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# Experiments in Upward Flame Spread

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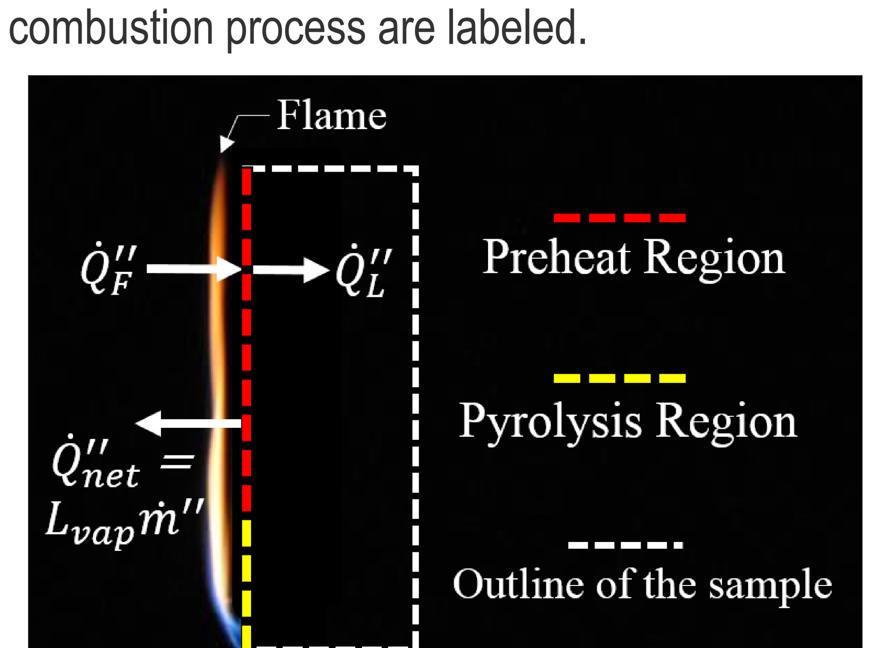
## Introduction

Being able to predict flame spread characteristics is a valuable skill in the field of Fire Protection Engineering, as well as fluid mechanics, when attempting to increase energy efficiency of solid fuels. The physical driving factor that allows engineers to predict flame behavior is the rate at which the flame heats up the fuel/material surface, or the heat flux (heating rate per unit area). The heat flux onto the fuel surface is often assumed to be constant in calculations, but empirical data and logic indicate otherwise. Measuring the net heat flux directly is impossible, as it would require placing expensive equipment in direct contact with the flame. Therefore, indirect means of measuring the heat flux from the flame are required. Performing an energy balance at the surface of the fuel being preheated shows that the sought after heat flux can be inferred by knowing the heat conducted into the material, the latent heat of vaporization, and the mass flux (the mass loss rate per unit area currently undergoing pyrolysis). Pyrolysis is the process by which burning fuel decomposes without the use of oxygen. The fuel gasifies into fuel vapor and combusts, thereby producing a flame. In this experiment, Poly(methyl methacrylate) (PMMA, or "Plexiglass") is used because it is a relatively clean burning fuel, and it produces little soot. The mass loss rate of the PMMA sample and the area where combustion is occurring, known as the pyrolysis region, are measured simultaneously using instantaneous mass measurement and image processing. The simultaneous measurement of these quantities has never been done before.

**Figure 1 -** (below) A digital photograph taken at UB of a combusting PMMA sample. Depictions of the preheat region, pyrolysis region and the driving heat fluxes in the combustion process are labeled.




$\dot{Q}''_F = Heat\ Flux\ from\ the\ Flame$

$\dot{Q}''_L = Heat\ Flux\ lost\ from\ Conduction$

$\dot{Q}''_{net} = Net\ Heat\ Flux\ Gained$

$\dot{m}'' = Mass\ Flux$

$L_{vap} = Latent\ Heat\ of\ Vaporization$

## Material & Methods

As mentioned previously, the energy balance at the surface of the preheat region yields the following equation:

$$\dot{Q}''_F - \dot{Q}''_L = \dot{Q}''_{net} = L_{vap}\dot{m}'' \quad (1)$$

As with $\dot{Q}''_F$, the mass flux is also commonly assumed to be constant. Since $\dot{Q}''_F$ is known to actually not be constant, $\dot{m}''$ cannot be constant either, as dictated by equation 1. Therefore quantity of interest at this step in determining the heat flux from the flame is the mass flux, $\dot{m}''$. The mass flux can be calculated by measuring the mass loss rate of the sample, and the area of the pyrolysis region, as defined by the following equation:

$$\dot{m}'' = \frac{\dot{m}}{A} \quad (2)$$

$\dot{m} = Mass\ Loss\ Rate\ ,\ A = Pyrolysis\ Area$

To acquire these two quantities simultaneously, a PMMA sample is hung from a highly accurate mass balance and set on fire. The instantaneous mass of the sample was measured using a high accuracy mass balance. The mass loss rate is computed from these values by taking the mathematical derivative of the mass with respect to time. A camera with an external flash simultaneously takes time-lapse digital photographs of the pyrolysis region. The flash cuts through the flame, illuminating a pyrolysis front that can be easily identified and processed in MATLAB.

The appeal of using PMMA as opposed to other materials is that the pyrolysis (or "bubble") front can be readily tracked when illuminated using a laser or LED light. The bubble front is the upward moving boundary of the pyrolysis region, which shows exactly where gasification is occurring in the material.

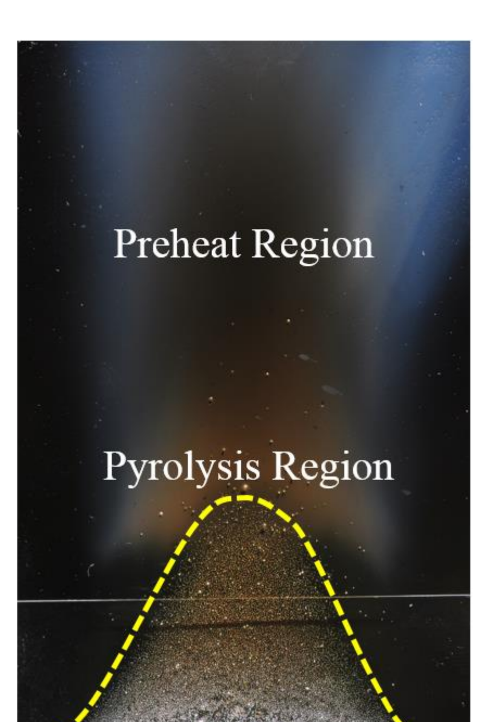



**Figure 2 -** (left) A digital photograph taken at UB of the pyrolysis region where the moving pyrolysis front is highlighted in yellow. The preheat region is labeled as well.

## Image Processing

In order to distinguish the shape of the pyrolysis region and measure the area, the digital images were imported and processed using the MATLAB Image Processing Toolbox.

The process that was developed involves converting the raw image of the combustion experiment into a binary image (pixels of only black and white), where the only white object in the image is the pyrolysis region. Once the region is represented by only the white area, it can be outlined, and the outline then used to extract the dimensions. To demonstrate the process, we have processed a single image of the combustion of PMMA, as seen below:

Figure 3: Raw Digital Image

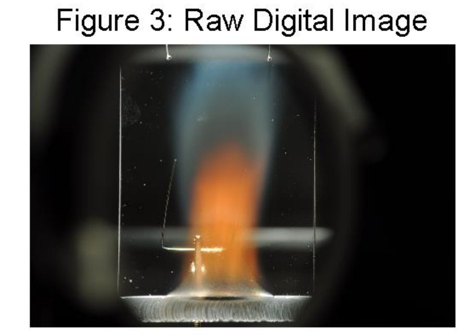
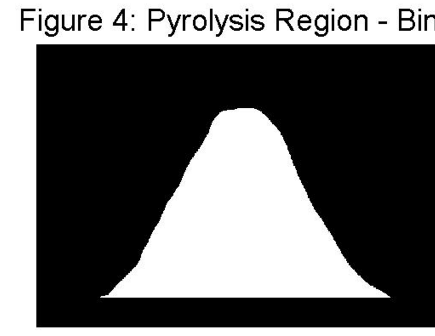


Figure 4: Pyrolysis Region - Binary



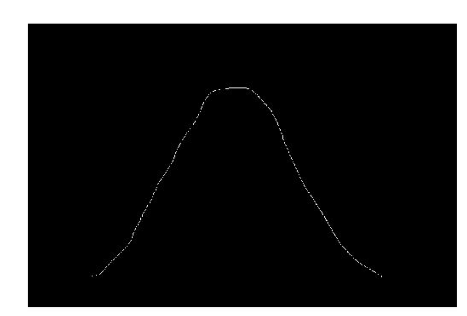


Figure 5: Pyrolysis Region Boundary

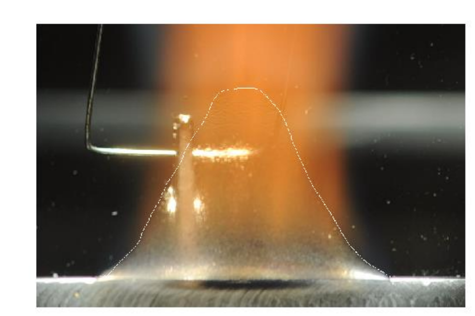


Figure 6: Original Photo with Boundary Overlay

**Figure 3 –** Import the raw photograph into MATLAB
**Figure 4 –** Highlight the pyrolysis region if necessary, then convert the image to a binary image
**Figure 5 –** Determine the location of the pyrolysis region boundary
**Figure 6 –** Overlay the outline onto the original photo to verify that the outline is an approximate representation of the pyrolysis region shape

By performing this procedure over all of the time-lapsed images, the area is determined as a function of time.

## Data

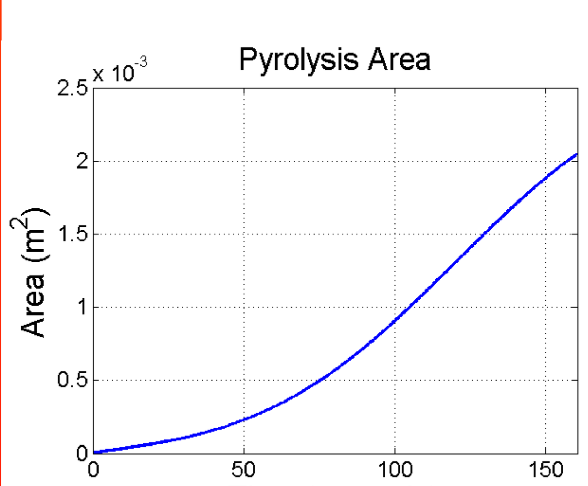



**Figure 7:** The pyrolysis area is plotted as a function of time. The data is acquired through image processing of the images of the pyrolysis region.

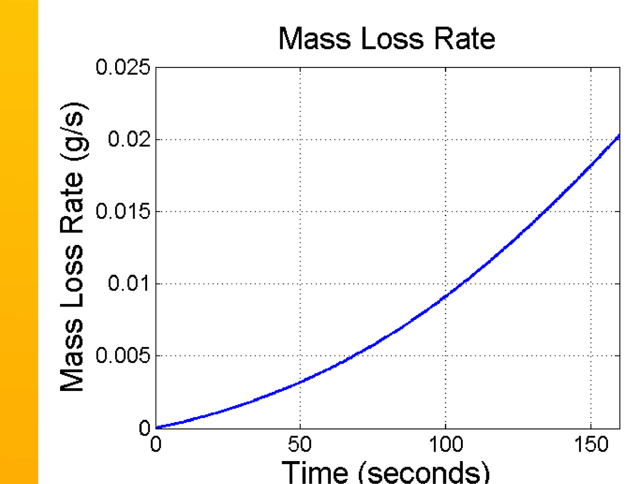



**Figure 8:** The mass loss rate of the sample is plotted as a function of time. The data is acquired through instantaneous mass measurement of the PMMA sample.

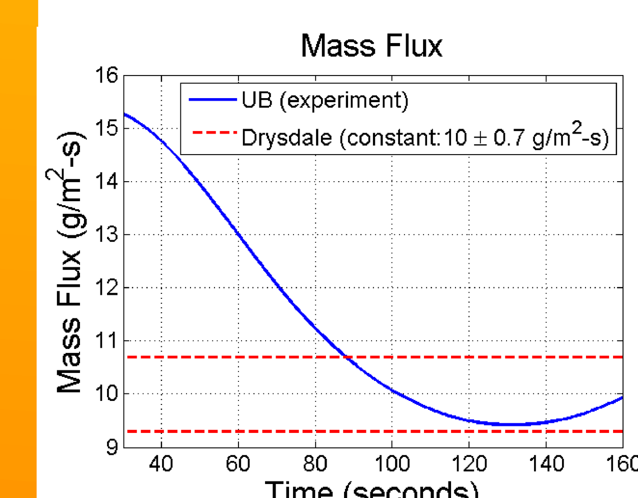



**Figure 9:** The mass flux is plotted as a function of time. Obtained by dividing the mass loss rate by the pyrolysis area, both of which where measured simultaneously.

As seen in Figure 9, the mass flux does not remain constant over time. When compared with Drysdale, the UB mass flux readings remain bounded by the range of constant mass flux given by Drysdale, but only for times 90 seconds past the beginning of combustion. This indicates that the range of constant mass flux given by Drysdale does not represent mass flux for times at the beginning of combustion.

Through this experiment, simultaneous mass measurement and image processing were used to indirectly measure the mass flux as a function of time, an accurate process that has never been used before. Future plans involve embedding PMMA with thermocouples to measure the heat flux lost due to conduction, thereby providing the final measurement necessary to successfully indirectly measure the heat flux from the flame.

## References

- Boonmee, Nathask, and James G. Quinitiere. *A Theoretical Investigation of Surface Glowing Ignition Leading to Gas Flaming Autoignition*. Diss. University of Maryland (http://www.iafss.org/publications/fss/8/139/view)
- Xie, W. and DesJardin, P.E., "An Embedded Upward Flame Spread Model using 2D Direct Numerical Simulations," Combustion and Flame, pp. 522-530, 2009
- Drysdale, Dougal. *An Introduction to Fire Dynamics*. Second ed. Chichester: John Wiley and Sons, 1998.

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