Heat transfer components at the surface of burning thick PMMA slabs

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Abstract. Mass pyrolysis rate is the key parameter to predict fire behavior. It is generally deduced from the energy balance at the surface of the solid material. However, due to lack of knowledge, existing pyrolysis models use simplifying assumptions neglecting all or part of in-depth losses into the solid material or the net radiation at its surface. In order to improve the accuracy of pyrolysis models, experiments are conducted to quantitatively evaluate the heat transfer components at the surface of burning thick clear poly-methyl-methacrylate (PMMA) slabs at steady state. The contributions of each transfer mode including radiation and convection from the flame, surface re-radiation, and in-depth losses, to total heat flux are determined from two series of experiments. Pure pyrolysis (non-flaming) cone calorimeter experiments are first carried out to evaluate in-depth losses in horizontally-oriented slabs exposed to an incident heat flux below that of ignition. A specific procedure based on video processing is used to track the position of the PMMA regressing surface with time. The second series of experiments consist in burning vertically-oriented slabs from 2.5 cm to 20 cm in height, 10 cm in width and 3 cm in thickness. It is found that only a small part of flame radiation is transmitted through the virgin solid, most in-depth radiation being absorbed by the bubble surface, which in turn strongly emits radiation inward. An excellent agreement is obtained between the local mass loss rate deduced from the energy balance and literature data.

1. Introduction
For steady-state flames over a dry semitransparent solid fuel (here, clear PMMA), mass pyrolysis rate can be related to heat fluxes through an energy balance equation at the surface of the solid material:

\[ \dot{m}h_g = q_{fl} - q_{rr} - q_{rad}^{id} - q_{cond}^{id} \] (1)

In this equation, \( h_g \) is the heat of gasification, \( q_{fl} \) is total heat flux from the flame, \( q_{rr} \) re-radiative heat flux, and \( q_{rad}^{id} \) and \( q_{cond}^{id} \) are radiant and conductive in-depth heat fluxes, respectively. The left-hand term represents the energy consumed in pyrolyzing the solid fuel.
Among the existing pyrolysis models (e.g. latent heat, chemical kinetics, etc.) only a few of them are capable of reproducing the pyrolysis process in simple and well-ventilated situations. The main difficulty comes from the assumptions used to simplify model formulation, neglecting all or part of in-depth losses into the solid fuel (Figure 1). In studies dedicated to upward fire spread, Orloff et al. [1], Beaulieu and Dembsey [2], Gollner et al. [3] and Tsai and Wan [4] developed specific experiments to determine the contributions of some components of the energy balance. However large discrepancies between reported data are found.

In the present study two series of experiments are conducted to determine the contributions of all possible heat transfer mechanisms in order to better understand the pyrolysis process of solid fuels at steady state.

The procedure follows a predetermined sequence of operations:

- Re-radiative and in-depth radiant heat fluxes are evaluated from pure pyrolysis (non-flaming) cone calorimeter experiments using horizontally-oriented PMMA slabs. The slabs are exposed to radiant flux levels lower than the ignition heat flux, which renders convective effects negligible. Conductive heat flux is deduced from Equation (1) using mass loss data and incoming radiation from cone heaters.
- From flaming experiments using vertically-oriented PMMA slabs, total heat flux from the flame is determined.

2. Pure pyrolysis (non-flaming) experiments using horizontally-oriented PMMA slabs

Specific mass loss cone calorimeter experiments for horizontally-oriented 3-cm-thick PMMA slabs (Figure 2) are performed in order to determine the last three terms of the right-hand side of Equation (1), namely \( q_{rr} \), \( q_{id}^{rad} \), and \( q_{id}^{cond} \).
Data from a radiant heat flux gage placed beneath the sample to measure the transmitted heat flux through the slab are coupled with those obtained from a video processing to locate the bubble surface $\delta_{\text{reg}}$ [5] (Figure 2). For side view access, the lateral faces of the samples have been polished. A CCD camera of high resolution (1392x1040, giving a pixel size less than 0.1 mm) is used. Rear lighting is provided by an array of diodes (Figure 2). Light traverses the sample and is scattered by the bubbles. The video images are processed by establishing a gray-level intensity threshold.

The radiant heat flux received by the gage is the sum of the transmitted part (through the bubble layer and the virgin material) of radiation coming from the cone calorimeter, and of the transmitted (through the virgin material) part of bubble surface emission. In order to distinguish these contributions, the sample is alternately exposed to and hidden from the radiative source, using an insulated reflective material as a radiant barrier. It is worthy noticing that $q_{\text{rad}}^{\text{rad}}$ corresponds to in-depth radiant heat flux at the pyrolyzing surface and not to that measured by the gage.

Two slabs of 11 and 18 mm in thickness are used.

Surface re-radiation, $q_{rr}$, is also measured using a radiative heat flux gage located just above (2mm) the pyrolyzing surface. The mass loss rate is measured using electronic scales. Experiments are repeated at least four times in order to assess repeatability.
As shown in Figure 3, measurements provide information on the total radiant heat flux and that of the bubbling surface received by the heat flux gage placed at the rear of the sample, but at the same time (by difference) on the transmitted part of the incoming radiation. Total radiation and bubbling surface contribution are plotted as a function of the remaining material thickness, \(d(t) = \delta - \delta_{reg}(t)\), in Figures 5 and 6 for an incident heat flux of 23 kW m\(^{-2}\). Time evolution of the pyrolyzing surface regression is obtained by the video processing as mentioned above.

The intercept values of the two curves (in the limit as \(d \to 0\)) are the values of total and bubble surface in-depth radiant heat fluxes at the sample surface, \(q_{id,rad}^{rad} = q_{id,bubble}^{rad} + q_{id,CC}^{rad} = 7.57\) kW m\(^{-2}\) and \(q_{id,bubble}^{rad} = 6.33\) kW m\(^{-2}\). Therefore, \(q_{id,CC}^{rad} = 1.24\) kW m\(^{-2}\), which means that only 5.2 % of the incident flux is transmitted through the virgin material. This is in agreement with the value of 4 % obtained by Jiang et al. [6].

![Figure 4. Total radiation (left) and part of the bubbling surface radiation (right) transmitted through the slab versus thickness. Incident heat flux is 23 kW m\(^{-2}\).](image)

Results obtained from pure pyrolysis of horizontally-oriented slabs allows determining simultaneously mass loss rate, \(m_{hor}^{\prime}\), surface re-radiation, \(q_{rr}\), and total in-depth radiant heat flux, \(q_{id}^{rad}\). Therefore, using the energy balance equation at the surface and replacing the flame contributions with that of the cone calorimeter, \(q_{CC}\), we can deduce the conductive heat flux from:

\[
m_{hor}^{\prime} h_g = q_{CC} - q_{rr} - q_{id,rad}^{rad} - q_{id,cond}^{\prime}
\]

The results are summarized in Table 1. Values reported are averages of six experiments, which leads to an average value of the conductive heat flux of 2.5 kW m\(^{-2}\), using a value of the heat of gasification of \(1.7 \times 10^6\) J kg\(^{-1}\) proposed by [8] for radiative heating experiments.
Table 1. Pure pyrolysis experiments using horizontally-oriented clear PMMA slabs: surface re-radiation, non-conductive and conductive in-depth heat fluxes (in kW m\(^{-2}\)) for horizontally-oriented PMMA slabs.

| \(q_{rr}\) | \(q_{id}^{rad}\) | \(q_{id}^{cond}\) |
|-----------|----------------|----------------|
| 6.5± 0.5  | 7.5± 0.5       | 2.5± 0.5       |

The whole in-depth losses contribution is found to be approximately 10 kW m\(^{-2}\) adding different contributions. This is in agreement with the value of 8 kW/m\(^2\) found by Kulkarni and Kim [7], using thermocouples.

3. Flaming experiments using vertically-oriented PMMA slabs

The experimental apparatus consists of a vertical sample of poly-methyl-methacrylate (PMMA) 10 cm in width, and 3 cm in thickness. Samples 2.5, 5, 10, and 20 cm in height are tested. They are mounted on an aluminum holder and covered with a metal plate, as illustrated in Figure 2. The metallic screen allows only the front surface of the PMMA to ignite and burn. For each experiment, the sample is ignited at the bottom using a 2kW-electrical stainless steel rod.

Heat fluxes are measured at steady state when the mass loss trace exhibits a plateau, typically from \(t=1500\) s. This observation is in agreement with the experimental results of Kulkarni and Kim [7]. Total heat fluxes to the upward heating zone are measured by mounting Captec heat flux gages at four heights on the metal plate above the burning sample, as shown in Figure 2. “Total” refers the sum of the radiative and convective heat flux components.

Total heat fluxes transferred from the flame to the solid surface are reported in Table 2.
Table 2. Heat fluxes (in kW m$^{-2}$) from the flame to the slab surface at elevation heights of 2.5, 5, 10 and 20 cm.

| $x$(cm) | $q_f$ |
|---------|-------|
| 20      | 32.4  |
| 10      | 33.5  |
| 5       | 38.2  |
| 2.5     | 42.6  |

As expected, the total heat flux decreases from 42.6 to 32.4 kW m$^{-2}$ as the distance from the leading edge increases.

4. Burning rate

Let us now determine the burning rate of PMMA.

A simple approach consists in assuming that the surface re-radiation is considered as constant and that in-depth fluxes obtained from the pure pyrolysis case are unchanged. This means that the pyrolysis temperature is assumed to be the same for both non-flaming and flaming cases and that emission spectra from the cone calorimeter and the flame are similar.

The local burning rate can be calculated from Equation (1) using the values of heat fluxes from Tables 1 and 2 and using a value of the heat of gasification of $2.5 \times 10^6$ J kg$^{-1}$ proposed by [8] for convective heating experiments.

Table 3 summarizes the local burning rates obtained along the slab. As expected, the local burning rate decreases as the elevation height increases. A comparative analysis with the local burning rates measured in [5] shows a good agreement (Table 3).

Table 3. Comparison between burning rates (in g m$^{-2}$ s$^{-1}$), at elevation heights of 2.5, 5, 10 and 20 cm, deduced from Equation (1) using current measurements and those obtained in [5].

| $x$(cm) | $\dot{m}^n$ Eq. (1) | $\dot{m}^n$ [5] |
|---------|---------------------|------------------|
| 20      | 0.0055              | 0.0055           |
| 10      | 0.0059              | 0.0055           |
| 5       | 0.0078              | 0.0070           |
| 2.5     | 0.0096              | 0.0081           |
5. Conclusion
The contributions of heat flux components to the steady-state energy balance at the surface of pyrolyzing PMMA slabs are determined from cone calorimeter experiments. A special emphasis is put on in-depth losses, showing that a small proportion of the incoming radiation is transmitted through the solid fuel and that a significant part of in-depth losses is due to bubble surface emission into the solid. Conductive heat transfer into the solid has also to be considered. Current results will help in improving the accuracy of pyrolysis models. Further work would need to investigate the pyrolysis of other materials.

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