5]. The presence of a step may be advantageous for flame holding and stabilization, but it becomes a disadvantage in flame suppression and extinction. Takahashi et al. [8] studied the stabilization and suppression of methane flames formed behind a step in a wind tunnel. A re-circulation zone was formed behind the step and they showed that the minimum mass fraction of the agent required to extinguish the flame increased with the volume of the re-circulation zone. It is therefore expected that effects of moving boundary would reduce the effectiveness of suppressing agents in boundary layer fires over non-charring solids.

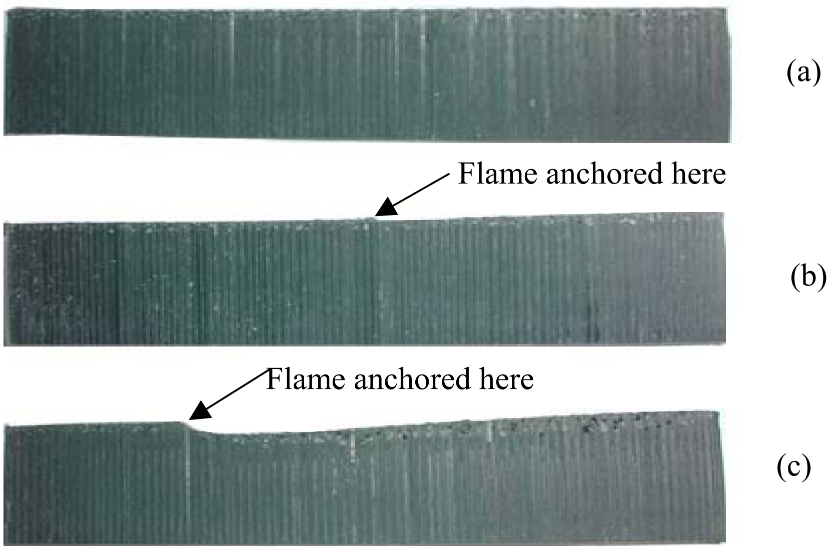

Figure 5: Sample surface profiles for tests with 18.8% Oxygen and flame extinguished (a) while flame was retreating from the leading edge (stage 1); (b) just as flame stabilized (stage 2) and (c) after flame has spread upstream for 5 minutes (stage 3).

Figure 6: PMMA Surface profiles after (a) 5 min, (b) 10 min and (c) 20-min burns; Tests with 19.4% oxygen; flame spreading within X< 20 mm

CONCLUSIONS

The results presented above reveal the effects of moving boundary on counter-current boundary layer flame spread over a non-charring solid near the flame extinction limits. Tests were conducted at low oxygen concentration (≤19.4%) and air velocity of 87 cm/s. This created an initial quenching distance (≥20 mm) where the flame could not sustain while the surface was pyrolyzing and flat. As the flame stabilized, a small step is formed under the leading edge of the flame where the heat feedback is the highest. This small step was observed to grow deeper and bigger with time. The step (valley) appears to have played a critical role in the flame stabilization and spread within the quenching distance, where it could not sustain when the surface was flat. Therefore, the effects of moving boundary enhance flame spread and stability significantly and may make it difficult to extinguish the flame.

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