Prediction of Flame to Surface Heat Feedback and Vertical Flame Spread in Wall Fires

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Motivation

The growing prevalence of synthetic polymers in buildings and transportation vehicles 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.

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) and hence provide little indication of material performance outside of standard test conditions.

This work (Fig. 3) 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, \( q_{f} \).

By developing a model that predicts flame heat feedback as a function of material burning rate and coupling it with a numerical pyrolysis solver, ThermaKin2D, which computes the transient rate of gaseous fuel production of a material in response to this energy transfer, a high accuracy simulator of upward, natural-convection-driven flame propagation has been produced.

Experimental Work

By measuring sample burning rate and flame heat flux throughout each test, a highly spatially resolved flame heat feedback profile (both in the steady region of the flame, \( y < y_{b} \) and farther downstream) can be defined solely as a function of sample burning rate. Here, flame height, \( y_{b} \) is defined by a threshold value of wall flame heat flux, rather than simply based on visual observations.

\[
\frac{dm}{dt} = \frac{d\dot{q}}{dy} \left( y - y_{b} \right)
\]

Model Verification

Verification studies show excellent agreement between experimentally measured flame heat flux and the values predicted by the model defined by the equations above. As seen in Fig. 7, flame height is well predicted and there is no consistent over- or under-prediction of heat flux farther downstream. Overall, total heat transfer [kW] to the material is calculated, on average, to within 5% of measured values throughout the full duration of experiments.

Values in the legend at right indicate \( t \), after sample ignition with the subscript ‘p’ designating model-predicted values.

Model Validation and Prediction of Upward Flame Spread

Measured peak, steady state flame heat flux, \( \dot{q}_{f} \), was validated by conducting mass loss tests on 4 cm tall PMMA samples, which were entirely covered by the continuous portion of the flame shortly after ignition. These tests were simulated in ThermaKin2D (Fig. 8) with model calculations confirming the accuracy of measured values of \( \dot{q}_{f} \) and their parameterization in ThermaKin2D.

A 17.5 cm tall PMMA sample was similarly defined in ThermaKin2D to test the model's ability to predict the full flame spread process. Fig. 9 shows the accuracy of these results – time to ignition and initial mass loss rate are both well predicted and model calculations of the rate of rise and peak sample mass loss rate also show good agreement with experimental measurements.

Moving Forward – A Generalized Model

Significant advancements in this model's capabilities can be made by generalizing it through straightforward scaling such that it can predict the behavior of a wide range of common wall materials.

Already, preliminary measurements of material burning rate and flame heat flux of Acrylonitrile Butadiene Styrene (ABS), High Density Polyethylene (HDPE), High Impact Polystyrene (HIPS), cast PMMA, Polyoxymethylene (POM), and Polypropylene (PP) provide promising evidence that such a generalization is possible; however, additional testing is required before formal comparisons can be made.