Evolution of Flame to Surface Heat Flux During Vertical Flame Spread on Poly Methyl Methacrylate (PMMA)

1. Introduction

The growing prevalence of synthetic polymers in buildings and other structures has reinforced the need to evaluate and understand the hazards that they pose, specifically in fire scenarios. Flame spread over a material, which is governed by flame heat feedback to the unburned fuel surface, is the key determinant of the early stages of fire growth.

2. Impact

Many standards currently used to rate material flammability offer limited insight into the physical processes that govern incipient fire growth (e.g., UL 94—a widely used test for plastic material flammability—‘Fig. 3’) and hence provide little indication of material performance outside of standard test conditions. This work (Fig. 4) allows for a quantitative study of sample ignition and upward flame spread, at the critical length scale at which flame spread determines fire growth, by providing direct measurements of sample mass loss rate and flame to surface heat feedback.

3. Experimental Work

Following uniform ignition of a 5 cm wide, 0.5 cm thick sample of PMMA at its base, a flame is allowed to freely propagate upwards over its surface until the entire sample is involved. Detailed heat flux measurements are recorded at the top of each sample using a 0.95 cm wide water cooled Schmidt-Boelter heat flux gauge. By varying sample height in 1 cm intervals, from 2 to 15 cm, data from each test can be combined to provide an effective heat flux profile across full sized, 15 cm tall, samples. This approach avoids complications that would arise if multiple thermostated elements were placed across the sample to measure the entire flame heat flux profile at once. Sample mass loss rates are determined separately, in a similar manner, but at 2 cm intervals in sample height. Using these measurements, an analytical expression relating the flame heat feedback profile to material burning rate has been developed.

4. Results

Fig. 6 exemplifies the data collection process—individual tests (here, mass loss rate of 13 cm tall samples) are repeated and data from each is averaged together to produce a representative curve at that sample height. These curves are then smoothed and plotted as a function of sample height, from 3 cm to 15 cm.

Incident heat flux was measured similarly as described above. At 6-15 cm above the bottom edge of the flame, the maximum heat flux value, \( q_{\text{flame}} \), was found to be on the order of 35 kW m\(^{-2} \). From 2-5 cm above the flame bottom, where the flame is thinner and closer to the sample’s surface, the maximum heat flux is slightly higher, about 40 kW m\(^{-2} \). Spatially resolved heat flux profiles were obtained from time dependent measurements as exemplified in Fig. 7.

Coupling these results with mass loss rate data allowed for the production of the analytical model expressed below, which has been shown to accurately predict the measured flame heat flux profile as a function of material burning rate. Symbolic terms \( q_{\text{flame}} \), \( x \), and \( y \) represent measured flame heat flux, height above the base of the sample/flame, and flame height, respectively. Additional parameters \( a, b, r, \omega, \) and \( \gamma \) are empirically derived constants.

Analytical Model of Flame Heat Flux:

\[
q(x, y) = q_{\text{flame}}(y) \left( 1 - \frac{x}{L} \right) \left( 1 - e^{-\gamma y} \right)
\]

where \( q_{\text{flame}}(y) \) is given for various heights above the flame base, \( y \), and the convolution integral is solved numerically.

5. Future Work

Preliminary work has been performed to couple this analytical model of flame heat flux with a two dimensional pyrolysis solver, ThermaKin2D, as seen in Fig. 8. Once all elements of the model are validated, it is expected that this will provide highly accurate simulations of the flame spread dynamics of this system with reasonable computation time.

Further experimental work is also aimed at possible generalizations of the analytical model to both larger sample geometries and additional polymers. The burning rate and flame heat feedback profile of a second material, acrylonitrile butadiene styrene (ABS), has recently been extensively studied, similarly as described above for PMMA. Experiments have revealed that surface flame spread across ABS is controlled by a secondary effect—the formation of a thick soot/char layer that grows beneath the flame, at the surface of the unburnt material, as it burns in the vertical configuration (Fig. 9).

Acknowledgements

This work was supported by the Federal Aviation Administration under Grant Number 09-G-018, monitored by Dr. Richard E. Lyon.