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Research Paper

Determination of critical breakage conditions for double glazing in fire

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HIGHLIGHTS

- Critical heat fluxes of exposed and ambient panes are 6 kW/m^2 and 25 kW/m^2.
- Critical temperature difference of fire side pane is around 60 °C.
- The ambient pane survives three times longer due to radiation filter and air gap.
- Heat transfer in double glazing is revealed by a heat flux based theoretical model.

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ABSTRACT

Double glazing unit normally demonstrates better fire resistance than single glazing, but the knowledge on its thermal behavior and heat transfer mechanism during fire is limited. In this work, nine double glazing units were heated by a 500 × 500 mm^2 pool fire. The incident heat flux, temperature on four surfaces, breakage time and cracking behavior were obtained. The critical breakage conditions for interior and exterior panes were determined through gradually decreasing the glass-burner distance from 750 mm to 450 mm. It is established that in double glazing the pane at ambient side can withstand significantly more time than the pane exposed to fire. The critical temperature difference for interior pane is 60 °C; the critical temperature of exterior pane breakage is much higher due to no frame-covered area. In addition, the heat flux at the time of crack initiation is 6 kW/m^2 for the pane at fire side, while more than 25 kW/m^2 for ambient side pane. To reveal the heat transfer mechanism in glazing-air-glazing, theoretical and numerical investigations are also performed, which agrees well with the experimental results.

1. Introduction

Glass is extensively employed in building façades, but different from concrete and steel, it is very prone breaking and falling out when subjected to a fire and thus considered as the weakest part in envelope materials [1,2]. During the fast development of a compartment fire (normally ventilation controlled fire), the fracture and fallout of glass will create a new vent that allows fresh air entrance and fire spread outside. Flashover or backdraft will occur at this time, finally resulting in serious disasters. Therefore, glass breaking in fires is an important structural issue and its accurate prediction is critical to fire modeling. After Emmons' pioneering work [3], a large amount of experimental [4–9] and numerical [10–13] work has been performed to investigate the glass behavior under fire conditions. Some factors, including glass types [5], frame protection [6], edge condition [11] and fire location [13], which may affect glass breakage, were analyzed. A consensus has been reached that the thermal gradients between the shaded and exposed regions of the glass is the primary cause for glass crack initiation.

To date, almost all the previous work studied fire response of single glazing, however, very limited research has focused on double glazing unit [14]. Double glazing involves two layers of glass with a small air gap between them. Compared with single glazing, double glazing unit is a very poor conductor which reduces the rate of heat loss through the window (or façade) and unwanted noise [15]. Thus, in advanced glazing systems, double glazing instead of single glazing is increasingly used to provide more environmentally friendly and energy conservation building surfaces. Nevertheless, the extensive use of double glazing brings new fire potential risk and makes the façade easily fail to comply with national fire safety codes. The current information concerning heat transfer and fracture mechanism in double glazing is insufficient to provide reference for fire safety design.

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Nomenclature

A	glass area
E	energy
c	specific heat conductivity (J/(kg·K))
F	view factor
G	incoming radiative heat flux, or irradiation (kW/m^2)
g	acceleration of gravity (m/s^2)
h	heat transfer coefficient (W/(m^2·K))
I	radiation heat flux (kW/m^2)
k	thermal conductivity (W/(m·K))
L	burner-glazing distance (m)
Nu	Nusselt number
n	direction vector
q	heat flux (kW/m^2)
Ra	Rayleigh number
T	temperature (K, in equation; °C, in measured data)
t	time (s)
Greek	
α	thermal diffusivity
β	thermal expansion co-efficient (1/K)
Δ	difference
δ	glass thickness (m)
ε	emissivity
E	modulus of elasticity (Pa)
κ	absorption coefficient (1/m)
ν	Poisson's ratio
ρ	density (kg/m^3)
σ	stress; Stefan-Boltzmann constant
τ	transmissivity
Subscripts	
c	center of glass pane
cond	heat conduction
conv	heat convection
g	generation; bulk glass
0	shaded glass edge
R	reference
rad	radiation
s	surface
st	system
sur	surface
tot	total
tr	transmitted
∞	ambient

Cuzzillo and Pagni [16] and Shields et al. [17] respectively conducted excellent numerical and experimental research on double-pane glazing. It was concluded that, comparing with traditional single glazing, double glazed units consistently perform much better regarding the provision of integrity [18]. A real fire in Oakland Hills also shows that the dwellings with double paned windows survived while their single-paned neighbors did not [19], but its behavior in fire is significantly more complicated that needs to be studied further and the critical condition for its integrity loss is still unknown [17]. Thus, in recent years, interest has been growing in revealing the heat transfer and behavior of double glazing. For example, Aydın [20] analyzed the heat transfer through a double pane window that focused on the determination of the optimum thickness of the air layer trapped between the panes; Xamán et al. [21] investigated the thermal performance of double glazing with or without a solar control coating; Nam et al. [22] conducted experiments in ISO 9705 to study the failure of double glazed curtain wall under radiation conditions. It is anticipated that the fire performance of double glazing may be much different from single ones.

In the present work, in order to investigate the fire performance of double glazing, a total of nine full scale experiments were performed. The double glazing unit with a dimension of $600 \times 600 \times 18$ mm^3 (two 6 mm glazing panes separated by 6 mm thick air) was heated by a pool fire. To measure the temperatures on four surfaces, thermocouples were attached before sealing glazing unit. With graduate decrease of glazing-burner distance, the critical breakage criterion was obtained. Important parameters, including incident heat flux (HF), temperature on four surfaces, breakage time as well as cracking behavior, were recorded and analyzed. Meanwhile, to reveal the process of heat transfer in unit, numerical simulation using COMSOL Multiphysics (a finite element analysis software), was conducted and compared to experimental results.

2. Experimental setup

The experimental setup primarily consisted of a fire source, double glazing and measurement system. The double glazing used in experiments included two clear float glass panes (each with the dimension $600 \times 600 \times 6$ mm^3) separated by an air filled space (6 mm thick). A well-designed frame made of stainless steel was employed for glass support, as illustrated in Fig. 1(a). The width of the covered region at the glass edge was 20 mm. In the thickness direction, the glass pane was clamped using several thin strips, and the clamping pressure was controlled by revolving screws. What is more, the four edges of frame can be conveniently moved to adjust to the size of glass pane. This design ensured the glass pane to be appropriately constrained in the x, y and z directions so that the condition of an actual double glazing unit could be approximated as closely as possible.

Sheet K-type thermocouples were attached to the glass panes using high temperature resistant adhesive. The glass pane at fire side is named Pane 1 and the other Pane 2. The temperatures on four surfaces of the double glazing, named S1, S2, S3 and S4 from the fire side to the ambient side, were recorded. The thermocouple distribution is shown in Fig. 1(b). Thermocouples are numbered as TC x-y, for which x and y represent glass surface number and thermocouple number in each surface, respectively. Excluding TC2-1, TC3-1 and TC4-1, all thermocouples were attached on S1. It should be noted that we invited a professional manufacturer to attach two thermocouples (TC2-1 and TC3-1) on S2 and S3 while assembling the double glazing unit and ensured the unit well sealed using an aluminum frame and binder around the perimeter. In addition, a sheathed thermocouple, with a diameter of 1 mm, was positioned closely in front of glass to measure the air temperature. Because of direct radiation heating on these thermocouples, uncertainties in temperature measurement were estimated at 5%. A data acquisition system with 16 channels for thermocouples was used, with the sampling time adjusted to 1 s.

A Gardon water cooled total heat flux gauge with a measurement range of 0–50 kW/m^2 was employed to measure the incident heat flux on the glass. The gauges were fixed off the side of each glass pane and mounted flush to the surface of the glass sections, so as to situate them as close to the measurement location as possible. The glass pane was monitored by a standard video camera with a framing rate of 50 frame/s. N-heptane fuel in a 500×500 mm^2 square tray was used to facilitate a pool fire and

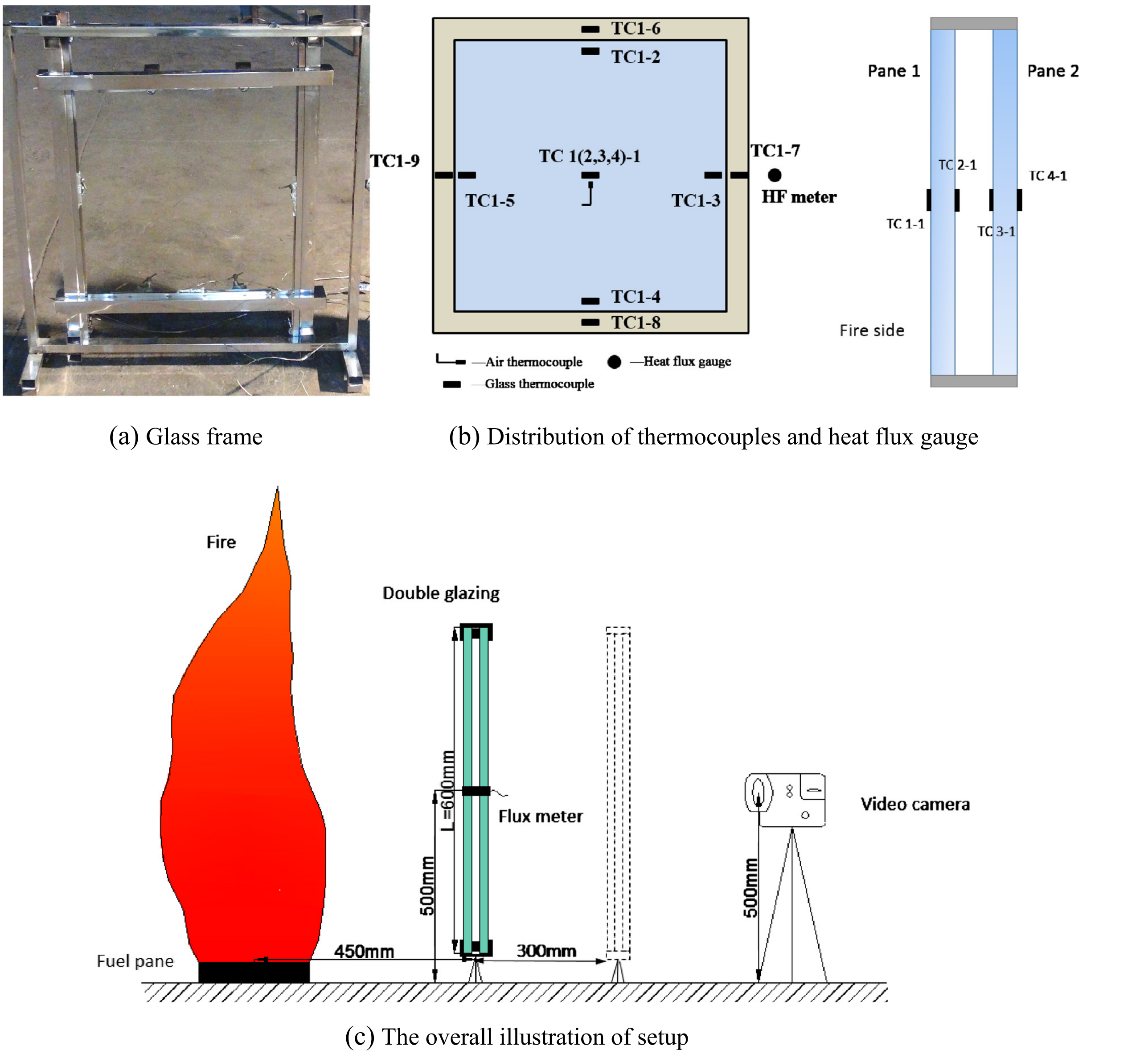


Fig. 1. The schematic of double glazing experimental system in fire.

the distance between fire and glazing was changed from 750 mm to 450 mm. The precise arrangement is shown in Fig. 1(c).

3. Experimental results

To determine the fire performance, nine full scale experiments were conducted with different burner-glazing distances and fuel mass, as summarized in Table 1. The distance was changed from 750 mm to 450 mm, and the fuel mass was increased from 2 kg to 6 kg, to seek the critical breakage conditions of Pane 1 and Pane 2. The pool fire, with a maximum heat release rate (HRR) of 800 kW, maintained more than 12 min during experiments that ensures sufficient thermal loading on glass pane. The detailed results are presented in the following sections.

3.1. The time of breakage and fracture behavior

Once crack is initiated, glass pane will likely fall out in a very short time, thus breakage time is of great importance to the compartment fire development. Using digital camera, the time of first crack occurrence was recorded, as shown in Table 2. In Test 1, glass pane located 750 mm from fire and the maximum temperature on glass surface reached around 150 °C. However, since temperature distribution was much more uniform with the glass pane being placed far away from the fire, no crack occurred. Then the distance was changed to 700 mm with the incident heat flux and tempera-

Table 1
The summary of experimental tests.

Test number	Burner-glazing distance (mm)	Mass of fuel (kg)	Burning time (s)
1	750	2	365
2	700	2	377
3	700	4	552
4	650	4	522
5	600	4	548
6	550	4	538
7	550	6	743
8	500	6	754
9	450	6	715

Table 2
Breakage time and crack initiation location.

Test number	Time of first crack occurrence (s)		The first crack position (viewed from fire side)	
	Pane 1	Pane 2	Pane 1	Pane 2
1	–	–	–	–
2	222	–	Left edge	–
3	172	–	Left edge	–
4	292	–	Top edge	–
5	204	–	Right edge	–
6	136	–	Left edge	–
7	141	–	Right edge	–
8	127	–	Right edge	–
9	96	617	Left edge	Right edge

ture increasing. It was found that Pane 1 cracked at 222 s, while there was no crack in Pane 2. The first pane acted as a band pass filter that flames and hot layers did not radiatively heat panes beyond the first exposed in double glazing [14], so the temperature in Pane 2 increased very slowly making it difficult to satisfy crack condition. This also took place until the distance decreased to 450 mm in which both Pane 1 and Pane 2 broke during fire. Test 9 is the only one that both panes cracked, and it may have been caused by larger temperature gradient and heat flux when glass pane was very close to fire. The breakage and integrity loss of glass pane at ambient side (Pane 2) normally signify the failure of a double glazing unit [16], the failure time of 617 s in Test 9 is three or four times greater than that of ordinary single glazing under similar thermal conditions [5,6,23], which conforms that the fire resistance of double glazing is much better than single ones.

In order to demonstrate the breakage time variance more clearly, Fig. 2, concerning Pane 1 breakage time, was plotted. Point supported glass breakage time in our previous study [24] is also added in this figure to make a comparison. It can be seen that the breakage time improves steadily with the distance increasing both in the present and previous work. Through linear fitting, it was found that the correlation coefficients in the two curves are relatively high, which are 0.81 and 0.97 for Pane 1 and point supported glass breakage time respectively. In the results, the breakage time of Test 4 is evidently different, so if excluding it, the correlation coefficient for Pane 1 would reach around 0.90. In addition, the fuel mass changed twice in our experiments. It inevitably affected heat release rate of a pool fire [25], considering which, the coefficient of 0.81 is reasonable. Therefore, it can be concluded that the breakage time of a glass pane increases linearly with the burner-fire distance increasing. The detailed theoretical explanation will be presented in the discussion section.

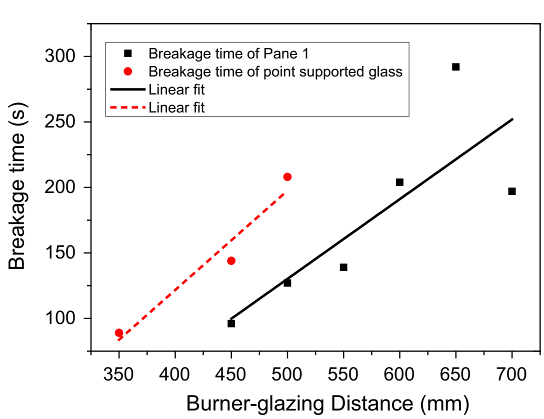


Fig. 2. The breakage time variance with burner-glazing distance increasing.

The temperature gradient resulting from glass frame protection may induce thermal stress, and cracks will be initiated where the stress in glazing exceeds its tensile strength [26]. With respect to double glazing unit, the covered or shaded areas are different in interior and exterior panes: for Pane 1 the glass panel is four edges covered, while there is no covered areas to fire for Pane 2. Thus, the breakage behavior of Pane 1 is anticipated to be similar to ordinary window glass pane, in which cracks are prone to initiating from glass pane edges [4,27]. From Table 2, it can be seen that in our experiments all the cracks did initiate from glass edges, especially left and right edges because of relatively great temperature difference. At top and lower edges, the flame may directly heat the frame and glazing, temperature difference in vertical direction is not as large as that in horizontal direction due to the shape of fire plume [28], thus only in one test the crack initiated in these areas. This phenomenon also took place in previous work [23]. On the other hand, because of no shading area and direct heating, Pane 2 is much more difficult to break. In Test 9, Pane 2 cracked a long time (7 min) after Pane 1, and the crack initiation position was at right edge (viewed from fire side) that appears opposite to Pane 1. Actually, the crack in Pane 2 may initiate at each edge with the same probability according to its stress distribution. In this work float glass was employed to render the cracking behavior clearer, and glass pane remained in frame after crack initiation. For toughened glazing, once cracking, glass pane will fall out immediately [7], the crack initiation in Pane 2 normally represents the new vent formed for whole toughened glazing system.

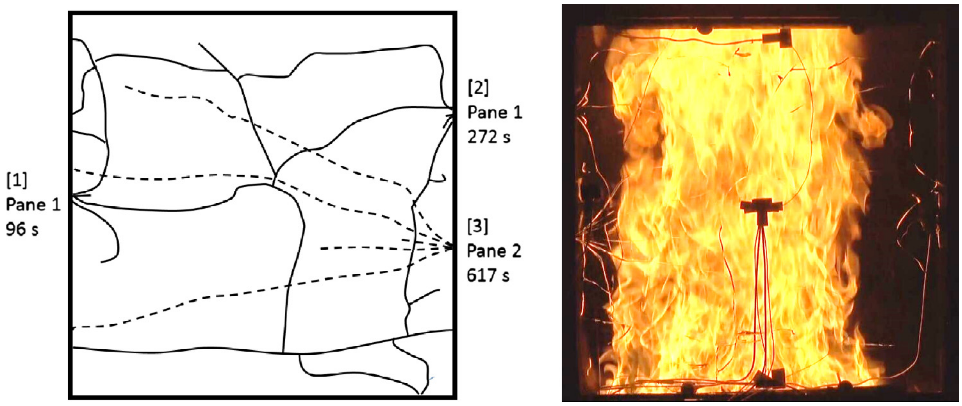
After initiation, crack will propagate to the center of pane. The crack path in Test 9 is shown in Fig. 3. It can be seen that a total of three cracks initiated during fire: the first and second occurred in Pane 1 at left and right edge respectively; the third occurred in Pane 2 at right edge. In Pane 1, the cracks in two opposite edges bifurcated, propagated and cross with each other, forming some islands. The islands are considered the most easily falling out areas [14]. However, as the experiments were performed in open space where the pressure variance was very limited, the cracked pane may remain in the frame. In other eight tests, no pieces of glass fall out neither due to absence of wind loading or significant interior overpressures. While in some previous work conducted in an enclosure [4,6], almost all panes fell out. It should be noted that for a double glazing, the fallout of Pane 1 renders partial Pane 2 directly exposed to fire or hot layer, accelerating the failure of double glazing unit. Thus, in a real compartment fire, the failure of glazing unit may occur in a shorter time than that in experiments.

3.2. Temperature and heat flux

The breakage and fallout of glazing can be attributed to the exceeding temperature and heat flux. To obtain the temperature distribution, twelve thermocouples were attached on glass surfaces (as shown in Fig. 1(b)) and one thermocouple was positioned very close to glass pane to measure air temperature at fire side. As a typical example, the temperature variance of S1 and air temperature in Test 3 are plotted in Fig. 4(a). It was found that the temperatures recorded in exposed areas (from TC1-1 to TC1-5) are markedly higher than that in covered areas (from TC1-6 to TC1-9). The thermal gradient caused by frame protection in perimeter may cause greater thermal stress than the central part, which can be simply estimated using the following Eq. (1):

$$\sigma = E\beta(T_c - T_0) \tag{1}$$

In addition, it is known that there are many defects at glass edge due to cutting and manufacturing, thus the combination of relatively great stress and existing flaws becomes the primary cause of crack initiation at glass pane edge. Our experiments, in which



(a) The sketched crack path, viewed from fire side (b) The photograph captured during fire, viewed from ambient side

Fig. 3. The crack path in one typical test in which both panes cracked (Test 9).

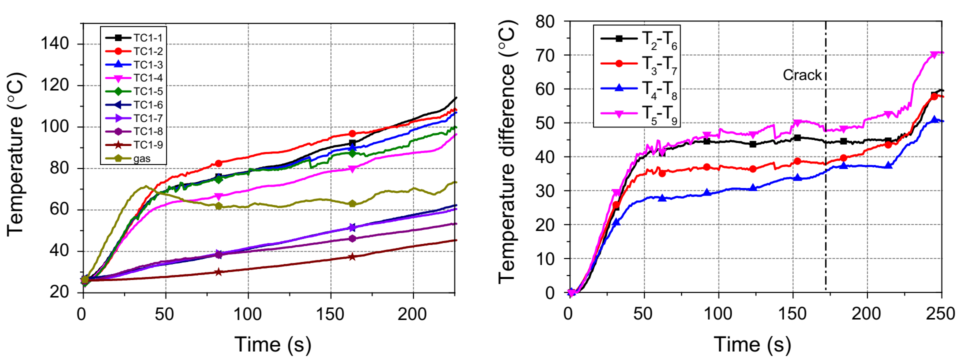
all cracks were initiated in these areas, confirm this issue. What is more, the following equation may help to determine at which edge the crack will be initiated:

$$\mathrm{Max}\{T_2 - T_6, T_3 - T_7, T_4 - T_8, T_5 - T_9\} \tag{2}$$

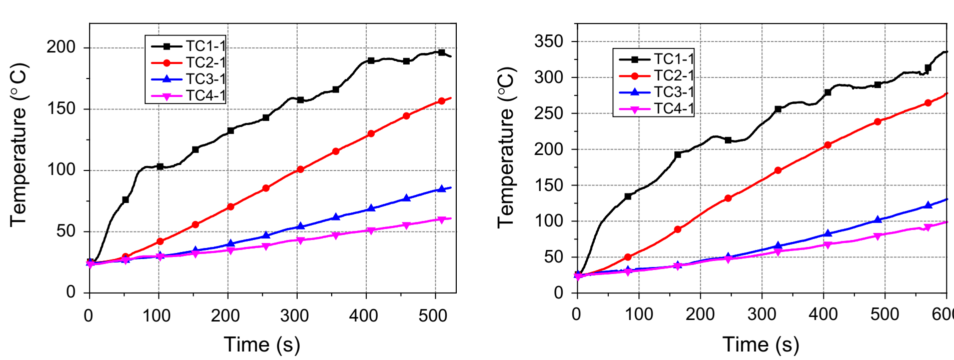
Fig. 4(b) illustrates the temperature difference variance at four edges of Test 3. It can be found that $T_5 - T_9$ is the greatest temperature difference that suggests the stress in left edge is maximum. This is the reason of the first crack initiating from left edge in Test 3. In other tests (except Test 4), all the cracks initiated from where the temperature difference is maximum as shown in Table 3. The temperature difference at the time of crack is around 60 °C that is similar to previous study of single glazing [14]. In addition, to illustrate temperature variance of the whole glazing unit, the temperatures at four surface centers are plotted in Fig. 4(c). It can be seen that the temperature of Pane 2 increases very slowly and significantly smaller than that of Pane 1. It suggests that the heat insulation from Pane 1 and air gap plays an important role in the protection of Pane 2. At the breakage time of Pane 2 in Test 9, its central temperature is 176 °C. Thus much more time is needed to satisfy the temperature condition for Pane 2 breakage.

Incident total heat flux was measured in experiments. If we assume the glass plate to be a thermal lump and using an energy balance it follows that [29]:

$$\Delta E_{st} = E_{in} - E_{out} + E_g \tag{3}$$



(a) Temperatures monitored on S1, Test 3 (b) Temperature difference at four edges, Test 3



(c) Temperatures monitored at centers of four surfaces, Tests 4 and 8

Fig. 4. Temperature history in Tests 3, 4 and 8.

Table 3
The parameters at the time of first crack occurrence.

Test number	Temperature at center, TC1-1 (°C)	Maximum temperature difference (°C) and location, Pane 1	Heat flux, Pane 1 and Pane 2 (kW/m^2)
Test 1	–	–	–
Test 2	121	78, left edge	–
Test 3	96	48, left edge	6.13, –
Test 4	159	63, right edge	8.41, –
Test 5	110	68, right edge	6.43, –
Test 6	123	59, left edge	7.24, –
Test 7	129	65, right edge	7.18, –
Test 8	157	59, right edge	10.16, –
Test 9	204	67, left edge	10.34, 25.29

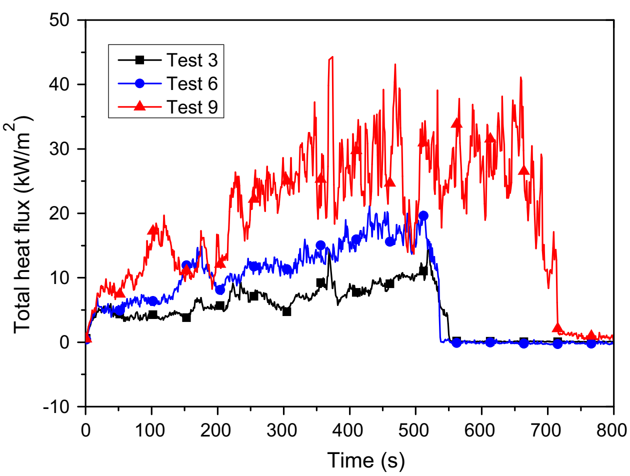


Fig. 5. The imposed heat flux in tests with burner-glazing distances of 700, 550 and 450 mm (Tests 3, 6 and 9).

In double glazing unit, E_g is zero, so:

$$\rho\delta Ac\frac{dT_g}{dt} = q(t)A - hA(T_g - T_\infty) - \varepsilon\sigma A\left(T_g^4 - T_{sur}^4\right) \quad (4)$$

It should be noted that the radiation term is very small, so sometimes it can be ignored [5,17]. From above equation, it is known that the heat flux imposed to glass pane is the only one source of temperature increase, so the variance of incident heat flux becomes the substantial reason of temperature increase resulting in different breakage time. Test 3, 6 and 9 were selected as typical examples to show the variance of heat flux in our experiments, as shown in Fig. 5. With the burner-glazing distance decreased, the heat fluxes increased: the maximum incident heat flux of Tests 3, 6 and 9 are around 10 kW/m^2, 20 kW/m^2 and 30 kW/m^2. The specific heat fluxes at the time of first crack occurrence are listed in Table 3. The values appear to slightly increase when burner-glazing distance decreases. From Test 2, glass started to break, therefore the value in Test 2, around 6 kW/m^2, is considered to be the critical heat flux for Pane 1 breakage. It is very close to critical heat flux of single glazing [23,30]. However, there is a very high critical value of 25 kW/m^2 for Pane 2, thus Pane 2 can keep intact for much longer time than Pane 1. Furthermore, by comparing the air temperature and TC1-1 in Fig. 4(a), it was established that, almost all the time, the air temperature was smaller than that at glass central part, therefore the heating of glass pane may be primarily attributed to radiation flux rather than convective heat transfer. This is because the experiments were conducted in an open space where flowing air would cool down immediately, however, this will change to be convention dominating when conducted in an enclosure [17].

4. Comparisons and discussion

Nine tests with different burner-glazing distances were conducted to investigate the critical condition of breakage in double glazing unit. The experimental results suggest that the criterions for Pane 1 and Pane 2 are considerably different.

4.1. Discussion of Pane 1

For Pane 1, due to similar installation form to normal window glass pane, the temperature difference of 60 °C and heat flux of 6 kW/m^2 at the time of first crack occurrence are almost identical to that of single glazing (60–90 °C, 4–5 kW/m^2) [30]. This finding implies that the effect of air gap and Pane 2 on the fire performance of Pane 1 is very limited and thus can be ignored. From Eq. (1) and critical temperature difference in Table 3, the breakage stress can be simply obtained 27–44 MPa, which also agrees well with that of single float glass [31]. Therefore, we can use the breakage model of single glazing to predict the breakage time of Pane 1. Assuming incident heat flux is constant, Eq. (4) can be transferred to the following form [5]:

$$t_{crack} = \frac{c\rho\delta}{h_{S2}}\ln\left(\frac{q}{q - h_{S2}(T_g - T_\infty)}\right) \quad (5)$$

From Fig. 5, the heat flux in Test 9 can be considered stable, approximately 25 kW/m^2. From Fig. 4(a), it is found that the bulk glass temperature stabilized around 373 K. Then, with $T_g = 373$ K, $T_\infty = 298$ K, $h_{S2} = 0.04$ $kW/m^2{\cdot}K$ and $c = 0.92$ kJ/kg·K, the breaking time can be estimated using Eq. (5) which is 95 s. The predicted time is similar to experimental breakage time, 96 s, and the slight difference might be caused by the assumption of constant heat flux and ambient temperature.

In addition, from Fig. 2, it was found that the breakage time increases almost linearly with the burner-glazing distance increases. The substantial reason is clearly the increasing imposed heat flux with the distance decreasing. From experimental results, the heat transfer form fire to glass pane is predominantly radiation in open space [23]. While for radiation transfer, it might be significantly absorbed by the air, especially CO_2, H_2O between fire and glass. In a volumetric phenomenon, the spectral radiation absorption is a function of the absorption coefficient κ (1/m) and the burner-glazing distance L. The function may be expressed as [29]:

$$dI(x) = -\kappa I(x)dx \quad (6)$$

$$\int_{I_0}^{I}\frac{dI(x)}{I(x)} = -\kappa\int_0^L dx \quad (7)$$

According to Beer's Law, the transmissivity through air can be thus defined as:

$$\tau = \frac{I_L}{I_0} = e^{-\kappa L} \quad (8)$$

Assuming the fire radiation from fire is a constant value I_0, then we can obtain the incident heat flux expression:

$$q = I_0 e^{-\kappa L} \quad (9)$$

The above equation might explain the reason that the heat flux imposed on glass decreases with distance increasing. Thus, the relationship between burner-glazing distance and first breakage time can be obtained from Eqs. (5) and (9):

$$t_{crack} = \frac{c\rho\delta}{h_{S2}}\ln\left(\frac{I_0 e^{-\kappa L}}{I_0 e^{-\kappa L} - h_{S2}(T_g - T_\infty)}\right) = \frac{c\rho\delta}{h_{S2}}\left(\ln(I_0) - \kappa L - \ln\left(I_0 e^{-\kappa L} - h_{S2}(T_g - T_\infty)\right)\right) \quad (10)$$

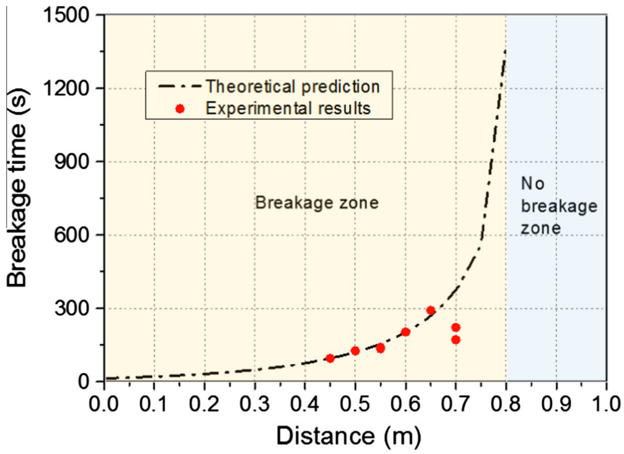


Fig. 6. Comparison between theoretical model and experimental data.

At the critical condition for cracking, the rate of heat loss from glass surfaces is equal to the imposed heat flux [5]:

$$q_{crack} = h_{S2}(T_g - T_\infty) \tag{11}$$

Then, the first derivative of Eq. (10) is:

$$t'_{crack} = \frac{\kappa c \rho \delta}{h_{S2}} \left(\frac{I_0 e^{-\kappa L}}{I_0 e^{-\kappa L} - q_{\text{crack}}} - 1 \right) \tag{12}$$

This equation is evidently >0, thus the breakage time is a monotone increasing function of burner-glazing distance. It should be noted that we only discuss the condition when incident heat flux is larger than critical heat flux:

$$0 \leqslant L < \frac{\ln I_0 - \ln q_{\text{crack}}}{\kappa} \tag{13}$$

If $L \geqslant (\ln I_0 - \ln q_{\text{crack}})/\kappa$, the glass pane will not crack despite $t = \infty$.

Using Eq. (9), the absorption coefficient is estimated 4 m^{-1} and the radiation heat flux on the flame is approximately 150 kW/m^2 from the experimental measurement. Then the prediction of breakage time under experimental condition in the present work is drawn in Fig. 6. It can be seen from the diagram that the breakage will occur when the distance is within a scope of 0–800 mm. When the glass pane is positioned 750 mm away from fire, the needed heating time for breakage is around 560 s, while in experiments the heating time of 365 s cannot satisfy the condition, so no crack occurred. What is more, if the distance is larger than 800 mm, even though the pane is heated for infinite time, the pane will not break. This agrees well with experimental results. By comparison, there is also a high level of agreement between the theoretical prediction and the experimental breakage time. The results suggest that this simplified model can give relatively reliable and reasonable prediction of first breakage time of Pane 1. If the burner-glazing distance is far to the critical point (approximately 700 mm in the present work), the breakage time may be assumed to linearly increase, as illustrated in Fig. 2. It is intended to provide useful relevance to fire safety design of glass façades. It should be noted that under other fire conditions, the curve will differ significantly due to the change of fire and glazing parameters.

4.2. Discussion of Pane 2

The breakage of Pane 2 indicates the failure of a double glazing system, so it is important to investigate the thermal performance of Pane 2. For a given double glazing in fire, the heat absorption is the sum of four terms: the portion of fire radiation that passes through Pane 1, the thermal radiation exchange between Pane 1 and Pane 2, the heat conduction in air gap and the convention that occurs on S3 because the glass is at different temperature than air gap. It can be expressed in the following equation:

$$\begin{aligned} q_{\text{tot,Pane 2}} &= q_{\text{rad}} + q_{\text{conv}} + q_{\text{cond}} + q_{\text{tr}} \\ &= \left(\frac{1}{\varepsilon_{S2}} + \frac{1}{\varepsilon_{S3}} - 1 \right)^{-1} \sigma (T_{S2}^4 - T_{S3}^4) + h_{S2,S3}(T_{S2} - T_{S3}) + q_{\text{tr}} \end{aligned} \tag{14}$$

In the present work, the width of air gap is 6 mm, and from a standard Rayleigh number correlation based on the gap distance [32],

$$Ra = \frac{g\beta(T_{sur} - T_\infty)\delta^3}{\nu\alpha} \tag{15}$$

$$Nu = \left[1 + (0.0303Ra^{0.402})^{11}\right]^{1/11} \tag{16}$$

it was found that conduction through stagnant air is the dominant transport mechanism for gaps ⩽10 mm. For 6 mm air gap in this work, the inter-pane heat-transfer coefficient $h_{S2,S3}$ is approximately 5 $W/(m^2{\cdot}K)$ [16]. As to the term of radiation transmission through Pane 1, its value will change in fire since the transmitted fraction of the incident radiation is a function of the source temperature [29]. It should be noted that temperature has a relatively minor influence on transmittance of glass, so it can be ignored as reported in [33]. The transmitted fraction of the incident radiation is a function of the source temperature, and when the source temperature changes from 600 K to 1400 K, the transmitted fraction varies from 1% to 31% [14]. Therefore, approximately 13% of the incident radiation was transmitted due to the flame temperature of 1000 K in our experiments. Then, Eq. (14) can be rewritten as follows:

$$\begin{aligned} Q_{\text{tot,Pane 2}} &= q_{\text{rad}} + q_{\text{cond}} + q_{\text{tr}} \\ &= \left(\frac{1}{\varepsilon_{S2}} + \frac{1}{\varepsilon_{S3}} - 1 \right)^{-1} \sigma \left(T_{S2}^4 - T_{S3}^4\right) + h_{S2,S3}(T_{S2} - T_{S3}) \\ &\quad + q_{\text{tr}}(T_{\text{flame}}) \end{aligned} \tag{17}$$

In previous work [16], the direct radiation flux reaching Pane 2 was assumed zero, when analyzing the heat absorption in cool pane. To investigate the assumption, a finite element software, COMSOL Multi-physics, is employed to predict the increasing temperature in a double glazing unit. In this model, a uniform radiation thermal loading was applied on S1. The four lateral surfaces (glass edge) are considered to be thermal insulation, since the areas of these surfaces are too small compared to the glass pane size (3:100). There is no significant heat transfer between glass perimeter and ambient. While the convection heat transfer exists on S1 and S4, and the absorption and emission of radiation occurred on each surface. Conduction through stagnant air is the dominant transport mechanism. Due to the limitation of software, the glass pane is assumed a kind of opaque graybody. The dimension and properties of glass are identical with the glazing tested in experiments, as shown in Table 4. The grid independence tests were

Table 4
Glass properties.

Properties	Symbol	Value
Density (kg/m^3)	ρ	2500
Modulus of elasticity (Pa)	E	6.7×10^{10}
Poisson's ratio	ν	0.22
Thermal expansion co-efficient (1/K)	β	8.46×10^{-6}
Reference temperature (K)	T_R	298
Specific heat capacity (J/(kg·K))	c	703
Thermal conductivity (W/(m·K))	k	1.38
Emissivity	ε	0.85

Table 5
The grid independence tests.

Element size	Grid number	Computing time (s)
Extremely coarse	4808	83
Extra coarse	8120	176
Coarser	13,642	608
Coarse	30,074	3561
Normal	65,198	24,247

conducted. When we increased the element number from 4808 to 65,198 (Extremely coarse, Extra coarse, Coarser, Coarse and Normal), the computing time varied from 83 s to 24,247 s, as shown in Table 5. The temperatures predicted are very similar in every point, especially for Coarser, Coarse, and Normal tests, with a difference smaller than 1 °C. Then the element size of coarse was selected due to its time saving and relatively good accuracy. A total of 30,074 tetrahedral elements were used in this thermal behavior simulation, as shown in Fig. 7(a). The time interval was set 1 s. The equations of the mathematical modelling are:

$$\rho c\frac{\partial T}{\partial t}+\nabla\cdot q=Q \tag{18}$$

$$q=-k\nabla T \tag{19}$$

where Q represents heat source. The whole heat transfer progress can be explained as follows:

(1) On S1, the glass receives radiation from the fire. Meanwhile, it radiates to ambient, convects with air and conducts heat into the glass pane:

$$-n\cdot k\nabla T=h\cdot(T_\infty-T)+q-\varepsilon\sigma T^4 \tag{20}$$

where T_∞ is the air temperature at fire side that is around 320 K during experiments.

(2) In the inner side of two glass panes, heat transfer progress includes conduction between air gap and glass, as well as radiation absorption and emission. The energy conservation on S2 is expressed as follows:

$$-n\cdot k\nabla T=\varepsilon(G_{S3}-e(T_{S2})) \tag{21}$$

$$G_{S3}=F_{S3}e(T_{S3}) \tag{22}$$

$$e(T)=n^2\sigma T^4 \tag{23}$$

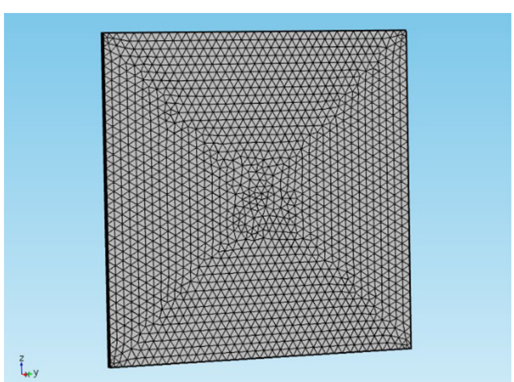
where $e(T)$is the blackbody hemispherical total emissive power; by definition, $0\leqslant F_{S3}\leqslant 1$ at all points. It should be noted that the energy conservation on S3 is similar to S2, so its equations are not included here.

(3) On S4, the glass radiates and convects with ambient, and conducts from the glass:

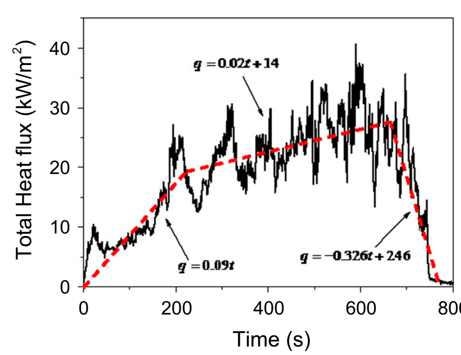
$$-n\cdot k\nabla T=h\cdot(T_\infty-T)+\varepsilon_\infty\sigma T_\infty^4-\varepsilon\sigma T^4 \tag{24}$$

where T_∞ is the temperature at ambient side that is equal to 293 K.

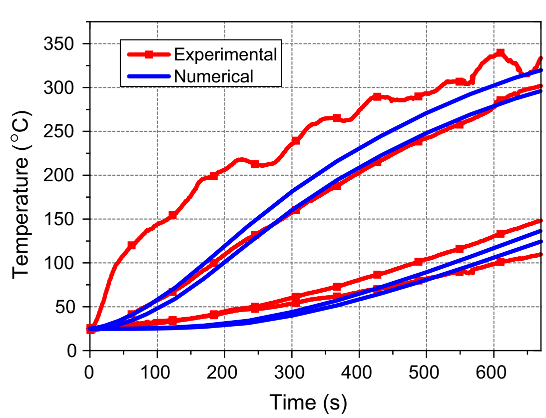
Test 8 is selected to make comparison. Total heat flux, extracted from experimental data, is used as thermal loading, as shown in Fig. 7(b). Note that since glass is heated by only ~65% of the radiation measured with a black, opaque heat flux gauge, actual heat



(a) Mesh grids in simulation



(b) Thermal loading



(c) Temperature comparison of Test 8

Fig. 7. Temperature comparison between numerical and experimental results.

flux applied on S1 is 0.65q in this simulation. The numerical results are presented in Fig. 7(c). Adding the transmitted radiation is currently a very difficult for this software, so there is some differences between numerical and experimental results. The temperature difference on S1 is primarily caused by the close flame in Test 8, and when flame become smaller at the end of burning, the difference on S1 is gradually decreasing. On S2, the temperature predicted is highly consistent with experimental results. However, in Pane 2, although the variance tendency is similar, the calculated temperatures are normally smaller than measured values. From Eq. (17), when temperatures on S2 are nearly identical, the primary reason may be the ignorance of radiation transmitted through Pane 1. In particular, at the beginning phase, temperature difference between S2 and S3 is relatively small, and the radiation transmitted through Pane 1 may dominate the heat transfer. With temperature difference increasing, the portion of heat conductivity increases gradually and thus in this end of simulation the predicted temperature is very close to the temperature measured in Pane 2. Therefore, only when the fire is relatively far away from glazing resulting in small incident heat flux (e.g. wildland & urban fire) or the Pane 1 can withstand relatively long time in fire, the numerical method and assumption can provide reasonable and reliable information. The temperature prediction of Pane 2 needs much more work in the future. It should be noted that, some other tests were also simulated, and the results are very similar to the comparison in Test 8, so they are not included in this paper. The numerical simulation concerning double glazing in fire will be systematically investigated in our future work.

5. Conclusions

To determine the critical breakage conditions for double glazing in fires, a total of nine glass panes were heated by a pool fire, with the burner-glazing distance changing from 750 mm to 450 mm. Important parameters of double glazing, in terms of breakage time, critical incident heat flux, temperature on four surfaces and cracking behavior, were obtained. Theoretical models are developed to reveal the heat transfer mechanism and predict the thermal breakage behavior of double glazing unit. Numerical study, using finite element method, is employed to predict surface temperatures, making a comparison with experimental result. It is established that the breakage condition of double glazing is significantly different from single ones. The specific conclusions are as follows:

(1) In double glazing the pane at ambient side can survive three or four times longer than the pane exposed to fire. Thus, the fire resistance of double glazing is much better than that of ordinary single glazing.
(2) For Pane 1, the critical temperature difference and heat flux are around 60 °C and 6 kW/m^2; while due to no frame covered area and radiation filter, the temperature needed for Pane 2 breakage is higher, and its critical heat flux is more than 25 kW/m^2.
(3) With the burner-glazing distance decreasing, the breakage time of Pane 1 decreases. Using the prediction model based on incident heat flux, the breakage time of Pane 1 can be well predicted.
(4) Through comparison, it is found that radiation transmitted through Pane 1 may be significant to Pane 2 heating in the beginning of fire and thus may not be ignored when predicting the thermal performance of Pane 2, but it needs to be further verified.
(5) The breakage of Pane 2 means the failure of whole glazing unit, but it may be affected by multiple factors, such as the thickness of air gap, breakage behavior of Pane 1. Much more work is needed to enhance the understanding of double glazing thermal performance in fire.

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