EXPERIMENTAL STUDY ON THE BREAKAGE OF TOUGHENED GLASS IN ENCLOSURE FIRES

Q.Y. Xie [1], H.P. Zhang [1], Y.T. Wan [1], Q.W. Zhang [2] and X.D. Cheng [1]
[1] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, 230027, China
[2] Fire Department of Guangdong Province, GuangZhou, 510640, China

ABSTRACT

Window glass breakage plays an important role in compartment fire dynamics as the window acts as a wall before breaking and as a vent after breaking. The objective of this work is to investigate the breakage behavior of toughened glass in enclosure fires. A series of full-scale experiments is carried out in the ISO 9705 test fire room to analyze the critical condition of the first breaking of toughened glass using oil pan fires with different heat release rates. The heat release rates, enclosure and local gas temperatures, exposed glass surface temperatures, shaded glass surface temperatures, time to first crack and crack patterns are measured. The dependence of glass breakage on critical parameters like the temperature differences between the exposed and shaded glass surface is analyzed. The results show that the crack of the toughened glass generally occurs initially near the edges of the windows. It is also indicated that the toughened glass breaks under the condition of larger temperature differences than those for float glass, however, almost the whole toughened glass falls out completely soon after the first breakage occurs. These experimental results can be used for the estimation of the occurrence of cracking and failure of toughened glazing assembly in performance-based fire prevention design.

KEY WORDS: Toughened glass, Breakage, Pool fire

INTRODUCTION

More and more window glazings are widely used in modern buildings [1]. However, the window glass breaking plays an important role in compartment fire dynamics as the window acts as a wall before breaking and as a vent after breaking [2-3]. Some previous works were conducted to study the breakage behavior of window glass in enclosure fires [4-10]. It is indicated that the temperature differences between the exposed and shaded regions of window glazing play an important role in the breakage of glass. Most of the previous works focus on the floated glass. However, little research is done for the crack and fallout of toughened glass in fires. Toughened glass, which is helpful for prevention of burglary, is also popularly used in some large and new buildings. In the development of fire safety engineering solutions, e.g. the performance-based fire designs for buildings, it is necessary to be able to predict the thermal behavior of toughened glass subjected to fire environments. In this case, full-scale experiments are carried out in the ISO 9705 fire test room to investigate the breakage behavior of toughened glass in enclosure fires using pool fires with different pan sizes.

EXPERIMENTAL

As shown in Fig. 1, the full-scale experiments of crack and fallout of toughened glass are carried out in an ISO 9705 fire test room, which is 3.6 m × 2.4 m × 2.4 m high [11]. The enclosure walls and ceiling are made of concrete 210mm in thickness and insulated with 20mm thick ceramic fiber board. In the centre of the south wall, there is an open door, which is 0.8 m wide and 2.0 m high. The products of combustion can be collected and exhausted by a hood, 3 m × 3 m × 1 m high, which is located close to the open door. The O_2, CO_2 and CO concentrations in the combustion products, which are sampled at the exhaust duct, can be continuously monitored. The temperature, different pressure and flow rate can also be measured at the exhaust duct. Heat release rate in the combustion room is measured by oxygen depletion calorimetry. At the end of the exhaust duct, there is an evacuation system to exhaust all combustion fumes. Three window glazings are incorporated in the west wall of the combustion room.

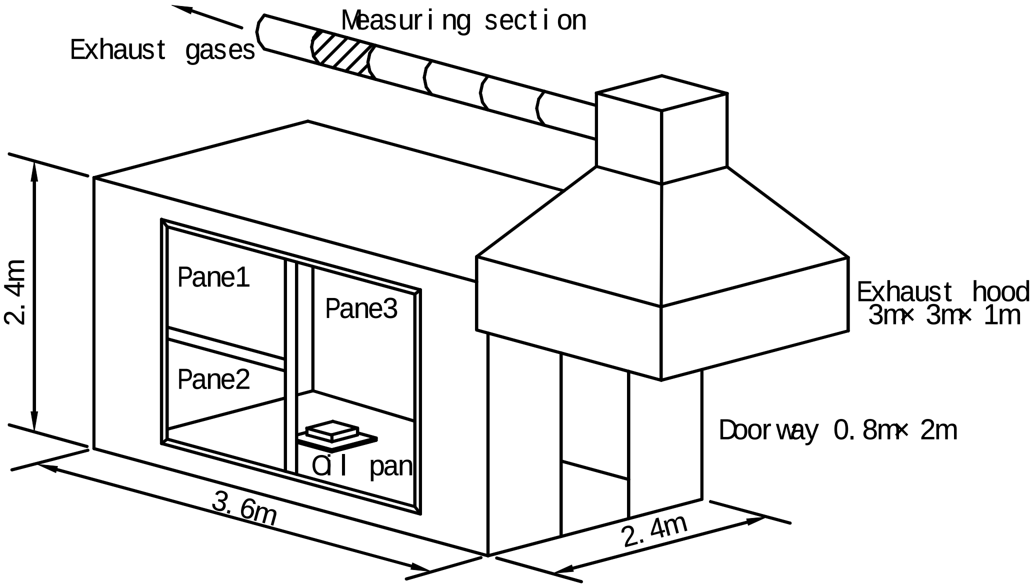
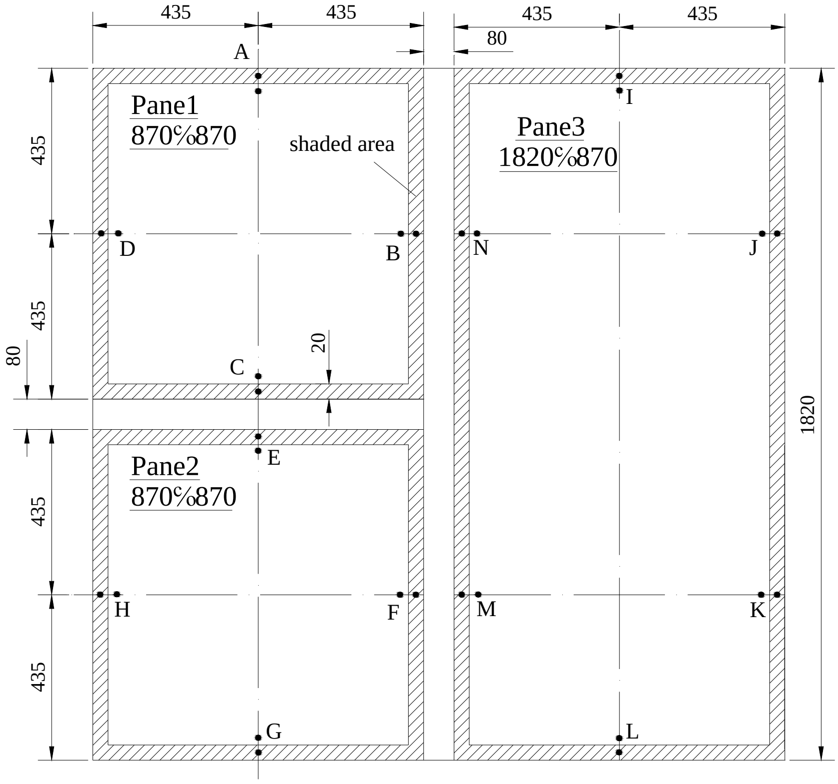


FIGURE 1. Schematic of the modified ISO 9705 full-scale experimental setup

Fig. 2 gives the detailed arrangements of the three window glazings and the thermocouples at the glazing edges. The 6 mm toughened glass, which is popularly employed in new buildings in China, is used in the window glazing. The sizes of both Panes 1 and 2 are 870 mm × 870 mm with Pane 1 primarily in the upper hot smoke fume layer and Pane 2 in the lower cool air layer. Pane 3, which is 1820 × 870 mm, is exposed to the hot smoke fume and cool gas layers over its full height. Frames with a width of 20 mm are used to fix the glass for the three glazings. The toughened glass is cut by machine and carefully installed after visual inspection for edge defects.

Here the crack and fallout of each pane in enclosure fires is analyzed respectively. Twenty-eight thermocouples are positioned at the typical top, middle side and bottom of the three panes, marked as Locations A~N in Fig. 2, to monitor the temperatures of local exposed and shaded regions of glasses. Specifically, as shown in Fig. 3, for each location, a thermocouple is positioned at the exposed region of the fire side with about 10 mm to the interface of the frame. A corresponding thermocouple is positioned at the shaded region of the ambient side with 10 mm to the frame interface. Thermal stress of a glazing edge is not only induced by the temperature difference between the exposed and shaded regions of glass at the fire side, but also by that between the temperatures at the ambient side and the fire side of glass surfaces. Therefore, the measured temperature differences through the above way consider the superposition of the two parts of temperature differences.



The unit of the dimension marked is mm.

FIGURE 2. Arrangement of window glazing and thermocouples

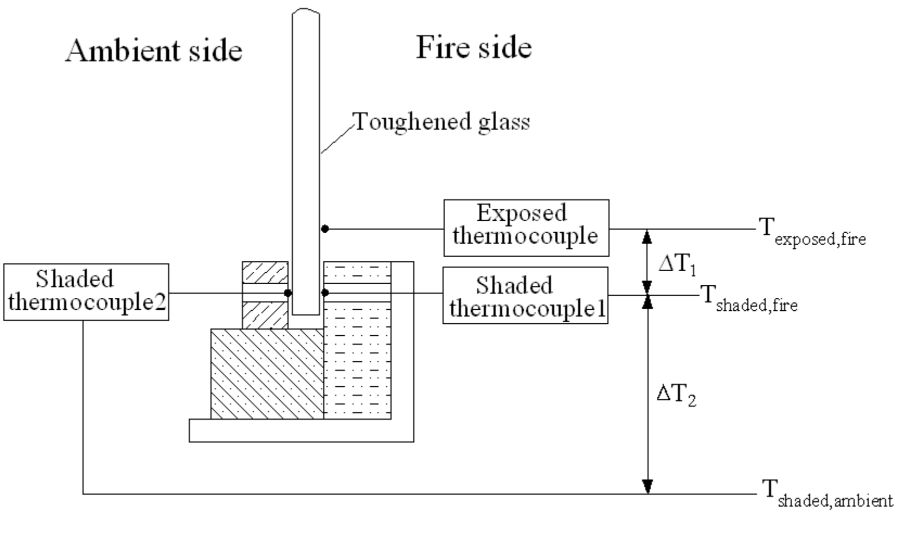


FIGURE 3. Description of the thermocouples at the glazing edges and the define of temperature differences

Here pool fires with different pan sizes, namely different heat released rates, are used as fire sources for the experiments. The pool fire is located at the center of the combustion room with the fuel of 20 kg diesel oil which is ignited with 50 ml alcohol. The flow rate in the exhaust duct is set as 3.0 m^3/s for each experiment.

RESULTS AND DISCUSSIONS

As indicated above, commercially available 10 mm thick toughened glass are used for the experiments with different size of pool fires. At least two runs are carried out for each set of experiment for the consideration of repeatability. Figs. 4 to 8 give the measured temperatures and temperature differences at those typical positions with the pan size of 800 mm * 800 mm. Similarly, Figs. 9 to 13 give the corresponding results for the pan size of 900 mm * 900 mm. The experimental phenomena show that the toughened glass don't break for the case of pan size of 800 mm * 800 mm. The toughened glass broke and fell out when the pan size is 900mm*900mm. It is suggested that there is generally a critical heat flux, or a critical temperature difference for the breakage of the window glazings with a certain thickness.

Fig. 4 gives the time-dependent temperature of glass surface exposed to fire with pan size of 800 mm * 800 mm. It is clearly shown that the temperature distributions fall into several groups. The temperature at upper hot smoke layer is obviously higher than those at lower cool air layer. Fig. 5 gives the time-dependent shaded temperature of glass surface at fire side. It illustrates that although the area of glass surface is shaded by the timber, the temperature still increases through the heat conduction. The increase of temperature may be as high as 200^{o}C at some positions. It is suggested that the assumption of constant temperature for shaded temperature may not be very reasonable. The increase of shaded temperature should be considered for the calculation of temperature difference between the exposed and shaded temperatures. Similarly, Fig. 6 shows the time-dependent shaded temperatures of glass surface at ambient side. The increase of temperature at these sides still cannot be omitted for calculation of temperature difference. The above shaded temperatures at glass surface indicate their influence on the temperature difference between the exposed and shaded temperatures.

Fig. 7 shows the time-dependent temperature differences between the exposed and shaded temperature of glass surface at fire side. Fig. 8 gives the temperature differences between the shaded temperature of glass surface at fire and ambient sides. The superposition of two temperature differences in Figs. 7 and 8 may be used as a criterion for glass breakage. As shown in Figs. 7 and 8, the temperature differences are also generally be larger at higher hot smoke layers and be smaller at lower cool air layers. The experimental results also show that the glass may break from the origin of those areas with maximum temperature difference.

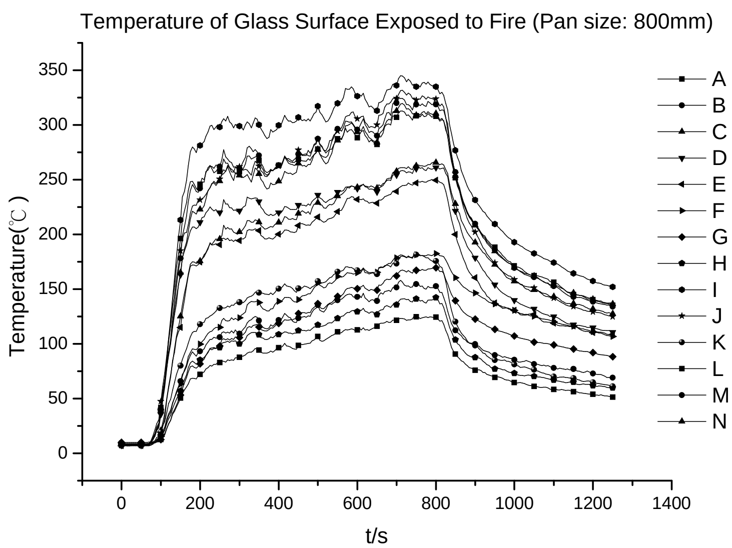


FIGURE 4. Temperature of glass surface exposed to fire (pan size: 800 mm * 800 mm)

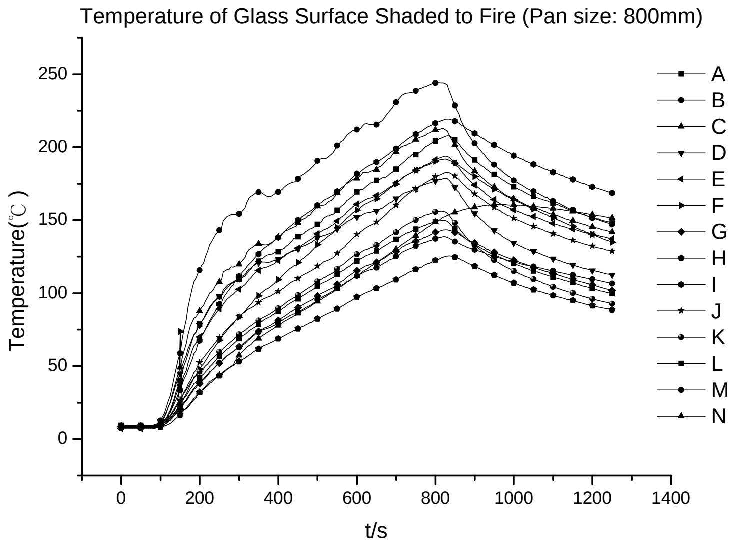


FIGURE 5. Temperature of shaded area of glass surface at fire side (pan size: 800 mm * 800 mm)

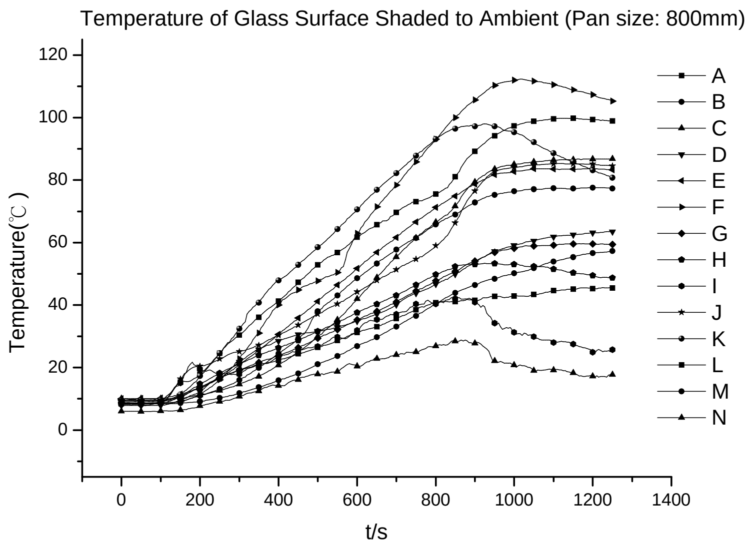


FIGURE 6. Temperature of shaded area of glass surface at ambient side (pan size: 800 mm * 800 mm)

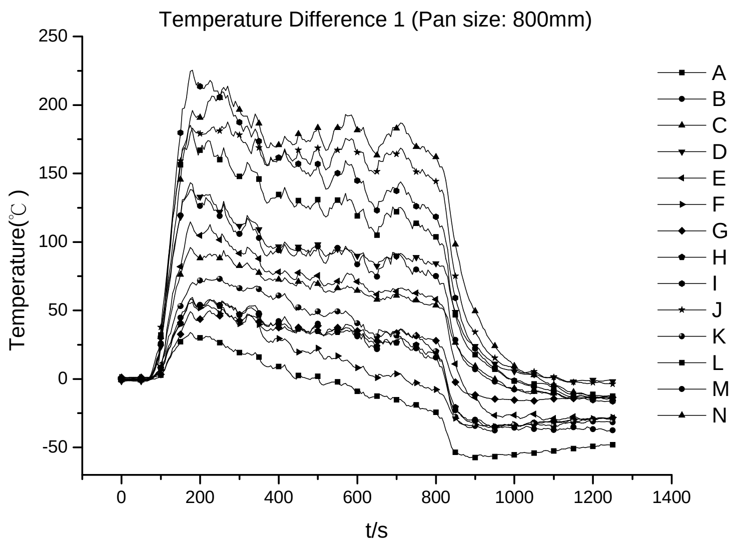


FIGURE 7. Temperature difference between the exposed and shaded area of glass surface at fire side (pan size: 800 mm * 800 mm)

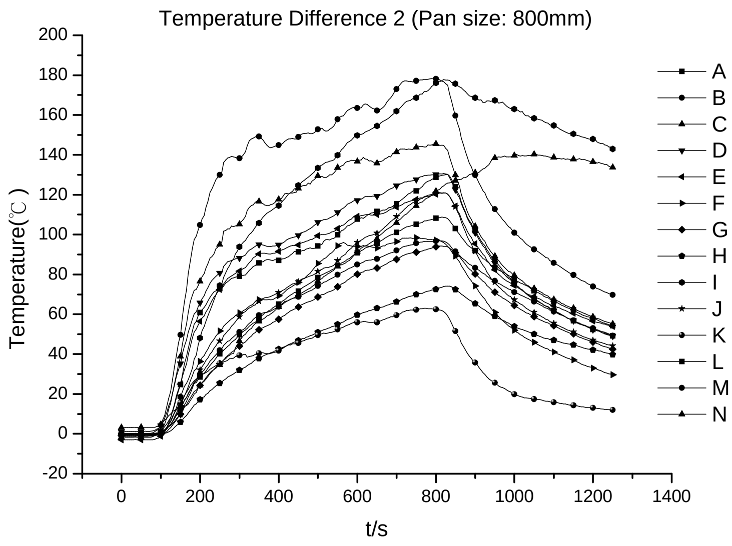


FIGURE 8. Temperature difference between the shaded area of glass surface at fire and ambient sides (pan size: 800 mm * 800 mm)

For the case of pan size of 900 mm * 900 mm, Panes 1 and 3 broke and fell out at 439 and 520 s after the ignition of pool fire, respectively. Fig. 9 gives the corresponding time-dependent exposed temperatures at fire side. It is shown that the exposed temperatures can also be divided into several groups after the ignition of pool fires. However, the temperature distributions seem a little disorder since the breakage of toughened glass, as well as the ignition of timber. Some thermocouples are directly heated by the flame of the burning timber. Figs. 10 and 11 respectively give the time-dependent shaded temperatures at the fire side and ambient side. Compared with those experimental results with pan size of 800 mm * 800 mm, it is shown that the shaded temperatures are larger than those values in Figs. 5 and 6. It is suggested that the shaded temperatures cannot be assumed as a constant value when the pool fire is relatively large. Similarly, Fig. 12 gives the time-dependent temperature differences between the exposed and shaded temperature of glass surface at fire side. Fig. 13 gives the temperature differences between the shaded temperature of glass surface at fire and ambient sides. After the breakage and fallout of glass, the timber slips are ignited when the hot smoke fume and flame pour out. That is the reason for the large negative values of temperature differences in Figs. 12 and 13.

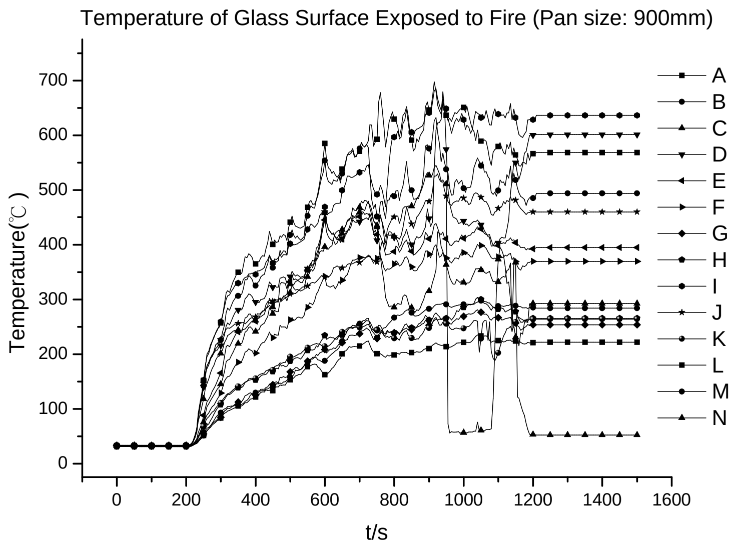


FIGURE 9. Temperature of glass surface exposed to fire (pan size: 900 mm * 900 mm)

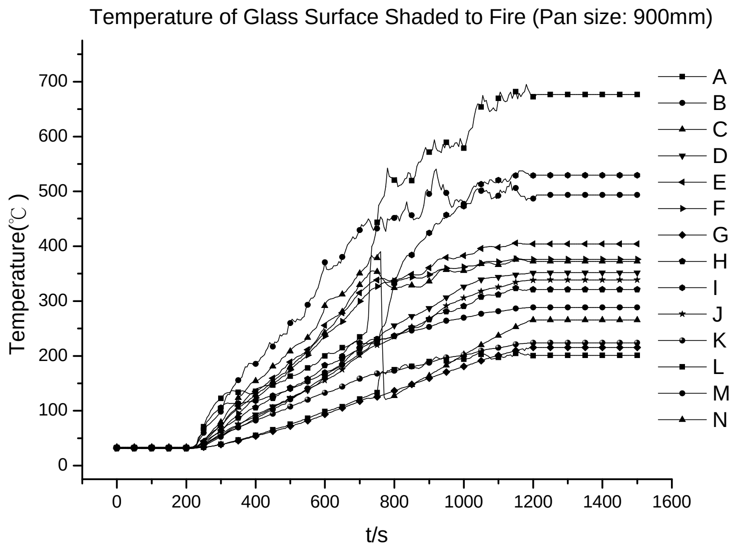


FIGURE 10. Temperature of shaded area of glass surface at fire side (pan size: 900 mm * 900 mm)

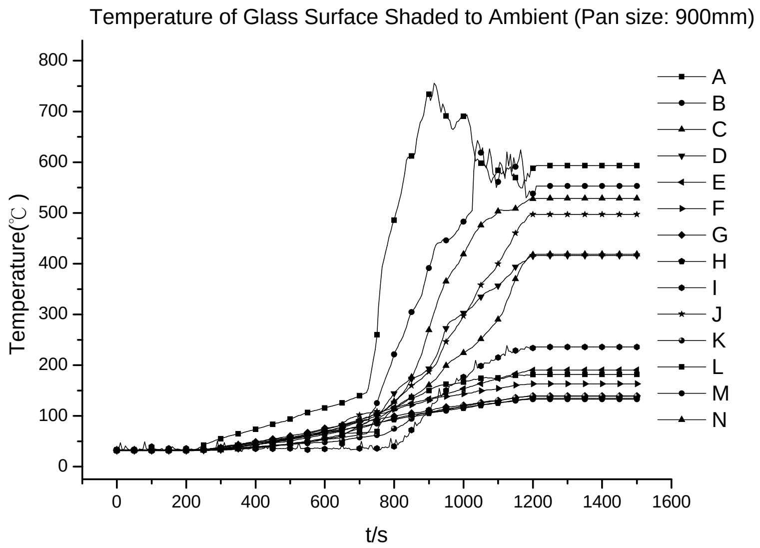


FIGURE 11. Temperature of shaded area of glass surface at ambient side (pan size: 900 mm * 900 mm)

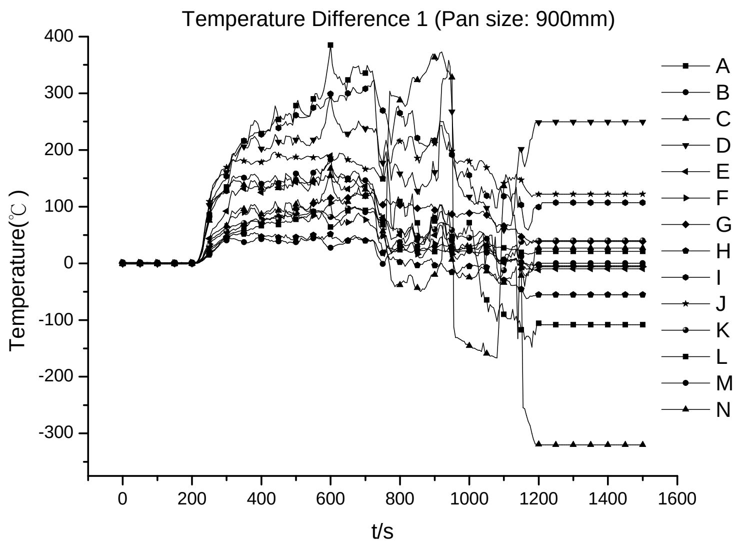


FIGURE 12. Temperature difference between the exposed and shaded area of glass surface at fire side (pan size: 900 mm * 900 mm)

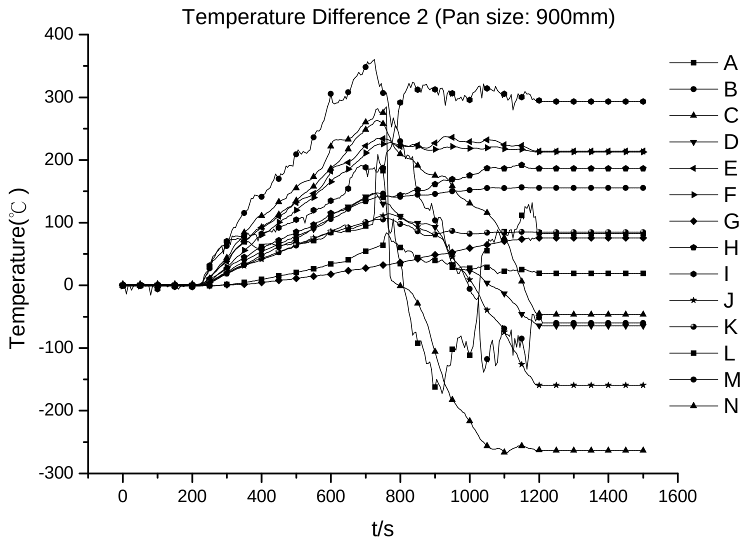


FIGURE 13. Temperature difference between the shaded area of glass surface at fire and ambient sides (pan size: 900 mm * 900 mm)

Figs. 14 and 15 give the breakage modes for toughened glass and float glass. It is shown in Fig. 14 that the toughened glass would fallout almost completely after the breakage. Therefore, relatively large vents may come into being. Although the float glass may break with lower temperature difference, as shown in Fig. 15, float glass will not fallout completely after the first breakage.

FIGURE 14. Breakage and fallout of toughened glass

FIGURE 15. Breakage and fallout of float glass

CONCLUSIONS

In this work, a series of full-scale experiments are conducted to investigate the crack and fallout of 10 mm thick toughened glass in ISO 9705 fire test room. Pool fires with different pan size are located at the center of the combustion room as fire source. The experimental results of 10 mm thick toughened glass illustrate that the whole piece of toughened glass cracks and falls out completely as long as any region of glass breaks. In this case, although the critical temperature difference for toughened glass is larger than that of floated glass. But relatively large window vents may come into being if the glass finally breaks. In addition, the results also illustrate that in the engineering applications, it is most effective to protect the toughened glass for those regions with maximum temperature difference using sprinkling or water mist.

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