DESIGN AND FABRICATION OF A HELE-SHAW APPARATUS FOR OBSERVING INSTABILITIES OF DIFFUSION FLAMES

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1. INTRODUCTION

Examinations of flame fronts spreading over solid fuels in an opposed flow of oxidizer have shown that the flame front fragments into smaller (*cellular*) flames. These "flamelets" will oscillate, recombine, or extinguish, indicating that they are in the near extinction limit regime (i.e., to one side of the quenching branch of the *flammability map*). Onset of unstable cellular flamelet formation for flame spread over thin fuels occurs when a heat-sink substrate is placed a small distance from the underside of the fuel. This heat-sink substrate (or *backing*) displaces the quenching branch of the flammability map in a direction that causes the instabilities to occur at higher air velocities. Similar near-limit behavior has been observed in other works [1-3] using different fuels, thus suggesting that these dynamic mechanisms are fuel-independent and therefore fundamental attributes of flames in this near-limit flame spread regime. The objective of this project is to determine the contributions of the *hydrodynamic and thermodiffusive mechanisms* to the observed formation of flame instabilities. From this, a model of diffusion flame instabilities shall be generated.

Previously, experiments were conducted in NASA drop towers [4], thereby limiting observation time to O(1-5 sec). The NASA tests exhibited flamelet survival for the entire drop time, suggesting that flamelets (i.e., small cellular flames) might exist, if permitted, for longer time periods. By necessity, experiments were limited to thermally thin cellulose fuels *(~.001 in* thick): instabilities could form by virtue of faster spread rates over thin fuels. Unstable behavior was unlikely in the short drop time for thicker fuels. In the International Space Station (ISS), μg time is unlimited, so both thin and thick fuels can be tested.

1.1 The Hele-Shaw Apparatus for Normal Gravity Simulation of Low-g Flow:

Hele-Shaw (HS) apparatuses have been used as flow visualization devices for irrotational fluid flow. For the HS geometry, buoyant flow between the two closely separated plates is suppressed. In essence, flame spread experiments in the HS apparatus are simulations of microgravity flames because the influence of gravity is minimized. Although the drop towers provide valuable information for flame instabilities, the Hele-Shaw is advantageous to this project because test times are unconstrained.

EXPERIMENT

Schematics of the test section and flow system of the HS apparatus, which in this project is called the "MSU Rig", are shown in **Figures 1** and **2**. The overall (outer) height of the apparatus was constant, however, spacer plates allowed test section (inner) heights to vary between *0.2-1.2 cm*. The very narrow gap along which the air flowed prevented the appearance of buoyant cells arising from the heated lower sample, caused by the flame spreading over it. For initial testing, thin cellulose fuels were used with a copper substrate backing in order to compare with prior NASA experiments. A high resistance wire ignited the sample. A quartz plate formed the transparent top of the test section. The flow above the sample (between sample and top of test section) was subsequently exhausted to the downstream ambient atmosphere.

The flow system provided low flow velocities from *1-30 cm/s* in the test section. The bulk velocities in the test section could be estimated during the course of each test. This was possible due to the O-ring system used to seal the MSU Rig. Preliminary testing indicated that higher flow velocities than those used in the thin fuel NASA drop tower tests (above ~ *6 cm/s*) were needed to generate a flat uniform flame front. In addition, plenum fill times for low flow rates were in excess of ~ ½ hour, so our needle valve arrangement provided near-instantaneous flows in the test section.

At the beginning of each test, the needle valve flushed the test section with oxidizer at a higher flowrate than the test condition for instabilities. Higher flow rates were needed because the top of the test section acts as a heat sink for the flame. When an even flame front was established, the needle valve was closed until the flame front became corrugated or broke apart into cellular flames. Usually, this occurred when the needle valve was fully closed and most of the air was directed through the channel containing the flow orifice.

A ramp inside the contraction increased the velocity of the air before it entered a sintered porous plate. Since the cross sectional area of the test section was changed for different tests, a contraction nozzle-type geometry---often used in wind tunnels---could not be used to produce uniform flow. This was due to the fact that the rigid apparatus materials could not flex with varying test section heights. Instead, a porous plate (*5 micron pores*) was used to diffuse vortices and/or flow irregularities from the plenum and ramp. Plates on either side of the porous plate prevented air losses from under the test section or from under the ramp. In other words, the ramp led to an opening that was as large as the test section on both sides of the porous plate. See **Figure 1.**

DEVICE PARAMETERS AND PRELIMINARY RESULTS

Each section of the MSU Rig was carefully constructed based on conservative estimations of the flow field. The porous plate was chosen based on the supplied pressure drop. When the pressure drop across the porous plate was at least two orders of magnitude higher than the dynamic pressure, any effects from vortices, etc. would not be felt in the test section.

Boundary layer calculations were made using extreme flow conditions in order to determine maximum test section entrance lengths. This ensures proper placement of the sample: no part of it should be located in the side-wall boundary layer. This calculation was used to decide the maximum sample width and length. It was sought to test with the widest possible samples, since repeating instabilities will occur across the entire fuel surface and a large width allows adequate resolution.

Preliminary tests of the MSU Rig showed that for test section heights from 0.3-0.9cm, and substrate distances of 0.5cm and 0.7 cm flat flame fronts result as shown in **Figure 3.a**. The uniform flame fragmented into cellular flames that created a fingering pattern like the one in **Figure 3.b**, which was very comparable to smoldering flames in the experiment of [2]. In many tests, upon decreasing the oxidizer flow, the entire flame front would begin to slowly oscillate resembling the motion of a standing wave produced by a string with fixed end nodes. A sine wave flame front would ensue, and the flame would abruptly change from sooty yellow color to a much thinner blue flame that was only a few millimeters across. In many cases, a very rapid pulse would travel across the length of the sooty flame front. Further decreases in the airflow caused the blue flame to corrugate and begin its fingering motion. Tiny cellular flames would meander down the sample, sometimes oscillating or extinguishing. The corrugation and oscillations resembled the flamelets seen in the drop tower experiments, however, the flamelets were often yellow in color and the oscillation frequencies were larger than in the NASA tests. Often the yellow flamelets would transform into bright blue crescent flames in which the curvature was in the direction of flame spread. These flame shapes were very stable, rarely oscillating, and they resembled the very stable oval flamelets with blue leading edges in the NASA tests. In some runs, after the flamelets extinguished, pulses and oscillations would occur and the entire front would re-ignite. *It is very important to observe that this series of events always occurred in the same sequence.*

All of these preliminary tests indicated very complex flame dynamics near the extinction limit, which were qualitatively similar to previous drop tower tests. Future testing will include surface thermocouple measurements. An energy balance will be evaluated for the flame spread process and compared with previous drop tower evaluations. Thicker fuels such as PMMA will be tested, as well as other thin fuels. A hotwire will be used to calibrate the variable area flowmeter, so transient air velocities can be measured *in situ*. The hotwire will also be used to determine turbulence (i.e., fluctuation) intensities downstream of the porous plate. Flamelet spacing and dynamics will be observed for various test conditions, and incorporated into the theoretical model.

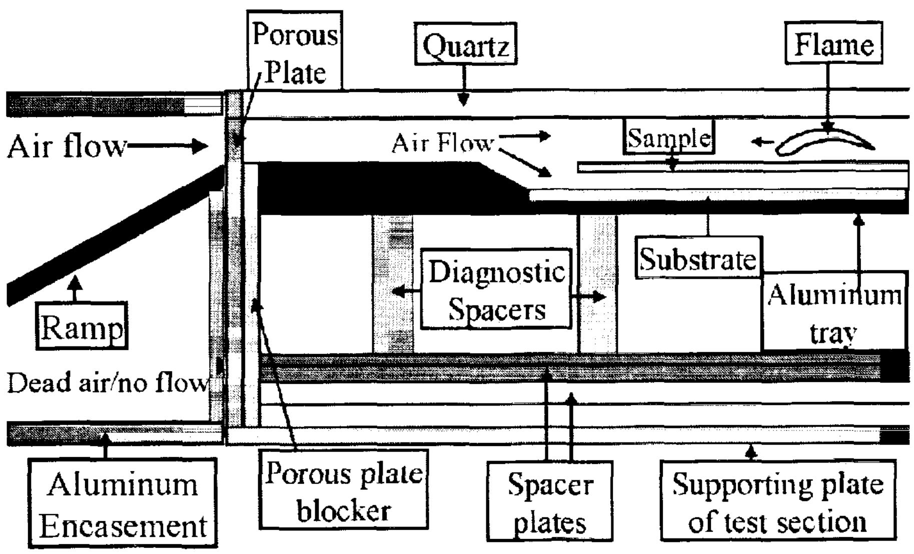


Figure 1. Schematic of MSU Rig test section.

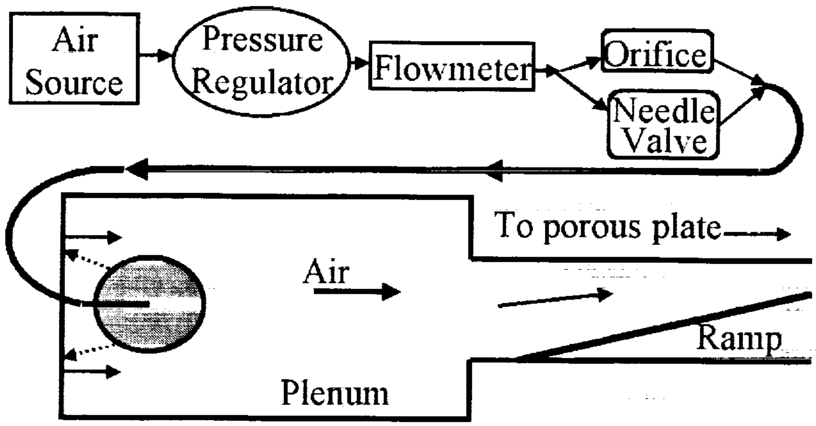
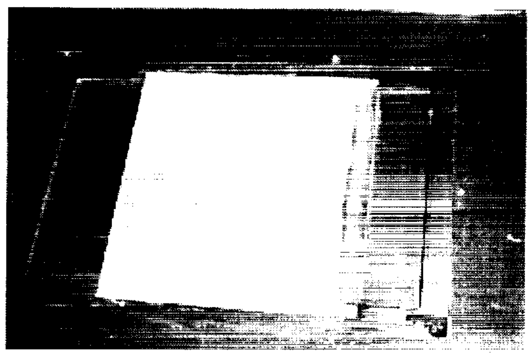


Figure 2. Schematic of MSU Rig flow system.



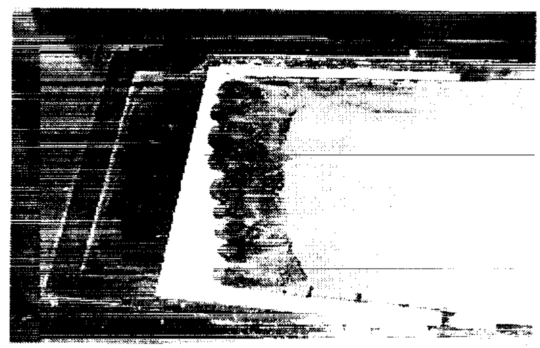


Figure 3.a. Uniform flame front **Figure 3.b.** Fingering instabilities

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