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Implementation and validation of an environmental feedback pool fire model based on oxygen depletion and radiative feedback in FDS

Jonathan Wahlqvist*, Patrick van Hees

Division of Fire Safety Engineering, Lund University, Sweden

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ABSTRACT

This paper has been aimed at implementing and validating a simplified environmental feedback fire model in FDS as a complement to more advanced pyrolysis models. The two main means of environmental feedback have been identified as the oxygen concentration close to the fuel base and the radiative feedback from the surrounding obstructions and smoke layer. The oxygen concentration at the fuel base has previously been identified to linearly influence the normalized burning rate compared to the free burning behavior; this correlation has been implemented in FDS as a simple way to compensate for the reduced radiative feedback the fuel surface receives when the oxygen concentration is lowered and the flame is cooled down, prolonged or detached from the fuel base. In large pool fires it is often considered that the net radiative heat flux to the fuel surface is the dominant factor compared to convection when determining the total mass loss rate, and in enclosed spaces the additional radiative heat flux feedback from other sources than the flame itself might be significant. To predict these environmental effects another simplified model has been implemented; the external radiative heat flux (radiative heat flux not sourced from the flames) divided by the fuel heat of vaporization is assumed to be directly proportional to the additional mass loss rate. This model is mostly needed in very hot enclosures and its effect has been limited in the cases used for validation in this paper. Overall the model produces accurate predictions of the mass loss rate as long as the overall flow is reasonably resolved by the model. The grid dependency has been observed to be relatively small even at coarse meshes which can be a benefit compared to more detailed models.

1. Introduction

The mass loss rate, and the resulting heat release rate, is one of the key elements in predicting the fire dynamics of a compartment fire. Computational simulations using a prescribed fuel mass loss rate, so called a posteriori simulations, have been shown to give good agreement with experimental results [1–8], but the burning rate in an enclosed space, with or without technical installations such as mechanical ventilation, is often not easily simulated without experiments of the exact same configuration. This work focuses on predicting the mass loss rate of enclosed fires using data collected in a free burning environment or data derived from correlations, for example the Babrauskas rate [9], by taking the environment feedback and interaction with the fire source into account.

A reason for having a simplified dynamic fire model is twofold; first, advanced pyrolysis models require a lot of detailed input data and are generally very complex; second, traditional pyrolysis models can be very sensitive to cell size since it greatly affects the radiative heat flux feedback to the fuel as seen in Fig. 1. This is largely due to the flame not being well resolved, which in turn affects the radiative feedback given back to the fuel. This model is intended to be a simplified “engineering model” in the sense that no advanced pyrolysis model is being considered; only the surrounding oxygen fraction and the external radiation (radiation not directly sourced from the flame itself) to the fuel surface will be accounted for.

2. Simplified feedback model

The implemented model consists of two distinct parts; lowered mass loss rate due to lowered oxygen levels close to the fire source, and increased mass loss rate due to radiation from external sources, such as walls and smoke layer.

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* Correspondence to: Brandteknik, LTH, Lunds Universitet, Box 118, 221 00 Lund, Sweden.
E-mail address: jonathan.wahlqvist@brand.lth.se (J. Wahlqvist).

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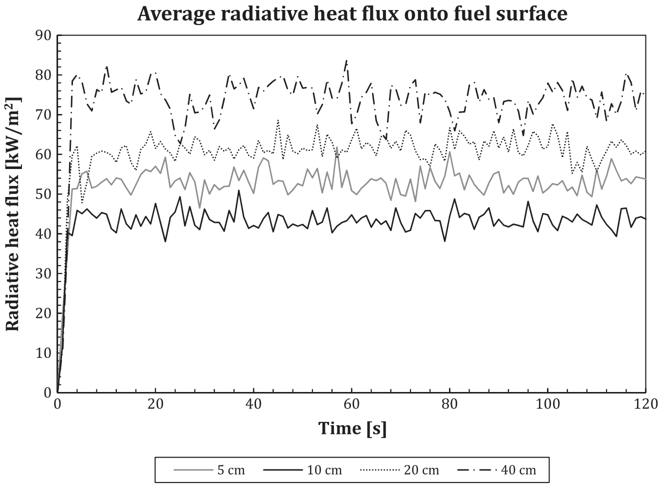

Fig. 1. Measured average radiative heat flux onto the fuel surface of a 1 × 1 m burner using different cell sizes in FDS.

2.1. *Influence of lowered oxygen levels*

A lot of work has been done to investigate the radiative properties of flames in oxygen depleted environments [10–16], and Peatross and Beyler correlated a range of experiments to determine a linear dependency between the oxygen fraction close to the flame base and the normalized mass loss rate compared to a free burning value [17]. The correlation provides fuel mass loss rate against oxygen concentration measured at the flame base for large-scale fire compartments. The data was taken for several different tests with different fuels. The resulting correlation can be seen in Eq. (1):

$$\dot{m}''_{O_2} = \dot{m}''_{\infty} \cdot \left(0.1 \cdot O_2[\%] - 1.1\right) \tag{1}$$

where $\dot{m}''_{O_2}$ is the predicted mass loss is rate, $\dot{m}''_{\infty}$ is the steady-state free burning value of a specific fire source and $O_2[\%]$ is the oxygen volume percentage close to the flame base.

The oxygen volume fraction at the flame base is used to describe the change of radiative feedback to the fuel caused by cooling of the flame, extension of the flame or detachment of the flame from the pool surface. The reduction in radiative heat flux feedback in turn results in lowered mass loss rate. Since simulating the decrease in radiative feedback from the flame can be very challenging, using the oxygen fraction at the flame base can potentially represent this behavior in a simplified model.

2.2. *Radiation from external sources*

In many cases the temperature of the fire room walls and smoke layer does not heat up enough to re-radiate any significant amount of energy to the fire source; this could either be due to well-ventilated conditions with a lot of air exchange or due to large heat losses through the compartment boundaries. But in some cases, such as sealed compartments or well insulated compartments, this re-radiation can amount to a significant portion of the total mass loss rate and in some cases even be the dominating contributor. Since the latter often coincide with low oxygen levels it is important to address this phenomenon in the simplified feedback model. Since the aim of the model is to be relatively simple a very basic approach was taken; the net radiative heat flux to the fire source that does not originate from the flame, as in radiation from heated walls and smoke layer, divided by the heat of vaporization of the fuel will result in a linear addition of mass loss rate, see Eq. (2). The outgoing term is approximated to be directly determined by the boiling temperature of the fuel [18].

$$\dot{m}''_{rad} = \frac{\dot{q}''_{rad.in,external} - \dot{q}''_{rad.out,fuel}}{\Delta h_{v,fuel}} \tag{2}$$

where $\dot{m}''_{rad}$ is the extra mass loss rate due to radiation, $\dot{q}''_{rad.in,external}$ is the radiative feedback from anything except the flame in the enclosure, such as the walls, ceiling or smoke layer, $\dot{q}''_{rad.out,fuel}$ is the outgoing radiate heat flux based on the boiling temperature of the fuel and $\Delta h_{v,fuel}$ is the heat of vaporization of the fuel.

2.3. *Total mass loss rate*

Combining Eqs. (1) and (2) yields the following simple equation:

$$\dot{m}''_{tot} = \dot{m}''_{\infty} \cdot \left(0.1 \cdot O_2[\%] - 1.1\right) + \frac{\dot{q}''_{rad.in,external} - \dot{q}''_{rad.out,fuel}}{\Delta h_{v,fuel}} \tag{3}$$

The total mass loss rate is then proportional to the oxygen volume fraction close to the fuel base and the radiation from external sources; the complex radiation from the flame is altogether ignored in the formulation (although indirectly included due to the user being forced to specify the free burning mass loss rate value). This formulation is similar to the one presented by Utiskul et al. [19].

3. Implementation in FDS

The proposed model was built into Fire Dynamics Simulator [20] (FDS) 6.1.1 (SVN 19953). The user has to input heat of vaporization, normal mass loss per unit area, total fuel mass (used to limit total burning time), and surface temperature (normally boiling temperature of the fuel [18]). It is optional to add ramping values for the mass loss rate and the surface temperature, both these parameters have been used for all presented cases.

3.1. *Influence of lowered oxygen levels in FDS*

Eq. (1) was directly implemented in FDS with some slight modification to compensate for the actual normal dry oxygen volume fraction in FDS. The oxygen volume fraction is then sampled in a volume specified by the user using a normal device with a specific identity. In all cases in this paper the sampling volume has been all cells touching the rim of the fuel pan, essentially forming a “ring” around the fuel pan (applies to the coarse cases, the refined cases used the same volume meaning it actually sampled from 16 times as many cells). The height of the “ring” has in all cases been 1 cell thick (on the coarse mesh) originating from the fuel surface and downwards. Since the size and location of the sampling volume might have a large influence on the resulting mass loss rate, a sensitivity study was done and is presented in the results section.

3.2. *Radiation from external sources in FDS*

To be able to only measure the external radiative heat flux, a new output parameter was added to FDS. To be able to calculate this output parameter, an additional routine was added to the radiation calculations in FDS where all radiation from the flame was ignored. Without any flame present, the model is identical to the radiation model already present in FDS (given that the fuel surface temperature is the same as the normal surface temperature), since the routine effectively calculates the radiation intensities that would occur if no flame was present. This was