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Thermal performance of window glass panes in an enclosure fire

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HIGHLIGHTS

- Review of studies on heat transfer to glass and glass fracture in enclosure fires.
- Three stages of glass temperature variations under different heat transfer.
- First stage is rapid heating, second steady heating, and third balancing hot gases.
- Three sets of partial differential equations with boundary conditions were solved.
- It provides basis for predicting breaking time and location of glass upon heating.

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ABSTRACT

Thermal performance of glass pane under fire was studied in this paper. Heat transfer to glass and associated fracture were reviewed first. Glass temperature profiles on the glass pane were then summarized into three stages based on heat transfer: The first stage is on rapid heating up, the second stage is on steady heating up and the third stage is on losing heat to a certain value. Partial differential equations were set up on predicting the glass temperature at each stage with appropriate boundary conditions.

By proposing different glass temperature variations for those three stages, three sets of partial differential equations were set up and solved. These three equations were then applied to study the heat up of glass with experimental data reported in the literature. The derived solution agrees reasonably well with experiment.

1. Introduction

Many buildings with glass facades were constructed in the Far East [1,2]. It is important to understand how glass breaks in an enclosure fire. Good estimation on the breaking time of glass panes would provide better design and installation of glass system. Note that breaking a glass window will supply more air to give a bigger fire. Efforts were made for 30 years [3–22] into investigating the glass surface temperature profile and the causes of breakage or fallout. Both experimental and theoretical analytical studies were carried out. Different combustibles have different burning characteristics to give variation of total heat release rate of compartment fires with time. In this paper, relevant works on studying temperature profiles of glass panes in enclosure fires [3–23] will be reviewed first. Available data are used to study heat transfer to the glass panes. Mathematical expression on temperature change in glass panes will be derived.

Glass panes would be heated up when the room adjacent to it has a fire. The edges of the glass panes are fixed to window frames and hence insulated to keep at the initial temperature T_0 for some time. The difference ΔT between the average temperature of the glass pane $\overline{T}(t)$ at time t and the local temperatures at the insulated edges is:

$$\Delta T = \overline{T}(t) - T_0 \quad (1)$$

The shaded window edge would lead to a large value of ΔT initially. The glass panes would be broken when ΔT reaches a critical value ΔT_b given in terms of the maximum glass tensile strain σ_b/E which is the ratio of the breaking stress σ_b over the Young's Modulus E; the thermal coefficient of linear expansion β; and a geometry factor g of order one by:

$$\Delta T_b = (\sigma_b/E\beta)g \quad (2)$$

Values of σ_b, E and β depend on the materials of glass products. Damage for a glass façade system in a fire depends on values of ΔT_b. For soda glass, σ_b is 50 MPa, E is 80 GPa and β is lying from

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Nomenclature

a	thickness with a = 0.003/0.006 m
b	height b = 0.85/1.91 m
λ	thermal conductivity λ = 0.8 W/(m^2 K)
c_c	specific heat c_c = 900 J/(kg K)
ρ	density ρ = 2220 kg/m^3
γ	absorptivity γ = 0.4
γ_λ	monochromatic absorption coefficient with γ_λ from 200 to 250
c	thermal diffusivity $c = \frac{\lambda}{\rho c_c}$, unit is m^2/s
l	mean beam length
T_0	temperature at edge or ambient
α_{01}	incident heat flux coefficient related to time with unit W/(m^2 s^2)
α_{02}	incident heat flux coefficient related to time and height, unit is W/(m^3 s)
α_{03}	incident heat flux coefficient related to height, unit is W/m^3
B_{02}	incident heat flux coefficient related to time, unit is W/(m^2 s)
B_{03}	part of incident heat flux, W/m^2
q_a	outgoing heat flux, unit is W/m^2
α_{q1}	absorption coefficient related to time, $\alpha_{q1} = \frac{\gamma \alpha_{01}}{\rho c_c}$, unit is m K/s^3
α_{q2}	absorption coefficient related to time and height $\alpha_{q2} = \frac{\gamma \alpha_{02}}{\rho c_c}$, unit is K/s^2
α_{q3}	absorption coefficient related to height, $\alpha_{q3} = \frac{\gamma \alpha_{03}}{\rho c_c}$, unit is K/s
B_{q2}	absorption coefficient related to time $B_{q2} = \frac{\gamma B_{02}}{\rho c_c}$, unit is m K/s^2
B_{q3}	absorption coefficient $B_{q3} = \frac{\gamma B_{03}}{\rho c_c}$, unit is m K/s

8×10^{-6} to 9×10^{-6} K^{-1}. Values of ΔT_b for soda glass lies from 80 °C to 110 °C. Therefore, the temperature profile of the glass panes upon heating up in an adjacent room fire should be estimated in studying fire hazard of glass façade.

Heat release rate Q of a compartment fire was recorded by Schifility et al. [24] to increase linearly with time t for slow burning rate of the combustibles. But in most cases, Q is proportional to t^2 expressed as $\alpha_1 t^2$ with different α_1 for different conditions. As reported by Hasemi and Nishinata [25], heat release rate of fuel changed linearly with the flame height y, depending on the area of the fuel. Heat would only be released from the fuel within certain height. Glass pane near to the fire source is related to the temperature of the burning gases, fresh inlet air mixture, size of the compartment and the area of the fuel.

Previous studies on thermal effects on glass panes under an enclosure fire were reviewed [1]. Joshi and Pagni [8,9] studied the fire-induced fields in window glass in a compartment of the dimension 1.52 m by 1.22 m by 0.99 m. The size of the glass panes tested was of the size of 0.28 m by 0.51 m and thickness of 2.4 mm and installed in the aluminum frame on one of the wall. The temperature of inner surface of the glass panes was measured. Glass temperature increased with time would follow a quadratic curve as reported [8]. A model [8] considering only the surface temperature of the glass panes was used to determine the breaking time of glass pane upon heating. This model was later developed to include variation of the temperature field in glass pane along the direction of thickness [7]. A model was developed by Joshi and Pagni to predict the temperature field of glass pane with protected edges. Results agreed well with experiments for the first 100 s [9]. Breaking stress of glass was found when the difference between the average and local temperatures at the protected edges rose to about 100 °C. Newton–Raphson's method was used [8] to approximate the integrals. This method had the limitation that each step length required evaluation of three very long kernel equations.

Cuzzillo and Pagni [11] treated the glass as a lumped mass to analyze the heat transfer from the fire room to the glass panes. This method works well when thermal conductivity λ of the glass pane is high and temperature rises slowly in glass pane. In their experiments, conductivity λ of the glass pane is low, and room temperature increased rapidly and is proportional to t^2. These conditions did not match with the ones required by the analytical method. The model by Joshi and Pagni [8] was extended to study double panes [11].

Keski-Rahkonen [5] calculated the temperature field in glass panes heated by thermal radiation, which was considered to be absorbed uniformly along the direction of the thickness. Hence, the temperature along the direction of the thickness was considered to be uniform. The temperature field was used to determine the quasi-static thermal stress field in the glass pane. This method works well when the Bi number (with $Bi = h/\lambda$ is less than 0.1 and h is the heat transfer coefficient). However, this condition was difficult to satisfy. In their experiments, λ of glass pane was low and h was high for at high fire temperature.

Sincaglia and Barnett[10] considered radiation in their fracture model for the glass panes exposed to compartment fires based on one-dimensional heat transfer. Thermal radiation was based on the studies by Gardon [3,4]. The developed model by Sincaglia and Barnettwas implemented into zone-type computer fire codes. Transient glass surface temperature were predicted and compared with experimental results. Both the predicted and experimental temperature increased rapidly and proportional to t^2 for the first 100 s.

Experimental investigations on surface temperature and surface incident heat flux of a single pane glazing were carried out by Shields et al. [13,14] in a room calorimeter. The fire source was located at the corner or in the center of the compartment. Temperature of the glass surface was measured at different locations at different height from the floor. Incident heat flux of the glass surface was recorded as well. Temperature field on glass surface measured in enclosure fire was used for theoretical analysis in this paper.

Xie et al. [21] repeated the work by Shields et al. under the same experimental conditions using toughened glass of thickness 6 mm. Temperature differences at glazing edges at various height y using fuel pan of length 800 mm and width 800 mm were recorded. The glass panes used were either of length 1820 mm and width 870 mm; or of length 870 mm and width 870 mm. Temperature difference reported [21] rose rapidly to reach a peak value in about 100 s. The temperature difference then became steady and rose slowly up to 800 s. This steady temperature difference was due to the steady heat release rate in burning. The temperature difference decreased rapidly while fuel burnt out. The temperature differences at different height y have similar trend. The temperature differences were said to be related to the amount fuel used and the size of the compartment. The observations by Xie et al. [21] agreed well with those by Shields et al. [13,14]. These experiments provided key information of heat transfer on glass panes during steady burning of fuel.

Chow and associates [18,19] conducted experimental studies on glass damages in the cavity of double-skinned façade. Chow and Gao [19] studied the thermal stresses over glass panes upon uneven heating by deriving correlation expressions on the