Applied Mechanics and Materials
ISSN: 1662-7482, Vol. 733, pp 437-441
doi:10.4028/www.scientific.net/AMM.733.437

Submitted: 2014-11-26
Accepted: 2014-12-06
Online: 2015-02-16

On Fire Severity of Building in Performance-Based Design

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Keywords: building fire; fire scenario; fire severity; fire severity coefficient.

Abstract. Analyzing fire severity of designed fire scene is necessary for building fire protection. Ordinary building fire times are calculated from statistic data of their fire heat release rates. Building fire is modeled mathematically to deduce its time-temperature function. Basing on this function curve and Simon Ingberg's fire severity definition, we establish fire severity classification theory for building fire, including definition and equation of its fire severity, and definition of its fire severity coefficient along with calculation of those coefficients of ordinary combustible solids, and calculation and classification steps for building fire severity.

Introduction

Building fires are caused by electrical supply and lighting, heating appliances, cooking appliances and other sources[1], and 2008 China fire statistics data showed that electrical fire 33.0%, industrial fire 11.5%, housing fire 6.7%, arson 5.3%, auto ignited fire 2.7%[2].

It is needed for building fire-protection to design some fire scenarios with 3 factors of combustible, spot and size, and calculate their fire severity to compare risks to evacuation and structure in different scenarios. To manage these fire risks, it is feasible to accept the smaller risk, and refuse all big fire hazards[3,4], therefore, smoke controlling system are fixed to extract smoke, and delay or hinder fire hazards appearance, extending evacuation time; fire partition, fire alarm, extinguishing system are also equipped to control fire and protect structure[5,6].

As codes of design on building fire protection and prevention have strict confinements for produce or store flammable gas or combustible liquid in buildings, combustible in building fire scenarios are mainly designed as solid[7,8]. Beginning from statistical data, common building fire times are calculated. Then building fire is modeled as a solid combustion to derive its fire temperature-time function. From this function and Simon Ingberg's early reports, building fire severity classification theory is established, including building fire severity definition and its calculation equation, solid fire severity coefficient definition and calculation of ordinary solid fire severity coefficients, building fire severity classification steps. Application of this theory on audit to buildings can calculate fire severity of its different designed fire scenarios, and then find out its severest fire scene, in servitude to audit for fire protection system availability to prevent fires and their possible damage.

Building fire time

P. G. Halloran etc. characterized the distributions of fire sizes, fire growth rates and times between events using a sample of building fire data collected over a five-year period 1996-2000 in the Greater London Area [1] as: slow fire 54%, medium fire 10%, fast fir 7%, other fire types 30%, and 95% of them have fire time 0-30 min from ignition to discovery of fire.

These building fire statistical data of London shows that building fire performs in a transient mode, which is generally designed as the ultra-fast, fast, medium or slow mode of the common t-square fire by 4 different performance coefficients [5,6]. Shanghai [9] collected maximum HRR in common building fires for reference of performance-based design engineers. Assuming a fast fire mode in building with fire performance coefficient $\alpha = 0.04689\, kW/s^2$, common building fire time (Tab.1) can be derived from these statistical data.

Tab.1 HRRs and times of ordinary building fire[a]

Buildings	Max HRR/MW	Fire time/s
Shopping market with/without sprinkler	3/20	253/653
Car storage house with/without sprinkler	1.5/3	179/253
Atrium with/without sprinkler	1/4	146/292
Office, guestroom with/without sprinkler	1.5/6	179/358
Public room with/without sprinkler	2.5/8	231/413
Industrial building with/without sprinkler	1.5/8	179/413

[a] Buildings with fast response sprinkler discount 40% HRR and fire time inside this table.

Building fire temperature-time function

As most of combustible in building is solid, a solid burning model is found to deduce its fire time-temperature function. For a thermally thin burning solid from its surface, the thermal penetration depth for heat conduction is less than its physical thickness, while for a thermally thick burning solid from its surface, the thermal penetration depth for heat conduction is more than its physical thickness[10], and its temperature declines along the thermal penetration depth as an approximate conics curve, such that its energy changes more complicated than that of a thermally thin solid, and then it is necessary to discuss the burning behavior of two kinds of solid separately.

Fire time-temperature function of a thermally thin solid. Select the control volume surrounding a thermally thin solid, and assume pressure inside this volume is the same as that of the ambient, the energy conservation equation and Eq.(1) solve fire time-temperature function of a thermally thin solid (d -physical thickness, and $d << \delta_T$ the thermal penetration depth for heat conduction, A -area, c_p -specific heat, ρ -density. t -fire time, s) as:

$$T = \frac{\alpha}{3\rho c_p dA} t^3 + constant \tag{1}$$

Fire time-temperature function of a thermally thick solid. For a thermally thick burning solid from its surface, the thermal penetration depth for heat conduction is more than its physical thickness, $d \geq \delta_T$. In a fire, common combustible has physical thickness $d \geq 0.078\ m$, and if boundary conditions on its back-face have little effect on burning behaviors, the solid approximately burns as a thermally thick one. Let us consider the semi-infinite (thermally thick) conduction problem for a constant temperature at the surface [11]. The fire time-temperature function comes from the conservation of energy. For the ignition time at long times

$$T \approx -\frac{1}{\sqrt{\pi}} \frac{\dot{q}_e'' \sqrt{k\rho c}}{h_t^2} t^{-1/2} + constant \tag{2}$$

Where: h_t -loss coefficient of total convective heat, $\dot{q}_e''$ - an incident radiative heat flux, k -thermal conductivity, c -specific heat. For the ignition time at small times

$$T \approx \frac{2\dot{q}_e''}{\sqrt{\pi k \rho c}} t^{1/2} + constant \tag{3}$$

Building fire severity

From the above fire time-temperature and Simon Ingberg's early reports, fire severity equation of solid induced building fire is derived. Out of this equation, fire severity coefficient is defined, and also common combustible solids' fire severity coefficients are calculated with combination of their thermal properties of conductivity, specific heat and its fire performance coefficient, for reference in auditing fire scenario and designing fire protection system.

Definition of fire severity. In the 1920s Simon Ingberg defined fire severity as an area under the time-temperature curve above a base temperature, and the fire severity in two fires is equal when the areas under their time temperature curves are equal[12,13]. With assumption that fire starts as soon as solid is ignited at normal atmospheric temperature 25℃and pressure 101.325kPa, t_0=0, T_0=0 , Eqs.(1) and (2) give the following solid fire severity calculation equations.

For a thermally thin solid: $$R_{s,\ thin} = \frac{\alpha}{12\rho c_p dA} t^4 \qquad (4)$$

For a thermally thick solid: $$R_{s,\ thick} = \frac{4\alpha}{7\sqrt{\pi k \rho c t}} t^4 \qquad (5)$$

As to the fire severity calculation of a thermally thick solid, its fire time-temperature function can take as two different Eqs.(2) and (3), however, with some modifications to the time-changing thermal property of solid, fire severities of a thermally thick solid of both long and small fire times can be calculated by Eq.(5).

Coefficient of sold fire severity. Seen from Eqs.(4) and (5),building fire severities, induced by both a thermally thin solid and a thermally thick solid, are proportional to the fourth power of fire time, so we define this proportion factor as coefficient of solid fire severity, r_s , and that of a thermally thick solid may change with fire time:

For a thermally thin solid: $$r_{s,\ thin} = \frac{\alpha}{12\rho c_p dA} \qquad (6)$$

For a thermally thick solid: $$r_{s,\ thick} = \frac{4\alpha}{7\sqrt{\pi k \rho c t}} \qquad (7)$$

At the assumption of building fire of fast mode, $\alpha = 0.04689\, kW/s^2$, and density, specific heat and thermal conductivity data of solids[10,14], Eqs.(6) and (7) give fire severity coefficients of solid in Tab.2.

Tab.2 Fire severity coefficients of solid's fast firea

thermally thin solid[b]	$r_{s,\ thin}$ $/K{\cdot}s^{-3}$	thermally thin solid	$r_{s,\ thick}$ $/K{\cdot}s^{-3}$
Polyethylene	1.970×10^{-3}	Hardboard, 0.635 cm	$0.011\, t^{-1/2}$ [c]
Polypropylene	2.188×10^{-3}	Carpet (acrylic)	$0.023\, t^{-1/2}$
PMMA	2.312×10^{-3}	Red wood, 5 cm	$0.032\, t^{-1/2}$
Polystyrene	2.960×10^{-3}	Plywood, plain, 0.635 cm	$0.022\, t^{-1/2}$
Polyoxymethylene	1.952×10^{-3}	Foam, flexible, 2.54 cm	$0.027\, t^{-1/2}$

[a] normal atmospheric temperature and pressure: 1atm, 25℃; [b]physical thickness 1 mm, area 1m^2; [c]fire time, s.

Stages to calculate building fire severity. A single combustible inducing building fire: calculation and classification of building fire severity induced by a single combustible need only compare fire time and combustible mass: the bigger is mass of combustible, and the longer is fire time, then the heavier is fire severity.

Multiple combustibles inducing building fire: in building with multiple combustibles of different ignition temperatures, fire is in fact initiated by the combustible of the lowest ignition temperature, as fire temperature rises, combustibles join to burn in their ignition temperatures sequence, until finally all combustibles in this building burn together into the most severe fire. Therefore the fire severity in these cases can be compared and classified under 3 conditions:

At a initial fire stage, fire is lighted by a single combustible, its mass is more heavier and fire time is more longer, then the fire is more severer;

As fire temperature, combustibles of similar ignition temperature may burn together, and Eqs.(4) and (5) calculate these fires severities with the known fire time in Tab.1, and the coefficients in Tab.2, and different building fires are classified after this calculation;

When all of the combustibles are involved in fire, the worst sort of fire appears, and this fire severity is a summation of all involved combustibles fire severities, which is of course the biggest fire severity in building.

Conclusions

We have just calculated fire times in common buildings, and established building fire severity classification theory, for fire severity calculation and audit in building performance-based design.

1) At fast fire mode, out of the max HRR statistical data, fire times in common buildings are calculated for uses in the following fire severity theory, references in fire-protection design and guidance to install fire system.

2) For most of building fires are actually caused by combustible solid, solid burning is modeled to derive building fire time-temperature function. Since solid can be categorized into 2 types of thermally thin and thick one with comparison of its physical thickness to its heat penetrating depth from surface, building fire time-temperature function has also 2 types.

3) Following the above fire time-temperature function and Simon Ingberg's early reports, building fire severity theory is established including: definition and equation of building fire severity, definition of solid fire severity coefficient, calculation of common combustible solid fire severity coefficients, how to calculate fire severity in building of a single and multiple combustibles.

4) The just defined solid fire severity coefficient involves its mass, size, thermal property, and is derived into 2 types of thermally thin and thick one, which of a thermally thick solid is changed with fire time.

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