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Heat transfer principles in thermal calculation of structures in fire

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ABSTRACT

Structural fire engineering (SFE) is a relatively new interdisciplinary subject, which requires a comprehensive knowledge of heat transfer, fire dynamics and structural analysis. It is predominantly the community of structural engineers who currently carry out most of the structural fire engineering research and design work. The structural engineering curriculum in universities and colleges do not usually include courses in heat transfer and fire dynamics. In some institutions of higher education, there are graduate courses for fire resistant design which focus on the design approaches in codes. As a result, structural engineers who are responsible for structural fire safety and are competent to do their jobs by following the rules specified in prescriptive codes may find it difficult to move toward performance-based fire safety design which requires a deep understanding of both fire and heat. Fire safety engineers, on the other hand, are usually focused on fire development and smoke control, and may not be familiar with the heat transfer principles used in structural fire analysis, or structural failure analysis. This paper discusses the fundamental heat transfer principles in thermal calculation of structures in fire, which might serve as an educational guide for students, engineers and researchers. Insights on problems which are commonly ignored in performance based fire safety design are also presented.

1. Introduction

This paper presents theoretical descriptions of the key heat transfer principles that govern the thermal behavior of structures in fire. In particular,

- Section 2 introduces the theory of heat radiation through a participating medium.
- Section 3 discusses thermal calculation in a post-flashover fire environment. The applicability of design formulae for predicting the temperature of bare and insulated steel members in fire is investigated by the theory of lumped heat capacity method. Theory of thermal radiation in participating medium is used to explain the variation of measured temperatures of steel members with the same cross section but at different locations in a fire compartment. A modified one zone model is discussed and used to investigate the heat sink effect of the steel members in a fire compartment.
- Section 4 discusses thermal calculation in a pre-flashover fire environment. Localized fire model is discussed and developed to calculate the heat fluxes to structural members in large enclosure. The applicability of design formulae (for post-flashover fires) for temperature calculation in localized fires is discussed. The usage of localized fire model to determine the safe distance from an unprotected steel column to a localized fire source is presented.

Section 5 gives the conclusion of this study; and Appendix A gives the correlations for calculation in localized fires.

2. Heat radiation through participating medium

The basic heat transfer principles, including conduction, convection, and radiation, are well documented and can be easily found in heat transfer textbooks like [1–3]. Below, the theory of heat radiation through a participating medium is presented, which is essential to understand the heating mechanism under fire conditions and is not commonly introduced in SFE textbooks.

For participating media like gases, the intensity of the incoming radiation will reduce with penetration distance by either the absorbing or the scattering effects of the medium. As shown in Fig. 1, consider a beam of radiation with intensity $E_{ir}(0)$ that passes through a participating medium of thickness L. By Beer's law the intensity of the radiation beam at point x is given by [1]

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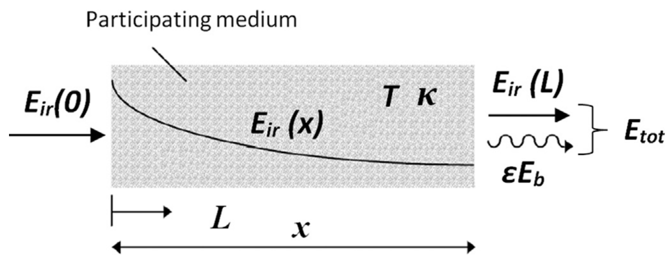

Fig. 1. Energy out from a participating medium.

$$E_{ir}(x) = E_{ir}(0)e^{-\rho\kappa x} \tag{1}$$

where κ is called the extinction coefficient, which is generally the sum of the absorption coefficient and the scattering coefficient; ρ is the density of the medium; and x is the penetration distance. Correspondingly, for the participating medium of thickness L, the absorptance $\alpha(L)$ is

$$\alpha(L) = \frac{E_{ir}(0) - E_{ir}(L)}{E_{ir}(0)} = 1 - e^{-\rho\kappa L} \tag{2}$$

By Kirchoff's law [1] we get the emissivity for the participating medium of thickness L, $\varepsilon(L)$, as

$$\varepsilon(L) = \alpha(L) = 1 - e^{-\rho\kappa L} \tag{3}$$

where $\rho\kappa L$ is called the optical path length or opacity.

The outgoing spectral radiation at L, E_{tot} in Fig. 1, is the sum of the reduced penetrating radiation and the emitted radiation by the participating medium [4]:

$$E_{tot}(L) = [1 - \varepsilon(L)]E_{ir}(0) + \varepsilon(L)E_b \tag{4}$$

where E_b is the black body radiation.

3. Thermal calculation in a post-flashover fire environment

3.1. Assumptions and simplifications

The following assumptions and simplifications are usually adopted in the thermal calculation in a post-flashover fire environment [5]:

- The gas properties are homogeneous in the fire compartment.
- Both hot gases and building components are assumed to be gray. The surfaces of building components are assumed to be opaque.
- In radiation calculation, the fire and the exposed surface are represented as two infinitely parallel gray planes that the view factor is taken as unit.

Correspondingly, the net heat flux transferred to an exposed surface is given by

$$\dot{q}'' = \dot{q}_c'' + \dot{q}_r'' = h[T_g(t) - T(0, t)] \tag{5}$$

where $\dot{q}_c''$ and $\dot{q}_r''$ are convective and radiative heat fluxes, respectively; $T_g(t)$ and $T(0, t)$ are temperatures of the surrounding gas and the exposed surface, respectively; and $h = h_c + h_r$ is the heat transfer coefficient. h_c is the convective heat transfer coefficient or film coefficient with values typically taken in the range 5–50 W/m^2 K [5]; and h_r is the radiative heat transfer coefficient:

$$h_r = \frac{\varepsilon_f \varepsilon_s}{\varepsilon_f + \varepsilon_s - \varepsilon_f \varepsilon_s}\sigma[T_g^2(t) + T^2(0, t)][T_g(t) + T(0, t)] \tag{6}$$

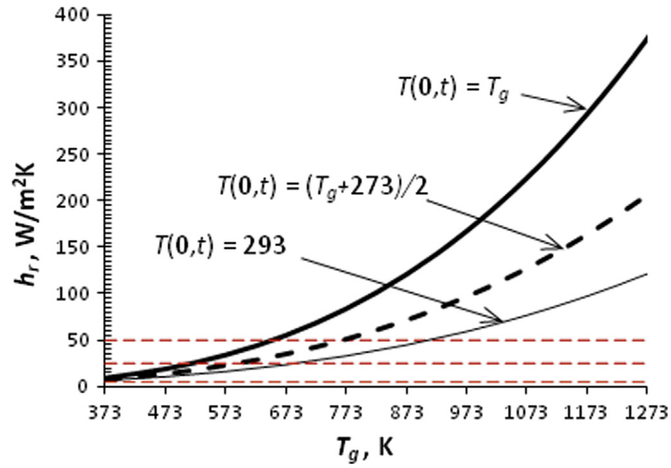

Fig. 2. Radiative heat transfer coefficient calculated by using Eq. (6) with $\varepsilon_f = 1$ and $\varepsilon_s = 0.8$.

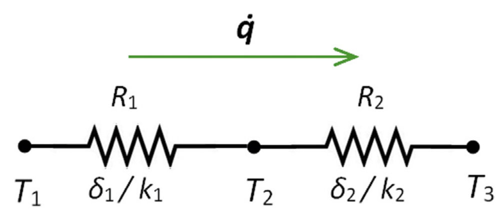

Fig. 3. An electrical analogy for 1D heat conduction.

where ε_f and ε_s are the emissivity of the fire and the exposed surface, respectively. Fig. 2 shows the calculated radiative heat transfer coefficient at different values of T_g. The convective heat transfer coefficient values of 5, 25 and 50 W/m^2 K are also plotted for reference. Convection dominates at low temperatures, but above 400 °C (673 K) radiation becomes increasingly dominant.

3.2. Lumped heat capacity method for steel temperature calculation

3.2.1. The lumped heat capacity method

The expression for Fourier's law is similar to that for Ohm's law in electric-circuit theory. As a result, an electrical analogy can be used to solve heat conduction problems. Fig. 3 illustrates an analogous circuit composed of two thermal resistances in series, which represents a 1D heat transfer model. R_i is the thermal resistance. For conduction, $R_i = \delta_i/k_i$, in which δ_i and k_i are the thickness and conductivity of material i, respectively. In steady state, if thermal resistance R_1 is much greater than R_2 ($R_1 \gg R_2$), the temperature difference ratio $(T_2 - T_3)/(T_1 - T_2) \approx 0$ and if R_2 is also small, $T_2 \approx T_3$. The *Biot* number is used to determine the applicability of the lumped capacity method [1]:

$$Bi = \frac{R_2}{R_1} = \frac{\delta/k}{1/h} = \frac{h(V/A)}{k} \tag{7}$$

where $\delta = V/A$ is the characteristic thickness of the solid which is subjected to a convection like boundary condition with heat transfer coefficient h. In practice, the lumped heat capacity method which assumes that a uniform temperature distribution in a solid can be used provided $Bi < 0.1$ [6].

3.2.2. Biot number for commonly used steel sections

Fig. 4 shows the calculated *Biot* number *Bi* for bare steel members with various section factors A/V. The section factor for commonly used steel sections ranges from 30 m^{-1} to 320 m^{-1} [7]. *Bi* decreases with temperature due to the increase of h_r. For steel members with small section factors (e.g. 30 m^{-1}, 50 m^{-1}), at low