An Experimental Study of Upward Flame Spread over Wavy Thin Solids

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Abstract: Experimental results of one-sided upward flame spread over wavy cellulosic paper samples are presented. The sinusoidal shaped samples with different wave length and amplitude are aligned perpendicular to the gravitational direction so the upward buoyant flow sees peak and valley along its flow path. Depending on the wave amplitude and wave length, the flame can spread from sample peak to peak initially but may later sustain slow burning from isolated flamelets inside the sample valleys or become quenched. The degree of fuel burning completeness, pyrolysis front spread rate and extinction limits (both local and overall) depend on the wavy parameters in a complex way as well as the ambient relative humidity. Flame spread over wavy samples thus has unique features not found in continuous flat samples or in discrete samples. Video record of the experiments supplied in the paper presents both the front and the side views of these interesting transient flame development.

1. Introduction

Upward flame spread over solids is profoundly influenced by buoyant-induced convective flow. Most upward flame spread data were interpreted using classical boundary layer concept [e.g. 1-4]. Complexity may arise with discrete samples [5, 6] or when the flame extinction problem is at issue. In the latter case, the leading edge elliptic zone needs to be resolved [7-9].

When the sample is not flat, the convective flow pattern can be more complex. Here we study the one-sided flame spread and burning over wavy sinusoidal shaped thin solids with gravity direction aligned with the wave. In this configuration, the flame can exhibit both continuous and discrete spreading and burning characteristics, depending on the wave amplitude and wave length. Flow past a wavy wall is a classical textbook example in fluid mechanics [e.g. 10]. There are also investigations in heat transfer [11-14]. However, we are not aware any work in combustion although there is a concurrent research project using thick PMMA sample with periodic square ribs [15].

Our interest in this problem originated from an investigation on the burning of corrugated cardboard [16, 17]. When the face liner piece is burned away, the exposed sample has a wavy corrugated structure. Although we have used corrugated board material in our initial tests [18], we are now using ashless filter paper as the fuel and fabricating the wavy structure in house for a more scientifically oriented investigation.

In this paper, the fabrication of samples will be described first, the experimental setup is given next followed by the experimental results including videos. In [19], modeling results have been presented. The model is two-dimensional (a simplification) while the experiments have three-dimensional effects because of the finite width samples. The main purpose of the model is to extract the essential features of the interaction between the flame and the sample geometry that has multiple heat and mass transfer and flame extinction modes as a result of the more complex flow patterns.

2. Sample Fabrication and Test Setup

Two types of sample materials have been tested in our work: liner board sheet that makes the corrugated box and ashless filter paper. The composition of cardboard material is more complex which contains inorganics and surface treatments. The burning includes extensive smoldering and ash. We opted to present the results using ashless paper which burns more cleanly. The ashless sample is supplied by I.W.Tremont Co. at New York with an area density 0.0096 g/cm^2.

To fabricate the wavy sample, we first made two sinusoidal shaped wood molds with specified amplitude and wave length using a laser cutter. The paper sample is wetted and softened with de-ionized water and sandwiched between the two molds. The sample is let to dry over night with a weight on top to form the desired sinusoidal shape. The sample is further dried in an oven for 2 hours using an oven temperature 120℃.

To keep the wavy shape intact even after the solid fuel burnout, the back side of the sample is taped with Kapton tape (1 mil thick from www.kaptontape.com). This prevents burn through and results in a one-sided burning. It was found that the Kapton tape retained the sinusoidal shape even with after the paper burnout. In addition, two Kapton strips are also taped on the front side of the sample to limit the burn portion to the specified width (5 cm). To support the sample (and also to avoid obstruction from side-view camera view), two wooden sections from the same mold are used as edge support. The paper sample is mounted on the wooden edge also using Kapton tape. The wood edges are screwed to two aluminum plates in the support frame. Between the two aluminum plates, a ceramic foam board is used which is placed 3mm away from the sample at the closest points. This arrangement of sample edges is crucial to enable a clear and un-obstructed side view of the flame inside the valley of the sample as illustrated in Fig. 1.

The entire setup is placed on a mass balance that is accurate to 0.01g. In order not to interfere with mass measurement, the zig-zag shaped heat ignition wire is attached to a small piece of paper sample (3mm high and 5cm wide) placed 1.5 cm below the sample. The wire is powered by an electric current at 3.8A, 21V for 8s. This small piece is first ignited and its small flame in turn ignites the main sample. In this arrangement, electric wiring is not in contact with the test assembly to be weighted thus there is no interference with mass recording. The mass loss data is recorded at 15Hz. Green LEDs are used to illuminate the setup in the dark. Data acquisition and ignition are accomplished using National Instrument devices and Labview.

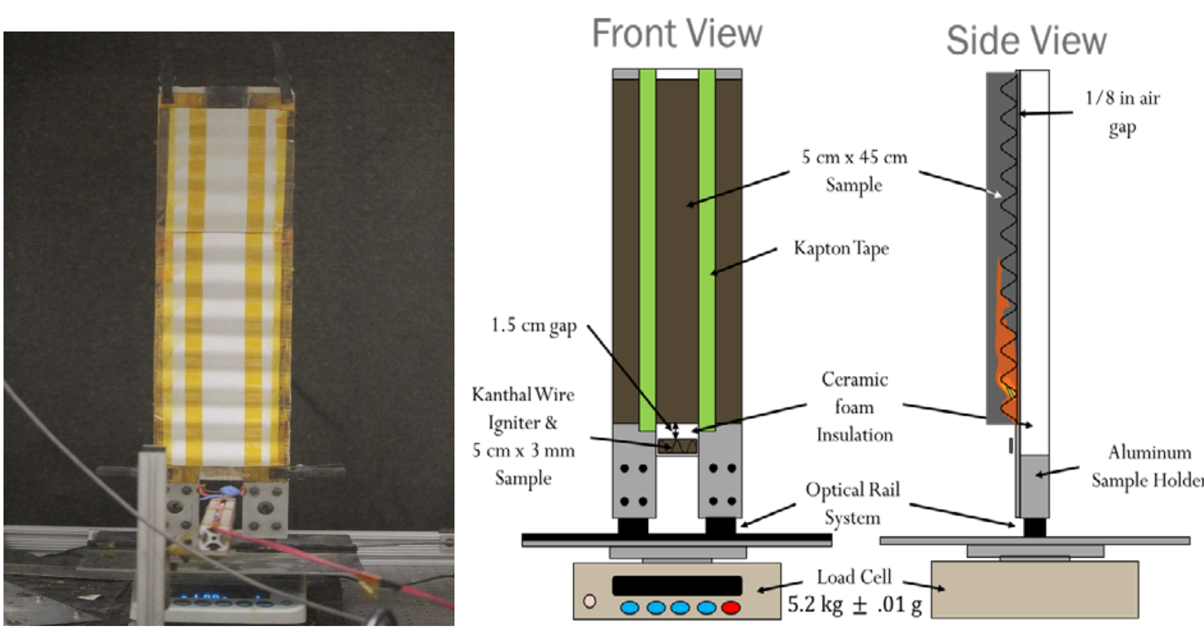


Fig.1 Illustration of wavy sample set up (right). Photo of a mounted fresh wavy sample (left)

During the test, two Cannon Rebel T3i cameras provide top and side views of the flame and pyrolysis region. The recording is filmed in 1080P and 24 fps.

The exposed sample size for burning is 5 cm wide and 45 cm long (projected length). Earlier tests with 30 cm long samples were marginal in deciding whether the flame will spread all the way or not. Samples greater than 30 cm is needed to ensure that the initial ignition preheating effect is eliminated at the top portion of the sample.

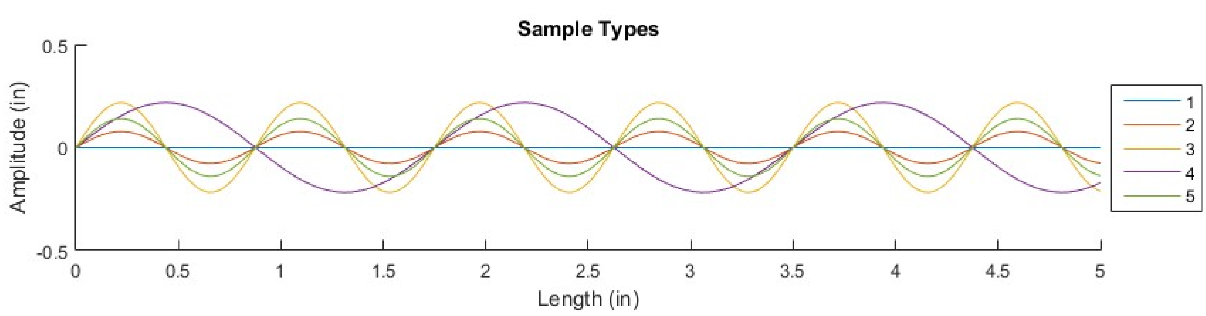
Five samples with different amplitude and wave length are chosen as listed in Table 1. Sample 1 is a flat sample, used as a reference for comparison purpose. Not that the flat sample also has the Kapton tape backing so the flame spread will be one-sided, same as the rest of samples. Samples 2, 3 and 5 have the same wave length (7/8 inches or 2.225 cm) but different amplitudes. They are respectively referred to as small amplitude (5/64 in or 0.176cm), large amplitude (7/32 in or 0.556 cm) and intermediate amplitude (9/64 in or 0.357 in). Sample 4 is referred to as the large wave length sample which has the same amplitude as sample 3 but twice the wave length (7/4 in or 4.445 cm).

3. Experimental results

Tests were made in two sessions during the year (summer and winter) with two different test room relative humidity but almost the same room temperatures. It turns out that the room humidity has a substantial influence on the extinction and spreading results. So in addition to sample geometric parameters, environmental relative humidity becomes an additional variable in this investigation.

Table 1 Sample shape and wave parameters of the five different types of geometries tested in the experiment.

Number	Name	Wave length	Amplitude	Arc Length for height of 45 cm (cm)
1	Flat	N/A	N/A	30
2	Small Amplitude	7/8in (2.225cm)	5/64 in (0.176cm)	48.35
3	Large Amplitude	7/8in (2.225cm)	7/32 in (0.556cm)	65.8
4	Large Wavelength	7/4in (4.445cm)	7/32 in (0.556cm)	51.3
5	Intermediate Amplitude	7/8in (2.225cm)	9/64 in (0.357cm)	54.9



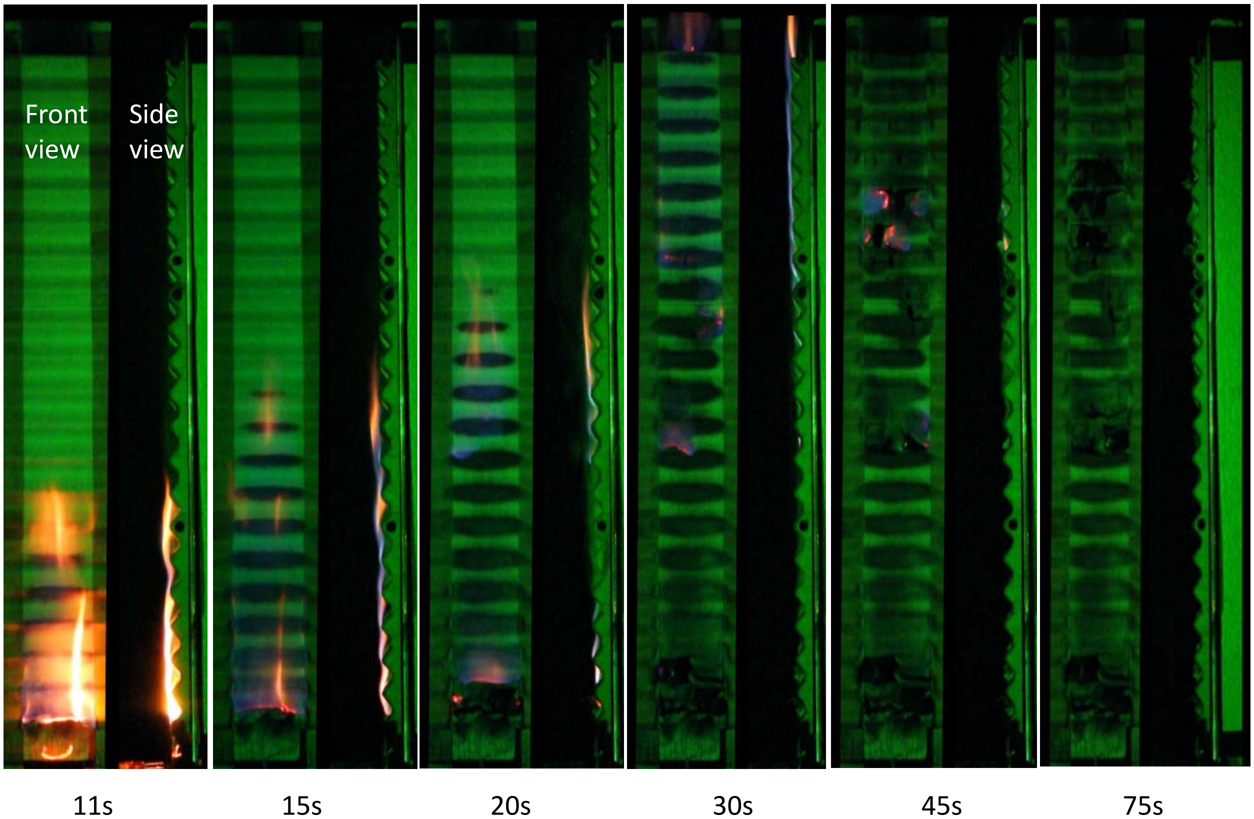


Fig. 2 Snapshots of flames at different times for sample 5 (medium amplitude) in low-humidity tests

3.1 Low humidity test series (Relative humidity, 18 - 20% and room temperature, 22 °C).

This series of tests were performed during the winter months in a room with low relative humidity Given the sample expose time of samples in the room before the test, it is expected that equilibrium has been reached between the sample moisture contents and the room air. This series of tests will be referred to as the “low humidity tests”.

In this series, the pyrolysis front reached the top for all the samples although the degree of burning varied. Fig. 2 shows the snapshot at 6 different times for the medium amplitude sample (sample 5). Both the front and the side views are given. At 11s after ignitor is energized, the flame tip reaches a height approximately 15 cm from the ignition point at the bottom of the sample. The flame color is predominately yellow indicating a strong flame. This is due to the boost of heating from the igniter. At 15s ignition effect begins to fade, the flame color changes to blue. The front view shows there is only a narrow streak of yellow soot with the rest mostly blue (not easily visible). The blacken part of the sample surface in the front view is the burned (pyrolyzed) portion of the sample peaks. The white parts are the un-pyrolyzed sample in the sample valley. The periodicity of the white vs black colors indicates that the flame spreads from sample peak to peak (at least initially) and the valleys are not or not fully pyrolyzed. This is collaborated with the side view of the flame. It shows that the flame is very close to the sample peaks (i.e. small flame standoff distance) with more heat transfer to this portion of the sample and hence burns first. The side view also shows that the flame impinges onto the fore side ahead of peak in the valley, as expected from the effect of upward buoyant convective flow. Inside the valley, a recirculation flow exists that can be seen from the video but the flame is not close to the bottom of the sample valley. At 20s, the middle of the flame extinguished after substantial part of the fuel near the peaks is consumed. The flame is split into two portions. Near the bottom, flame is sustained inside the valley, presumably from the heating of the ignition process that preheat the valley to render it more flammable. The upper part of the flame continues its spread upward. Note that the shape of the pointed tip of the pyrolysis front show the heat transfer in this region is three-dimensional in nature for the 5cm wide sample. At 30s, the flame reaches the top of the sample. Note that the flame is entirely blue. Flamelets appear near the bottom of flame. They appear to be isolated inside the valley and may exist only in one portion of an individual valley but may spread side ways to the other part slowly or may quench. At 45s, the continuous flame goes out, but several individual flamelets exist. The flamelets finally fully quenched at 75s.

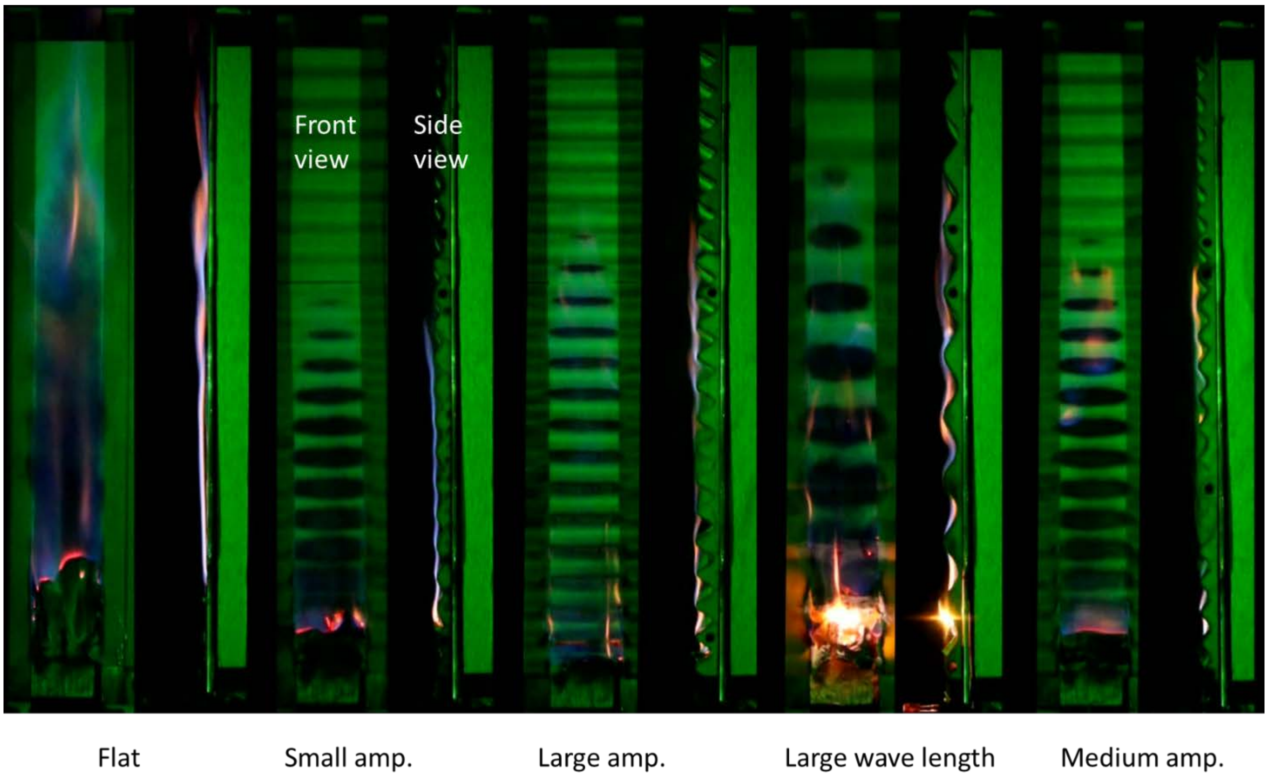


Fig.3 Snapshots at 22s after ignition for flames over 5 samples in low-humidity tests

The picture at 75s shows the leftover sample and give an indication of fuel burning distribution. Starting from the bottom of the sample upward, the burn is rather complete near the bottom because of the ignition energy input. The next upper portion, fuel is not completely consumed. Substantial part in the valley is unburnt. Going more upward, we see in some parts the burning is more complete because of the existence of flamelets and other portions with a less degree of burning. As a near-limit phenomenon, the appearance and the location of flamelets are not completely regular nor predictable. As will be shown later from the mass measurement, the percentage of the total fuel burnt in this case is about 60%.

Figure 3 is a snapshot of all the 5 samples listed in Table 1 at a time instance 21s after ignition. To examine the effect of the sample wave amplitude, we will first compare the photos of samples 1, 2, 3 and 5. They are respectively, flat, small amplitude, large amplitude and medium amplitude.

The flat sample 1 is used as a reference to be compared with the wavy samples. Its side-view shows a buoyant boundary layer flame staying very close to the surface. As mentioned previously, Kapton tape is attached to the back side of the flat sample. The resulting one-sided flame shown in Fig. 3 is more blueish than the normal two-sided flame for the same fuel. The front view shows yellow sooting traces in parts of the domain. This is in contrast to two-sided burning where the flame is almost entirely yellowish. With Kapton tape, the flame experiences additional heat loss from the back side. This results in a weaker flame with lower temperature and therefore a more blueish color. In sample 2, the small amplitude case, the wavy blue flame is continuous with no visible flamelet. But eventually the flame is separated into two portions just like the medium amplitude and large amplitude samples shown in Fig. 2. But in the small amplitude case, flamelets do not quench. They spread across the sample valleys, so the total fuel consumption rate is greater than 90%. In sample 5 (medium amplitude), the middle portion of the flame quenched as described earlier, so is sample 3 (large amplitude case).

Comparing the front view images in Fig. 2, we see that the peak regions of the sample are consumed first (blackened portion). The projected width (in the streamwise direction) of the pyrolysis zone is smallest with large amplitude (sample 3), followed by the medium amplitude (sample 5) and small amplitude (sample2). This can be attributed to the difficulty of air flow to reach deep into the valley. Comparing the pyrolysis front heights, one sees that the average flame spread rate is highest for the flat sample, followed by the medium and large amplitude samples (the latter two are about the same), with the slowest being the small amplitude sample. The order is not entirely monotonous with the amplitude.

To examine the effect of wave length, we compare sample 4 with sample 3. Both have the same amplitude but the wave length of sample 4 is twice as that of sample 3. For the large wave length case, the flow, hence the flame, is able to go into the valley without separation, the flame is able to follow the curvature of the sample valley as shown in the lower half of sample 4. This is in contrast to that for sample 3 where the flame stays mostly outside or close to the outer side of the valley. In the upper half of the samples where buoyant flow becomes greater, the flame tends to stay on the outer side of the valley for both cases. The front view of the two cases also show that the extent of the pyrolysis (blackened part) is greater for the large wave length sample. This is reasonable as more peak surface area is close to the flame. Comparing the position of the pyrolysis front at the top of the sample, we see that the spread rate for the large amplitude sample is slower than the flat sample but greater than all the other cases.

Figure 4 shows the percentage of mass loss (non-dimensionalized by the available fuel) with time for four cases. The left side of Fig. 4 is for the low humidity tests. Only about 60% of the fuel are consumed for the medium and large amplitude cases. But the fuel consumptions are more than 90% for the flat and small amplitude samples. Also note that the mass loss rate decreases then increases again for sample 2. This may be attributed to local flame extinction and flame re-growth we see in Fig. 2.

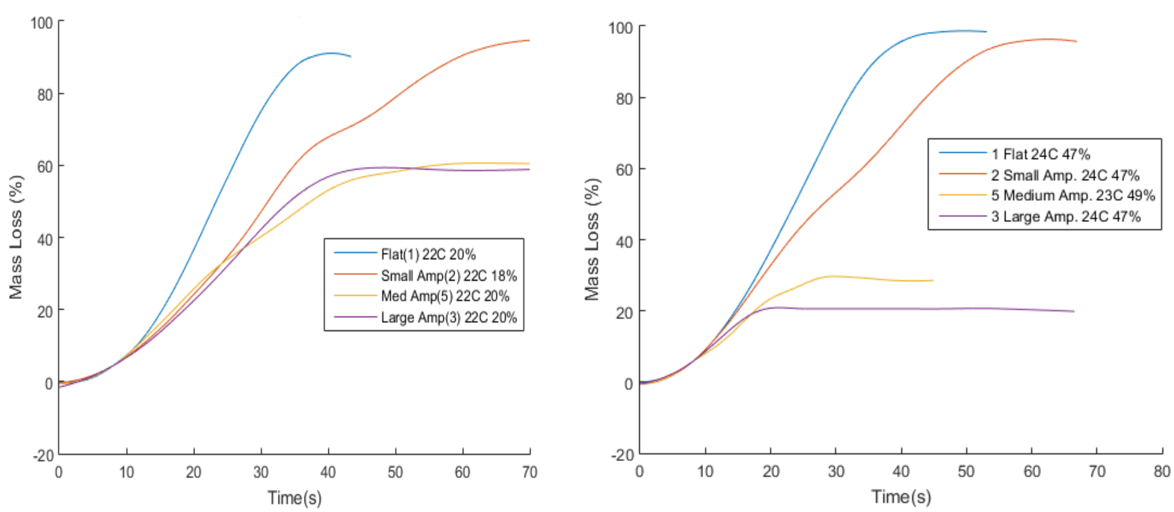


Figure 4 Percentage of mass loss with time with amplitude as parameter for (left) the low-humidity tests and (right) for the high humidity tests.

The entire transient flame development for all the five cases can be found in a video supplied in the supplement using the same format as in Fig. 3.

3.2 High humidity test series (Relative humidity, 47 - 49% and room temperature, $23 - 24°C$).

This series of tests were performed during the summer months with a “relatively higher” room relative humidity (47-49% vs. 18-20% in the low humidity series). The room temperatures for the two series are close (23-24°C vs. 20°C).). Same five types of samples were used.

Humidity in the environment has a significant effect on the test results. Higher humidity (therefore high water content in the sample) produces a weaker flame manifested by the more blueish flame color. The spread rate is lower. In three of our sample types (medium amplitude, large amplitude and large wave length), the flames extinguished and failed to reach the top of the sample. Fig. 5 is a snapshot at 37s after ignition. It can be seen that flames have gone out for samples 3, 4 and 5. Flame is still spreading and eventually reach the top for sample 2 (small amplitude). The spread rates of both sample 1 (flat) and sample 2 are slower compared with the corresponding cases in the lower humidity series. Their flame colors are also more blueish.

The right figure in Fig. 4 shows the percentage of mass loss (non-dimensionalized by the available fuel) with time for four cases. While the total fuel consumption percentages are more than 90% for the flat and small amplitude samples, they are very low for medium and large amplitudes cases (~30% and 20% respectively). This is consistent with Fig. 5 which shows the flame extinguished in the middle of the sample.

The entire transient flame development can be found in our attached video in the supplement.

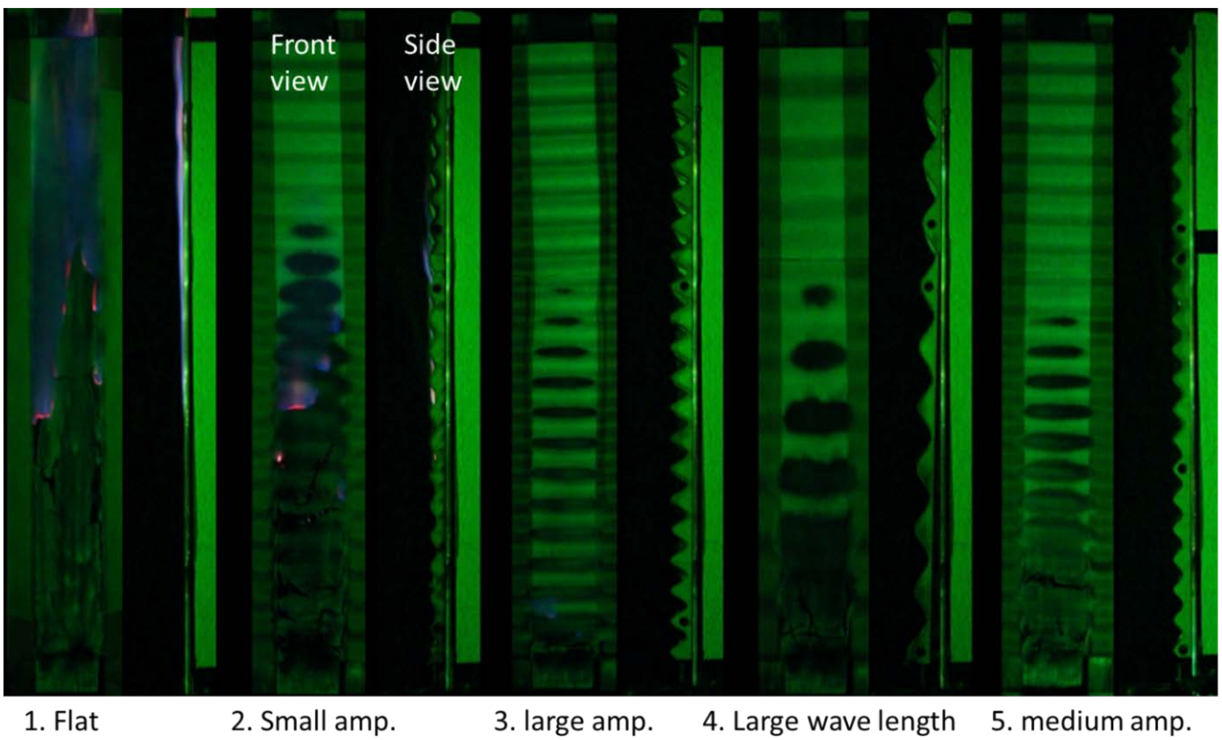


Fig. 5 Snapshots at 37s after ignition for flames over 5 samples in high-humidity tests

4. Concluding Remarks

(1) Upward flame spreads over wavy solid by jumping from sample peak to peak. In a sense, this resembles flame spreading over discrete samples. However, because the solid is really continuous, the degree of initial pyrolysis near the peak varies depending on geometric parameters such as wave amplitude and wave length.
(2) Flow inside the sample valley can be complex depending on the magnitude of the outer buoyant flow. A recirculation bubble appears when the buoyant flow is large and the flame stays mostly outside the valley. After the fuel near the peaks is nearly spent, the main flame base moves up. Then secondary slow-burning flamelets can occur inside some of the valleys after the passing of the main flame.
(3) Flamlets appear to be isolated, weak and very slow burning. Their shapes are irregular. They may spread from one side of the valley horizontally to the other side or become quenched. Their colors are blue. These are gaseous flames not surface smoldering.
(4) Burning in deep valleys may not be complete so that the total burning percentage can be significantly less than unity even when the main flame reaches the top of the sample.
(5) With back side inhibited (in our case by Kapton tape), the thin solid sample loses heat from the back side and is less flammable than the two-sided burning case. Many of the burnings of our sample configurations may be near-limit flames as a result. This is manifested in the high humidity series results; flames were not able to reach the top of the sample while in low humidity, they did.

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