Flamelet Formation in Hele-Shaw Flow

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Abstract
A Hele-Shaw flow apparatus constructed at Michigan State University (MSU) produces conditions that reduce influences of buoyancy-driven flows. In addition, in the MSU Hele-Shaw apparatus it is possible to adjust the heat losses from the fuel sample (0.001" thick cellulose) and the flow speed of the approaching oxidizer flow (air) so that the "flamelet regime of flame spread" is entered. In this regime various features of the flame-to-smolder (and vice versa) transition can be studied. For the relatively wide (~ 17.5 cm) and long (~ 20 cm) samples used, approximately ten flamelets existed at all times. The flamelet behavior was studied mechanistically and statistically. A heat transfer analysis of the dominant heat transfer mechanisms was conducted. Results indicate that radiation and conduction processes are important, and that a simple 1-D model using the Broido-Shafizadeh model for cellulose decomposition chemistry can describe aspects of the flamelet spread process.

Introduction

Prior to extinction, microgravity flames on solid fuels exhibit an instability that appears to be related to extinction or the return of flame spread. This "flamelet" behavior extends the flammability range by altering the geometry of the flame thereby enhancing oxygen delivery to the flame zone. Analysis of Thermal and Hydrodynamic Instabilities in Near-limit Atmospheres (ATHINA) is a space flight project that examines near limit flame spread over materials that resemble those found in spacecraft. Quantities influencing flammability are material physical properties spacecraft atmosphere, and magnitude and geometry of the flow across the surface.

In the near-limit case [when: (1) oxygen concentration approaches flammability limits; (2) heat losses sufficiently high; (3) air flow rate sufficiently low] a complicated form of flame spread behavior occurs. This behavior shows flame front breakup into separate flamelets and propagation of fingered flamelet fronts. Systematic causes and long-term behaviors of such flamelets are not understood: whether they are benign, whether they represent nascent precursor flames, whether they represent an intermediate state between flaming and smoldering. Flamelets develop in low-gravity conditions when the influences of buoyancy are smaller than under normal gravity conditions.

Previous extended zero-***g*** work includes Space-Shuttle studies of smoldering [Olson et al (1998)]. This research is a fully zero-***g*** version of the smoldering process studied in an Earth-based apparatus, the precursor to the MSU Hele-Shaw facility, by Zik et al. (1998). In the work of Zik the samples lay on the substrate. Both flame spread and smoldering were possible, although attention was focused on smoldering. Both Olson et al. (1998) and Zik et al. (1998) obtained smolder front bifurcations. We note that Olson et al. (1998) did not use a substrate, and that Zik et al. (1998) used elevated O_2 concentrations (not air). Olson et al. (1998) used a potassium acetate doped cellulose fuel to promote smoldering while inhibiting flaming.

Based on this previous research, a framework for ATHINA was built upon the notion that flame spread in near-limit conditions depended upon *two* quantities, (I) the *heat losses* and (II) the *oxidizer transport rate*. Quantity (II) is varied by changing: (1) the O_2 level or (2) the opposed flow velocity. In our work we fixed the oxygen mass fraction Y_O at the level in the ISS (23% in N_2). With the Y_O fixed, near-limit conditions are created by either continually increasing the sample-to-surroundings heat losses or keeping the heat losses constant while decreasing the oxidizer transport rate (i.e., the air flow rate). See **Figure 1** for a qualitative rendering of the influences of (I) and (II) on flame/flamelet transition.

In principle, there are many ways to accomplish the heat losses from the sample. The ATHINA approach is to insert, beneath the sample, a *backing* or *substrate* material that carries heat away from the sample (mostly by conduction and radiation). In the limit that the sample touches the substrate, Zik et al. (1998) obtained pure smoldering spread. When there is a gap, flamelet spread occurs.

Hele-Shaw Apparatus

A facility was constructed that produces zero-gravity-like conditions to provide "ground-based support" for the zero-***g*** ATHINA flight project. Flamelet behaviors were observed over time periods of the order of several minutes. The Hele-Shaw apparatus resembles the apparatus built by Zik et al. (1998) to study low-***g*** smolder front propagation in elevated O_2 atmospheres. The Hele-Shaw facility has a wide operating range. It yields data on flame spread analogous to present NASA drop tests. We provide a brief summary of some of the results of our research effort. In the Hele-Shaw apparatus, air flows from a plenum through a porous flow-straightening plate into the test section. Test section flow velocities are calculated using flowmeters. Tests have used the hot wire technique to measure the velocity field, which resembles a fully developed laminar channel flow.

In the test section, a backing (substrate), whose spacing can be adjusted, is placed beneath the sample, while a transparent quartz plate is placed above it. Air and combustion products are exhausted downstream to the atmosphere. Samples are ignited downstream of the inlet using a high resistance wire. Ignition of the sample occurs at a high flow velocity that is ramped down for the final test section flow speed. The ignition procedure establishes a uniform, flat flame front. Subsequent instabilities are then attributed to inherent flame dynamics, not initial irregularities of the flame front. The substrate is a heat sink made of polished copper. The samples are secured an equal distance between the copper backing and top quartz plate.

Results

At all test section/substrate heights, *h* (defined here as the distance between the sample bottom surface and the substrate), flames began as spreading uniform fronts. Reduction of airflow caused the blue front to either break apart or extinguish. The tiny flamelets remained present for most conditions. At lower oxidizer flow rates some of the cellular flames would continue spreading down the sample displaying additional instabilities. A test is shown in **Figure 2**.

Experiments indicated that for high gap spacings *h* the flamelet sizes increased and flamelets were more stable. This suggested that the flame front acts as a barrier to the oxidizer flow. Tests that were conducted in drop towers had a much larger *h* than the Hele-Shaw apparatus. Oxidizer was able to travel behind the flame front (i.e., "leak") around the flamelets, giving an oval shape. Flamelets rarely oscillated when this occurred. Only the side edges oscillated with a frequency of order 1 Hz. Oscillations either ceased and a more stable flamelet continued to spread across the fuel, or the oscillations led to extinction.

An interesting and unexpected behavior was seen for *h ~ 3,5,8 mm*. A fast flame pulse traveled across the flamelet front at frequencies ranging from *2 - 15Hz* at various flow velocities and test section heights. Pulses originated in either the middle or edge of the front and moved over the flame front. These pulsations may be related to the formation of a combustible partially premixed gas mixture of fuel vapors (volatiles) and air between adjacent flamelets that can, when "triggered," produce premixed flame propagation across the flamelet front. This mechanism requires further investigation by high-speed camera.

In some tests**,** the flamelets displayed fingering patterns like the smoldering/flame spread patterns found by Zik et al. (1998) and Olson, et al. (1998). In these cases, the flamelets were evenly spaced and rarely combined with each other. This suggested that adjacent flamelets competed for oxidizer. The substantial char-zone length before actual commencement of fingering suggests a long transition period for its occurrence. Some flamelets split and then branched, always readjusting to become evenly spaced. In cases with a single flamelet, several branches formed and burned to the end of the sample. For some tests at *5 mm* and *8 mm*, the blue thin continuous flame front did not break apart and spread to the end of the sample. The oxidizer flow was decreased but the oxygen transport was sufficient so the flame front did not corrugate. As the flame burned through the edge**,** it turned from blue to yellow and sooty and burned more vigorously, indicating either that the flame acted as a barrier to the oxidizer transport or there is oxidizer available at the edge. As the flame burned through the sample air filled the middle open section allowing oxidizer to penetrate behind the flame front. This produced a stronger burning flame since yellow soot, which forms at higher flame temperatures than in blue flames, was observed.

The research conducted in the Hele-Shaw apparatus has enabled the construction of the Hele-Shaw version of the Flammability Map (see **Figure 3**, which should be compared with the leftmost upper part of **Figure 1**).

It is possible to speculate that the instabilities are driven by reduced oxidizer transport rather than heat losses. When the sample to quartz plate gap distance is fixed and the flow velocity is constant, variation of the gap distance between sample and substrate can produce the full spectrum ranging from flame fronts to flamelet fronts. Thus, although reduced oxidizer transport is important when the gap between sample and quartz plate diminishes, the adjustment of heat losses can, without alteration of the geometry and flow of oxidizer, produce the full spectrum of flame responses.

Statistical results

Another task concerns the statistical behavior of the flamelets as they form, bifurcate and extinguish. The Hele-Shaw tests show the time progression of formation (birth) by bifurcation of an existing flamelet into two flamelets and extinguishment (death) by extinction of the flamelets as they run out of oxidizer or are starved of oxygen by their neighbors. In these tests, it required ~ 5s to establish the flow (flow speed = 5 cm/sec) which gave the precise conditions under which the flame breakup tests took place. The flamelets that formed were tracked and counted as bifurcations and extinctions occurred. The flamelets were numbered from top to bottom at the beginning of the breakup, and each one was followed through its history. The position-time data give good linear correlation for the test time period. The flamelet bifurcations and extinctions were tracked in time and the total population of flamelets as a function of time is determined from the data. Each bifurcation adds one flamelet. Each extinction subtracts one. The bifurcations and extinctions show a linear cumulative number of events, which means they occur at a nearly constant rate. The slopes are slightly different, however, which suggests a gradual increase in population (average) over the test time. However, the average population is sufficiently small that this difference is not apparent within the scatter of the population with time (avg ~12). The running average is shown for comparison. Only data after breakup are used.

In order to obtain meaningful population data, the cumulative number of events should exceed twenty (20) as a minimum. Although the flamelet spread rate seems to reach steady state quickly, it requires time to obtain population statistics. For a bifurcation and extinction rate of 0.14 Hz, 214 seconds of data after breakup are needed to observe thirty events. In addition, this sample was 18 cm wide, and flight samples will be 12 cm at most. Hence, the anticipated number of flamelets obtained will be 3-5 (based partly on drop tower experience, which gives 5 or 6 flamelets on a 15 cm wide sample). Each bifurcation and extinction (*+1* or *–1*) will strongly affect the running averages, hence more time is needed for good averages. A steady or "stable" population is one with a nearly constant value, with nearly equal "birth" and "death" rates. See **Figure 4** for representative results.

Calculations

A one-dimensional model for predicting heat and mass transfer in thin cellulosic fuels using the Broido scheme was developed in order to model heat and mass transfer during flame and flamelet spread over thermally thin cellulosic fuels. Using this model, a numerical study was performed to indicate: (1) the heat transfer mechanism that dominates flame spread; (2) the role of the "backing" or heat-loss substrate on the flame spread mechanism; (3) the influence of actual cellulose pyrolysis kinetics on the heat transfer, release of volatile combustibles and formation of char from the original solid fuel. A multi-step physical model for heat and mass transfer in cellulose decomposition was examined for the case of flamelet propagation over thin solid fuels. In this model, the cellulose decomposes to volatiles and char through active cellulose during the heating processes. The decomposition model uses the Broido-Shafizadeh mechanism.

A short temperature drop period was observed in the solid fuel during the heating and pyrolysis process. Numerical results indicated that the solid fuel temperature was sensitive to the chemical rate parameters E_v and E_c in the Broido-Shafizadeh scheme governing equations. Emissivity variation during the pyrolysis process had little influence on temperature profiles. The volatile diffusion process was numerically simulated and the results enabled the calculation of an approximate flame existence time, which agrees satisfactorily with experiments, suggesting that the parameters used in the numerical computations were reasonable

Conclusions

The Hele-Shaw facility is capable of examining numerous features of zero-**g** flamelet spread. It has the advantage of providing long test times and accurate flow field conditions. Hot-wire measurements of the velocity fields inside the test section showed good agreement with theoretical profiles. Many questions remain. Although oxidizer transport has been shown to be crucial, it remains to examine its influences when Y_O is changed keeping the flow constant. In this case, the fluid dynamical transport is unchanged but the mass transport to the flamelet is increased. This trade-off must be examined. Also, the details of the Hele-Shaw apparatus need to be scrutinized. In future experiments we will determine the degree to which simulated low-**g** conditions are attained when the present right-side-up Hele-Shaw apparatus is turned upside-down. If the upside-down tests differ greatly, **g** still plays an important role in the Hele-Shaw tests. Finally, and perhaps most importantly, we have not conclusively demonstrated (yet) that the flamelet regime is in fact a stable, non-transient (i.e., either temporary and unstable) actual intermediate physical regime lying between flaming and smoldering. To demonstrate this, long tests with many flamelets and flamelet "events" ("births" and "deaths") are required.

References

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Figure 1. Conceptual plot of flame spread instability process showing the stable flame spread dome surrounded on the left by the near-limit flamelet instability region and on the right by the blowoff regime.

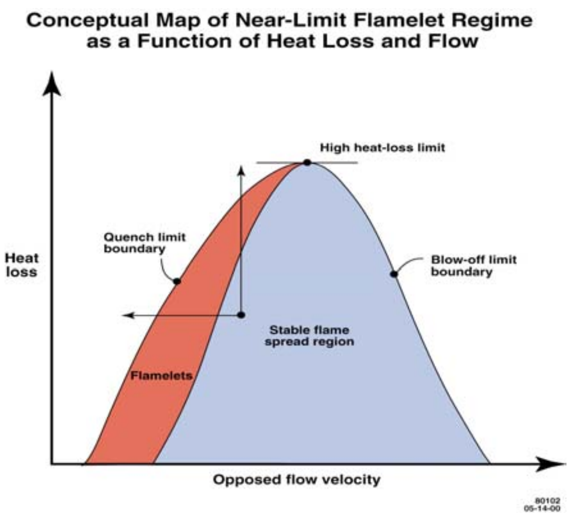

Figure 2. Instability development during flame spread. Note that the flame front breaks into fragments that later form flamelets, which may terminate or combine or divide.

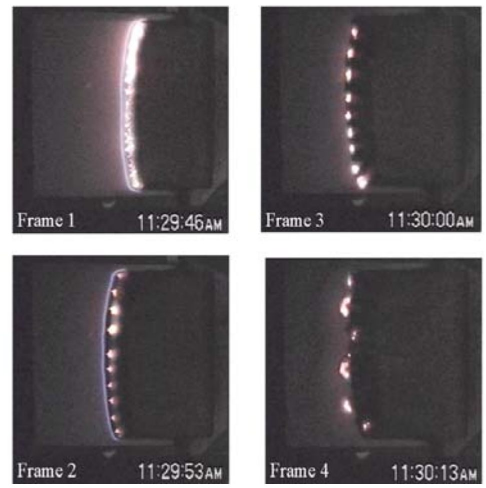

Figure 3. The Flammability Map for the Hele-Sh Rig. Also shown are data from other sources [Olson et al. (2001)].

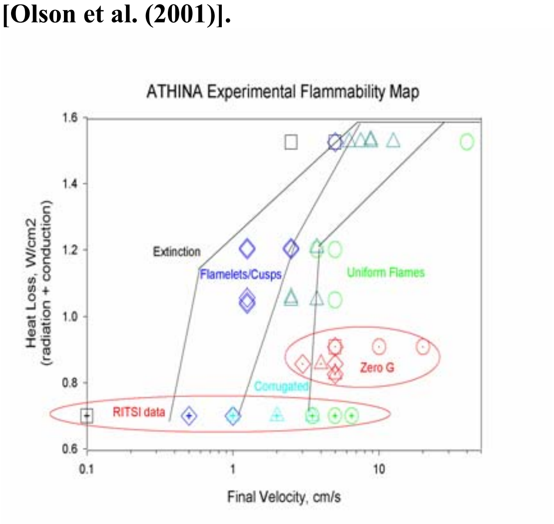

Figure 4. Flamelet bifurcations and extinctions counted cumulatively. The flow speed is 5 cm/sec. The gap spacing was 5 mm.