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Temperature development in steel members exposed to localized fire in large enclosure

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ABSTRACT

Accurately predicting the time–temperature relationship in steel members exposed to localized fire in large enclosures is a key issue in the design of structural fire protection. Although numerous methods for predicting the development of steel temperatures in compartment fires have been proposed, heat transfer between steel and flame in large spaces is disregarded in these classical methods. On the basis of the lumped heat capacity method, a modified model for tracing the temperature profile in steel members exposed to fire in large enclosures is proposed. In this model, a localized fire source is treated as a single-point fire source in evaluating flame net heat flux to steel. The increase in smoke temperature is used as a basis to develop a new approach to accurately predict the development of steel temperatures in large enclosures under fire conditions. To validate the model and approach, experiments are conducted which show that the predicted temperatures are satisfactorily consistent with the experimental data. The conclusions and experimental data serve as reference for fire simulation, hazard assessment, and fire protection design.

1. Introduction

The collapse of steel structures in standard fires has been extensively investigated by disaster prevention and mitigation engineers, who believe that temperature development in steel members is the key issue for consideration in the design of fire protection measures for steel structures. Accordingly, numerous methods for predicting steel temperature development have been proposed (Ghojel and Wong, 2005; Dwaikat and Kodur, 2012; Kay et al., 1996; Gardner and Ng, 2006; Wald et al., 2006; Barnard, 1976; Shi et al., 2011; Latham et al., 1987). In the developed methods, the heat that a steel element receives is classified into thermal radiation and heat convection between the steel member and the hot smoke. These relationships are depicted in Eqs. (1) and (2). Nevertheless, the heat transfer between the steel member and the flame is disregarded in these methods. In actual large enclosure fires, especially when the flame surrounds the steel members, steel members would receive considerable thermal radiation from flames at the same time. Thus current methods for calculating heat transfer between steel and localized fire in large spaces is incomprehensive.

$$q' = \sigma_0 \varepsilon F_s \times (T_g^4 - T_s^4) \tag{1}$$

$$q'' = F_s \alpha_c (T_g - T_s) \tag{2}$$

where σ_0 is the Stefan–Boltzmann constant, 5.67×10^{-8} W/m^2 K^4, F_s is the steel external surface area per meter (m^2/m), ε is the effective emissivity of steel, T_g is the smoke temperature (K), T_s is the steel temperature (K), and α_c is the convective heat transfer coefficient.

Previous investigations focused on steel temperature development in normal enclosure fires. The smoke temperature (shown in Eqs. (1) and (2)) in normal-enclosure fires is mainly based on standard fire curves such as the ISO 834 curve, ASTM-E119 curve, external fire curve and hydrocarbon curve. However, current research shows that the smoke temperature development in actual large-space fires highly differs from these standard fire curves. In large-enclosure fires, smoke temperature develops in a more complex manner; it is directly affected by heat release rate, enclosure profile, and fire size. Aside from the problems stated above, experiments on steel temperature development in large spaces are seldom carried out. The actual development of smoke and steel temperatures under localized fires in large spaces remains to be examined via full-scaled experiments.

Motivated by the discussions above, this paper experimentally investigates the development of smoke and steel temperatures under localized fires in large spaces. On the basis of observations, a new approach to accurately predict smoke temperature development in large-enclosure fires is put forward. This approach is

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expected to be more accurate than the use of standard fire curves. A modified model for tracing the temperature profile in steel members exposed to large-enclosure fires is also proposed. In the modified model, a localized fire source is treated as a single-point fire source in evaluating the flame net heat flux to steel elements. The experiments validate the accuracy of the proposed approach. The predicted temperatures are found to be consistent with the experimental data.

2. Smoke temperature rise in large-enclosure fires

Given that large enclosures are of huge dimensions (height and width), localized fires in large spaces mainly consist of a stabilized flame, a discontinuous flame, plume and ceiling jet, as shown in Fig. 1. The temperature distributions in different regions vary greatly. In these regions, the plume and ceiling jet are two primary factors which directly affect steel temperature development.

2.1. Plume temperature

The plume centerline is located in the center of the fire plume above the flame and its mean increase in centerline temperature, ΔT_0, at and above the mean flame height is provided by Eq. (3) from Heskestad (1984)

$$\Delta T_0 = 9.1\left(\frac{T_a}{g c_p^2 \rho_a^2}\right)^{1/3} Q_c^{2/3}(z - z_v)^{-5/3} \tag{3}$$

where c_p is the specific heat of air at constant pressure (kJ/(kg K)), T_a denotes the ambient temperature (K), g represents the acceleration due to gravity (m s^{-2}), ρ_a is the ambient air density (kg m^{-3}), z is the height above the base of fire source (m), and Z_v refers to the height of virtual origin (m) (Fig. 1). Q_c is the convective fraction of the heat release rate of the fire source, as calculated by Eq. (4) in kilowatts (kW).

$$Q_c = (1 - \chi)Q \tag{4}$$

where Q is the fire heat release rate (kW), and χ is the radiant energy release factor. Yang et al. (1994) and Koseki and Yumoto (1988) determined the value of χ on the basis of a series of experiments conducted by Yang et al. (1994) and Koseki and Yumoto (1988):

$$\chi = 0.35e^{-0.05D}. \tag{5}$$

On the basis of Heskestad (2002), the ΔT_0 under atmospheric conduction (g = 9.81 m s^{-2}; c_p = 1.00 kJ/(kg K); ρ_a = 1.2 kg m^{-3}; T_a = 293 K) can be simplified to

$$\Delta T_0 = 25.0 Q_c^{2/3}(z - z_v)^{-5/3} \tag{6}$$

where Z_v is the elevation of the virtual origin above the fire source. As described in Fig. 1, the virtual origin is a point source from which the fire plume above a flame appears to originate. Virtual origin height Z_v is estimated by Eq. (7) with reference to Heskestad (1972); this approach is recommended in ISO 16734.

$$\frac{Z_v}{D} = -1.02 + 15.6\left\{\left(\frac{c_p T_a}{g\rho_a^2(\Delta H/s)^3}\right)^{1/5} - 0.158\left[(c_p\rho_a)^{4/5} T_a^{3/5} g^{2/5}\right]^{-1/2} \alpha^{2/5}\frac{T_{0L}^{1/2}}{\Delta T_{0L}^{3/5}}\right\}\frac{Q^{2/5}}{D} \tag{7}$$

where D is the fire source diameter (m), ΔH is the net heat of combustion(kJ/kg), α is the convective fraction of the heat release rate, and T_{0L} is the mean temperature on the plume centerline at mean flame height (K).

The Z_v, in terms of Q and D under normal atmospheric conditions [g = 9.81 m s^{-2}; c_p = 1.00 kJ/(kg K); ρ_a = 1.2 kg m^{-3}; T_a = 293 K] could be reproduced as

$$Z_v = -1.02D + 0.083Q^{2/5}. \tag{8}$$

2.2. Ceiling jet temperature

After smoke plumes impinge on a ceiling, the ceiling surface causes these plumes to turn and move horizontally under the ceiling to other building areas that are distantly located from the fire. Consequently, a ceiling jet forms under the ceiling. Unlike the mean centerline temperature rise, ΔT_0, the increase in ceiling jet temperature, ΔT_{jet}, is determined by Alpert (1975):

$$\begin{aligned} \Delta T_{jet} &= 16.9\frac{Q^{2/3}}{H^{5/3}} \quad (r/H \leqslant 0.18) \\ \Delta T_{jet} &= 5.38\frac{Q^{2/3}}{(r/H)^{2/3}H^{5/3}} \quad (r/H \geqslant 0.18) \end{aligned} \tag{9}$$

where H is the height of the ceiling (m); and r is the horizontal distance from the plume axis (m).

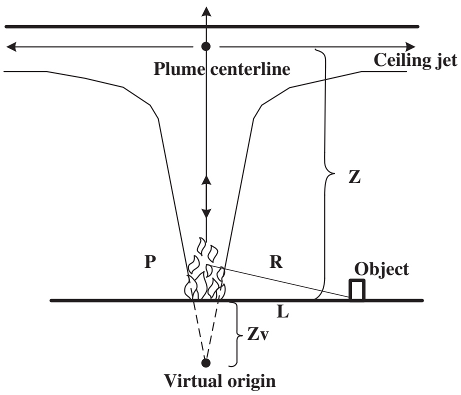

Fig. 1. Localized fire in large enclosure.

3. Modified model of steel temperature development in localized fire

3.1. Energy balance equation

Fig. 2 shows that a localized fire in a large enclosure transfers smoke radiation, smoke convection, and flame radiation to the steel member. We assume that steel members are black bodies and that no temperature gradients occur along or across these components. This assumption is created for the convenience of studying the heat transfer between the steel element and the localized fire. Considering such an assumption, a correction coefficient to accurately predict the net heat that steel members absorb is proposed. Following the guidelines in EN 1993-1-2:2005 (2005), a correction factor for the shadow effect is used to correct the net energy that is transferred between the fire and steel. The net energy is reproduced as

$$Q_s = (Q_{gr} + Q_{fr} + Q_{sc}) \times \varepsilon_s \tag{10}$$

where Q_s is the net heat flux (kW), Q_{gr} is the smoke radiation heat flux (kW), Q_{fr} is the flame radiation heat flux (kW), Q_{sc} is the smoke convention heat flux (kW), and ε_s is a correction factor for shadow effects.