Thermal response of low-E and float glass facades under various heating rates

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Abstract. Glass curtain wall has been widely employed in buildings. These glazing may easily crack and even fall out when subjected to a fire, which would influence the structural integrity and is especially vital for the interactive-external tridimensional fire development. Low-E glazing is extensively used which may bring energy conservation with potential fire risk. Here, low-E and float glazing were heated by a radiant source under various heating rates. Numerical simulation concerning the heat transfer was conducted to explore and compare the heat transfer mechanisms.

1. Introduction
For the past decades, glass facade has played a relevant role in buildings [1][2]. However, float glass which is extensively used in the past decades is by nature highly thermally emission. To improve these insulation and solar optical properties of thermal control, Low emissivity glass (or low-E glass) is manufactured due to its energy-efficient characteristic for sunrooms or high-rise curtain wall buildings [3]. The surface of the low-E glass is coated with a thin layer of low-Emissivity material and metal oxide. Because of the presence of this layer of film, the surface emissivity of low-E glass is greatly reduced, as shown in figure 1, which may result in the breakage behaviour discrepancy under fire condition compared with the float glass.
Figure 1. Spectral transmittance curves for glazing with low-Emissance coatings (Source: Lawrence Berkeley National Laboratory [4]).

The previous studies [5] with respect to the comparison of breakage behavior between low-E and float glazing under various heating rates were relatively limited, especially for the experimental study of low-E glass. In terms of the studies were investigated concerning various heating rates, Harada et al. [6] adopted radiant heating source to explore the breakage time and fallout behavior of wired glass by changing the intensity of thermal radiation and lateral constraint. The results showed that the fallout ratio was greatly influenced by the intensity of thermal radiation while was less affected by the constraint. When the glass pane was heated intensely (the intensity of thermal radiation was greater than 9 kW/m2), it was ripping off a large piece of glass whereas it only cracked without fallout. While the low-E glass, as a new type of glazing, which extensively adopted in modern energy conservation buildings, the fire performance are rarely concerned in structural fire-resistant design, which may underrate in its potential fire risk. Furthermore, in order to clarify the relevant standards of green building, in 1995, the US Green Building Council (USGBC) proposed a set of Leadership Qualifications and Leadership in Energy and Environment Building Certification System (LEED) [7]. Subsequently, numerous older buildings had been carried out curtain wall renovation. For example, a suspended low-Emissivity film was added to the previous glazing of Empire State Building (NY, USA). This was intended to reflect heat in order to retain temperature control [8]. Nevertheless, the curtain wall renovation may bring energy conservation with potential fire risk because the older buildings were in accordance with previous standards for fire-resistance of glazing generally without low-emissivity film. Experimental studies concerning fire performance of glazing systems between the float glass which have been extensively used in the older buildings and low-E glass for the prevention of glass fallout in fires are insufficient and no in-depth.

2. Experimental Setup

The data for a total of eighteen experimental studies comes from Zhang's doctoral dissertation [9]. Please refer to this document for detailed experiment introduction. Here, we briefly describe the experimental conditions and make further analysis. A total of 18 experiments under the heating rate of 5, 10, 20, and 25°C/min for low-E glazing and 5, 10, 15, 20, and 25°C/min for float glazing were conducted. The overall experimental tests are summarized in Table 1.

| Test number | Radiation-glazing distance (mm) | Heating Rate (°C/min) | Glass type |
|-------------|---------------------------------|-----------------------|------------|
| 1-2         | 500                             | 5                     | low-E      |
| 3-4         | 500                             | 10                    |            |
| 5-6         | 500                             | 20                    |            |
| 7-8         | 500                             | 25                    |            |
| 9-10        | 500                             | 5                     | float      |
| 11-12       | 500                             | 10                    |            |
| 13-14       | 500                             | 15                    |            |
| 15-16       | 500                             | 20                    |            |
| 17-18       | 500                             | 25                    |            |

3. Numerical simulation

3.1. Numerical model

Inhomogeneous distribution of temperature is a major factor that resulted in glass breakage caused by heat transfer which is largely dependent on the material characteristic of various glass types. The primary difference between low-E glass and ordinary float glass is that the surface of the low-E glass is coated with a thin layer of low-emissivity material. Because of the presence of this layer of the film, the surface emissivity of low-E glass is greatly reduced, leading to the breakage time difference between low-E and float glazing under the same heating rate. Therefore, for revealing the heat transfer mechanism, a FEM software, COMSOL Multiphysics® v. 5.4, was conducted to predict the temperature distributions of the
glazing and air in an enclosed compartment under radiant heating source. The sizes and physical properties of low-E and float glazing, cabinet, and radiant heating source materials were identical with those in experiments, as shown in Table 2. After the grid independence tests being made, the mesh grids within 6,637 triangle elements, 574 quadrilateral elements, 804 edge elements and 36 vertex elements were recommended in the 2D thermal analysis, as shown in figure 2 (b). The time step was set at 1 sec. As listed in Table 3, the position of temperature probes, which were used to predict the temperature variation, were in accordance with the experimental tests. In order to clearly depict the position of temperature probes, a coordinate system was built and the lower right corner of glazing was set as the origin point. The thickness and height directions were set as the z and y axis respectively.

In this model, the non-isothermal flow of air inside an enclosed compartment was simulated. All these three forms of heat transfer were taken into consideration. The heat generated in the radiant heating source was transported to the surroundings through radiation, convection, and conduction. As the air heats up, density and pressure change which induce a flow inside the enclosed compartment. The compressible formulation of the continuity and momentum equations was given by [10]:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0
\] (1)

\[
\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \cdot \left( \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^\top) - \frac{2}{3} \mu \nabla \cdot \mathbf{u} \right) + \mathbf{F}
\]

where, \( \rho \), \( \mathbf{u} \), and \( p \) are the density, velocity vector and pressure. \( \mu \) and \( \mathbf{F} \) denote the dynamic viscosity and body force vector.

This is a multi-physics model because it involves fluid dynamics coupled with heat transfer. The pressure \( p \) and the velocity field \( \mathbf{u} \) and \( \mathbf{v} \) are the solutions of the Navier-Stokes equations, while the temperature \( T \) is solved by the heat equation. These variables are all related through bidirectional multi-physics couplings. The density is given by the ideal gas law:

\[
\rho = \frac{M_p}{RT}
\] (2)

where, \( M \), \( R \), and \( T \) denote the molar weight, the universal gas constant, and the temperature.

With regard to the heat transfer of glass pane, it could be expressed by:

\[
\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot \mathbf{q} = Q
\] (3)

\[
\mathbf{q} = -k \nabla T
\] (4)

where, \( C_p \) and \( \mathbf{q} \) represent the specific heat capacity at constant pressure and heat flux. \( Q \) is radiant heating source. Since this numerical simulation undertaken to determine the heat transfer mechanism of low-E and float glazing under the same radiant heating source instead of exploring the influence of different heating rates, \( Q \) was taken as a constant value of 45 kW which was the rated power in the present experimental study.

At the exposed side surface of glazing, radiation is described by surface-to-surface radiation. In addition, the heat convection between the exposed side surface and the enclosed air was taken into consideration as an indispensable part of the heat transfer. Thus, the boundary condition at exposed side surface can be expressed by:

\[
-k \frac{\partial T}{\partial z} = h_0 \left[ T_{0z} (t) - T(0, t) \right] + \varepsilon_0 \sigma T^{4} (t) - \varepsilon_0 \sigma T^{4} (0, t)
\] (5)

At the ambient side surfaces of glazing, the heat was released to surroundings through radiation and convection.

\[
-k \frac{\partial T}{\partial z} = h_1 \left[ T(L, t) - T_{1z} \right] + \varepsilon \sigma T^{4} (L, t)
\] (6)

where, \( h_0 \) and \( h_1 \) denote the convective heat transfer coefficient at the exposed and ambient side surfaces. \( h_1 \) was taken as 40 W/(m²·K) [6]. \( T_{0z} \) and \( T_{1z} \) represent the air temperature near the exposed and ambient side surface. \( T(0, t) \) and \( T(L, t) \) are the glass temperature of exposed and ambient side. \( \varepsilon_0 \) and \( \varepsilon \) are the
emissivity from ambient air of exposed and ambient side to the glass and the emissivity from glass to ambient air. \( \sigma \) represents Steven-Boltzmann constant (\( \sigma = 5.67 \times 10^{-8} \text{W/(m}^2 \cdot \text{K}^4) \)).

(a) Sketch of numerical model  
(b) Grids in simulation

Figure 2. The numerical model and mesh generation.

Table 2. The properties of glass, air, steel, alumina (corundum) tube, and gypsum adopted in the simulation.

| Properties                        | Symbol | Value                                                                 |
|-----------------------------------|--------|----------------------------------------------------------------------|
| **low-E Glass**                   |        |                                                                      |
| Specific heat capacity (J/(kg·K)) | \( c_p \) | 817                                                                  |
| Thermal conductivity (W/(m·K))    | \( k \) | 0.90                                                                |
| Emissivity                        | \( \varepsilon \) | 0.25                                                                |
| **float Glass**                   |        |                                                                      |
| Specific heat capacity (J/(kg·K)) | \( c_p \) | 820                                                                  |
| Thermal conductivity (W/(m·K))    | \( k \) | 0.94                                                                |
| Emissivity                        | \( \varepsilon \) | 0.84                                                                |
| **Air** (Comsol built-in material library) |        |                                                                      |
| Dynamic viscosity (Pa·s)          | \( \mu \) | \(-8.38278e-7+8.35717342e-8\times T-7.69429583e11\times T^2+4.6437266e-14\times T^3-1.06585607e-17\times T^4\) |
| Ratio of specific heat            | \( \gamma \) | 1.4                                                                 |
| Density (kg/m³)                   | \( \rho \) | 352.716×T⁻¹                                                         |
| Specific heat capacity (J/(kg·K)) | \( c_p \) | 1047.63567-0.372589265×T+9.45304214e-4×T^2-6.02409443e-7×T^3+1.2858961e-10×T^4 |
| Thermal conductivity (W/(m·K))    | \( k \) | \(-0.00227583562+1.15480022e-4×T-7.90252856e-8×T^2+4.11702505e-11×T^3-7.43864331e-15×T^4\) |
| **Steel**                         |        |                                                                      |
| Specific heat capacity (J/(kg·K)) | \( c_p \) | 475                                                                  |
| Thermal conductivity (W/(m·K))    | \( k \) | 44.5                                                                |
| Emissivity                        | \( \varepsilon \) | 0.30                                                                |
| **Alumina (corundum) tube**       |        |                                                                      |
| Specific heat capacity (J/(kg·K)) | \( c_p \) | 900                                                                  |
| Thermal conductivity (W/(m·K))    | \( k \) | 27                                                                  |
| Emissivity                        | \( \varepsilon \) | 0.8                                                                 |
| **Gypsum** (Comsol built-in material library) |        |                                                                      |
| Specific heat capacity (J/(kg·K)) | \( c_p \) | 1050                                                                |
| Thermal conductivity (W/(m·K))    | \( k \) | \(0.2611374-8.71792e-4×T+2.682612e-6×T^2-3.135623e-9×T^3+1.353652e-12×T^4\) |
| Emissivity                        | \( \varepsilon \) | 0.5                                                                 |
Table 3. The position of temperature probes in the simulation.

| Point no. | Side          | Coordinate, (x, z) | Corresponding position of temperatures monitored in experimental tests |
|-----------|---------------|--------------------|---------------------------------------------------------------|
| 1         | Exposed side  | (0, 0.79)          | Point 3                                                        |
| 2         | Exposed side  | (0, 0.45)          | Point 4                                                        |
| 3         | Exposed side  | (0, 0.3)           | Point 17                                                       |
| 4         | Exposed side  | (0, 0.15)          | Point 12                                                       |
| 5         | Ambient side  | (0.006, 0.79)      | Point 21                                                       |
| 6         | Ambient side  | (0.006, 0.45)      | Point 22                                                       |
| 7         | Ambient side  | (0.006, 0.3)       | Point 18                                                       |
| 8         | Ambient side  | (0.006, 0.15)      | Point 28                                                       |

3.2. Numerical results

With regard to the temperature distribution in the enclosed compartment, as illustrated in figure 3, it was found that the temperature near the radiant heating source was relatively higher than the other regions. When the temperature changed, the density of the gas changed correspondingly, inducing a gas flow inside the cabinet. It was concluded that the buoyancy force lifting the fluid is the primary reason why the air temperature in the upper area was comparatively higher than that of the lower area. It should be noted that the convective heat transfer between the exposed side surface of glazing and the hot air inside the cabinet played a crucial role in the temperature rising of glazing.

In addition, the temperature distribution of low-E and float glazing were calculated under the same radiant heating source with the power of 45 kW. As illustrated in figure 4, the trend of temperature variance of monitoring probes (Point 1-8) of low-E and float glazing were similar. Take low-E glass, as shown in figure 4 (a), for an example, it was found that there were three distinct stratifications of temperature curves including the curves of the exposed area at the radiant side, exposed area at the ambient side, and covered areas. It should be noted that the temperatures of covered areas both at the exposed (Point 1) and ambient (Point 5) side were the lowest because this temperature rising of these areas were primarily attributed to the heat conduction from the exposed areas. This phenomenon is identical with the experimental result. In addition, the air temperature in the upper region of the cabinet was greater than that in the lower region, which enhanced convective heat transfer between the glazing and hot air, resulting the upper region temperature was greater than the lower region (Point 2>3>4, 6>7>8). This phenomenon is also consistent with the present experimental study.

![Figure 3](image-url)  
(a) Float glazing  
(b) low-E glazing  
Figure 3. The temperature distribution of two different types of glazing and cabinet at 175 s.
Figure 4. The calculated temperatures of two different types of glazing.

Figure 5 (a) demonstrates the temperature of central glazing (Point 3) at the exposed side surface. The numerical results indicated that the temperature of low-E glass was relatively lower that of float glass under the same heating rate which was consistent with the present experimental study. The numerical result corroborates the above theoretical analysis, which draws a conclusion that the temperature rising rate of low-E glass was higher than that of float glass at the exposed side surface (radiant heating source side). Furthermore, the temperature distribution in thickness at 175 s at the top and bottom edges are shown in figure 5 (b). The temperature rising at the ambient side was mainly attributed to the heat conduction from the exposed side, thus, the temperature of low-E glass was also lower than that of float glass at the ambient side surface. With regard to the heat conduction in the y-direction, due to the similar thermal conductivity of these two types glazing, the heat transfer was relatively identity. The numerical result further suggests that the low-E glazing has a better fire-resistance ability than that of float glass.

Figure 5. The temperature comparison of two different types of glazing.

4. Conclusions
The numerical results corroborate the experimental study and theoretical analysis, which draw a conclusion that the temperature rising rate of low-E glass was higher than that of float glass at the exposed side surface (radiant heating source side) and further suggests that the low-E glazing has a better fire-resistance performance than that of float glazing.

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