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Abstract	This document presents experimental tests on glass windows breakage realized at IMT Mines Alès ARMINES, aiming to check the performance criteria.
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1 Introduction

When investigating the dwelling exposure to the risk of wildfire, the first scenario to be taken into account is certainly the direct exposure to fire. When the flame front is severe enough, it can ignite the dwelling by radiation, convection or through flying embers. Fire can also spread through intermediate targets, which can be natural targets as hedges, trees, conifers or artificial fuels from various objects as storage, barriers, etc. located between the wildfire and the house itself.

In the building structure, openings such as windows and doors designed in glass are among the most sensitive to be the way of propagation of wildfire towards the interior of the dwelling because the glass can easily break under the effect of the flux radiated by the flames. In this context, we will study the thermal exposure of a window.

Performance Based Design (PBD) provides safety rules aiming at protecting glazing against fire events. However, many data can be found in the literature with a large variability. This work aimed to perform experimental tests aiming at checking applicability of PBD safety values.

Glass is a material commonly used in construction and it is a vulnerable material when exposed to fire. In confined fire problems, glass breakage creates openings, which will allow fresh air to enter in the combustion room and consequently will help in the fire development (flashover condition). On the other hand, in the problems of wildfire, the openings created by glass breakage, can expose the interior of the dwelling to a large heat flux and bring the different materials to their temperature ignition (self-ignition). Furthermore, glass failure serves as an entrance for the flying embers inside of the dwelling. The flying embers are statistically a source of ignition of more structures in this context. Therefore, the window glass fracture was identified as an important phenomenon in the fire of a house's structure.

Performance criteria were detailed in deliverable D4.2. This section highlights main considerations about glazing systems.

To identify when a glazing system will fail if exposed to radiation or flame impingement from a fire, performance criteria must be set for each material that composes a window. Three different criteria have been identified for a glass pane, although one of them can only be applied to glass with a thickness of 3 mm. These are the surface temperature of the glass, the temperature difference between the unexposed and exposed area on the glass surface, and the heat dose received by the glass, which is calculated by obtaining the heat flux onto the glass over time. Therefore, based on literature, the window is assumed to break in one of the following cases:

- a) The surface temperature of the glass reaches 150 °C [11];
- b) The temperature difference ΔT between the center and the edge of the glass reaches 58 °C [12];
- c) Or the heat dose received by the glass reaches 1840.06 (kW/m²)^{4/3}s [13];

The heat dose is a function of intensity and exposure time.

$$\text{Heat dose} = I^{\frac{4}{3}} \cdot t \left[(\text{kW/m}^2)^{\frac{4}{3}} \right]$$

To be able to find the heat dose from the heat flux measurements, the heat fluxes are first elevated to fourth thirds and then plotted. The heat dose is then the area under the curve (Figure 1).

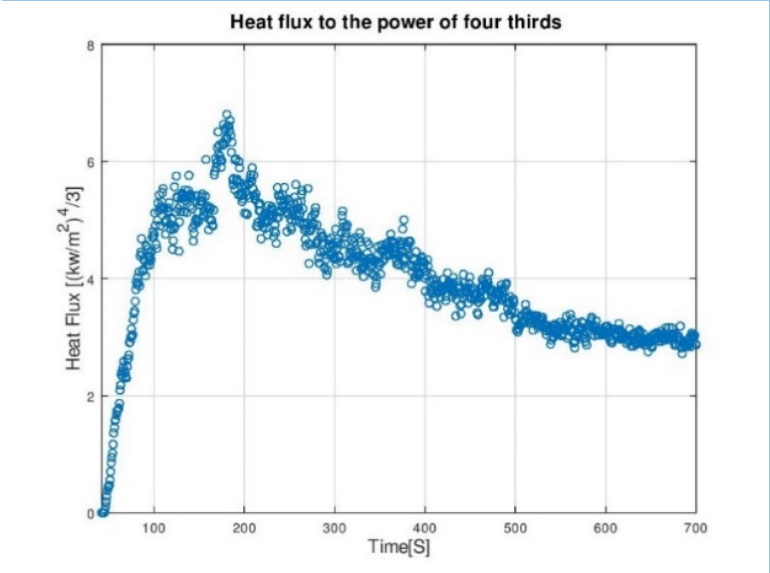


Figure 1: Heat fluxes to the power of four thirds (experimental test)

The obtained polynomial is then integrated over time.

$$Heat\ dose = \int A\ dt = B \left(\frac{kW}{m^2} \right)^{\frac{4}{3}} \cdot s$$

2 Experimental work on glass window breakage

A series of experiments aimed at investigating performance criteria for glazing systems breakage. Tests were performed at ARMINES facility called Spark on single and double pane glass windows of 0.51 x 0.51 m, with 4mm and 6mm thickness. The frame window used was in aluminum.

2.1 Experimental Setup

The experimental setup is mainly made up of a heat source, and a window fixing system which allows the adjustment of the distance between the window and the heat source from position 10 to 70 cm far from the panels, as can be seen in Figure 2 and Figure 3. The window was exposed to a constant radiative flux, generated by several gas radiant panels assembled side by side. The quantities such as the temperature of the glass, the heat flux received by the glass, the time of window's breakage were obtained using an infra-red thermal camera, type K thermocouples and heat flux sensors.

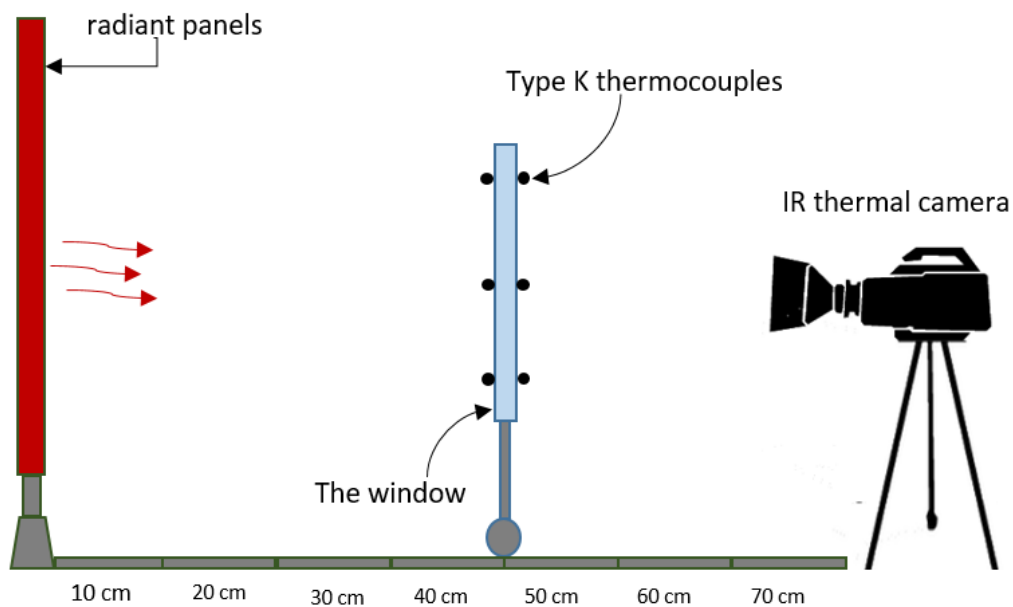


Figure 2: Experimental setup

1.2 Characterization of the gas radiant panels

2.1.1 Radiant device

The radiant panels used for these tests are made up of six radiating elements (23 x 12.5 cm) made of ceramic porous panels and an mirror-finished stainless steel part through which the panels were assembled side by side.

To evaluate the heat flux received by the window (incident heat flux) and the average flux radiated by the panels, an infrared thermal camera and heat flux sensors placed in front of the panels has been used.



Figure 3: The radiant panels and its gas supply system

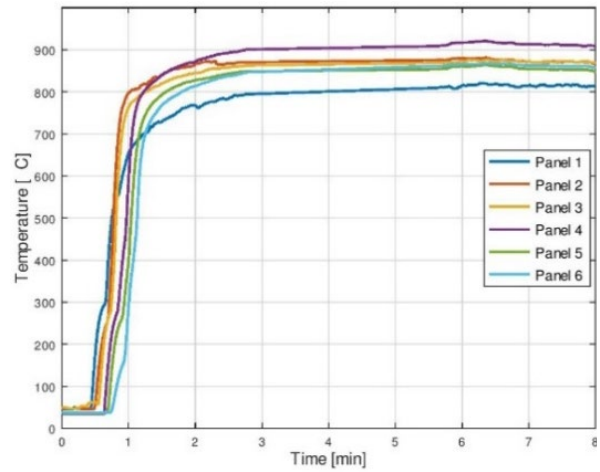


Figure 4: Radiant panels temperature

The system of 6 radiant panels forms a large panel of 103 cm long and 90 cm large and is powered by three gas cylinders of 13 kg propane each enabling a constant feed pressure.

K thermocouples were placed over each panel as given in Figure 4, data show that the first and the second radiant panel measured by the thermocouple 1 and 2 are 62°C colder than the four other panels measured by the thermocouples 3, 4, 5 and 6. We noticed that the panels take six minutes in average to reach steady state.

An infrared thermal camera allowed the visualization of the temperature field over the radiant panels (Figure 5), as well as an estimate of the heat flux radiated, taking an emissivity of 0.95 for ceramics, the radiative heat flux from each panel was calculated using the temperature given by the thermal camera.

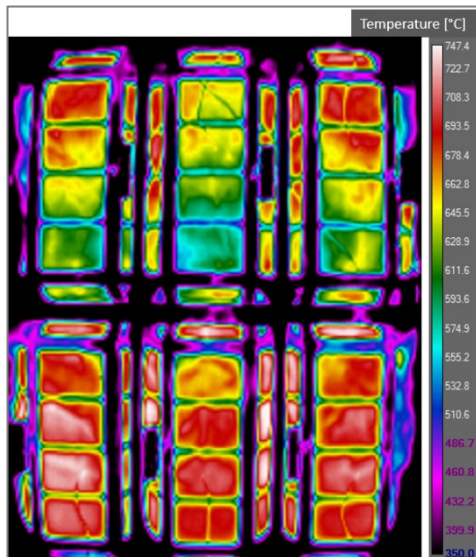


Figure 5: Radiant panels temperature in IR thermal camera

Radiant panels	1		2		3	
	T(°C)	Flux (kW/m ²)	T(°C)	Flux (kW/m ²)	T(°C)	Flux (kW/m ²)
min	462.6	15.78	497.4	18.99	489.8	18.25
max	718	51.98	680.2	44.50	720.7	52.55
Type K thermocouple	688.63	46.09	667.81	42.23	694.9	47.30
mean	641.1	37.63	613.2	33.25	647.9	38.76
Radiant panels	4		5		6	
min	563.6	26.41	556.5	25.52	551.9	24.96
max	739.7	56.69	715.1	51.38	724.1	53.27
Type K thermocouple	723	53.04	681.5	44.74	700.9	48.49
mean	688.5	46.07	659.8	40.81	671	42.80

Table 1: Temperature and heat flux of each radiant panel

The radiant panels are numbered from left to right, from 1 to 6; on the Figure 6 the temperature histograms of each panel given by the thermal camera can be observed.

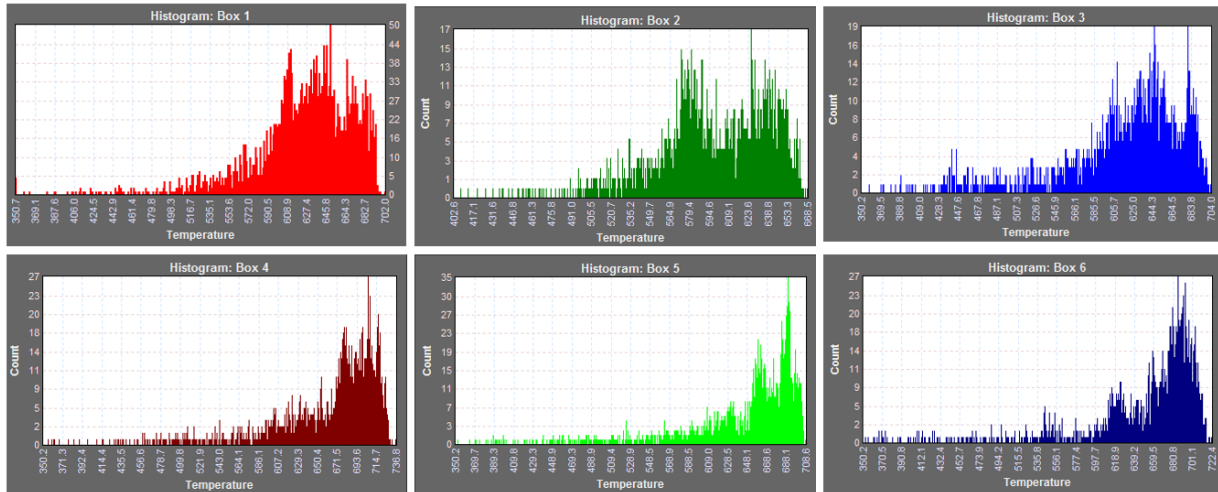


Figure 6: Temperature histogram of the six panels

The temperature displayed by the thermal camera depends on the emissivity chosen by the user as well as other parameters such as the distance of the camera. As a result, this is a much more average measurement, while the type K thermocouples give a local measurement, which can explain the difference in the temperature values given by the camera and thermocouples.

2.1.2 Window instrumentation

Six heat sensors were placed on front of the panels, at the location supposed to be the window, in order to create a map of the radiative flux received and emitted by the glass in the different positions depending on its distance from radiant panels (Figure 7 and Figure 8). In fact, the heat flux sensors are distributed over the glass surface as given in the figures below, and through these measured points, all others glass points can be estimated by the moving averages method.

The heat flux sensors are placed in the middle and in the right side of the glass and by the symmetry observed on the radiant panels, the left side of the glass can be considered equal to the right. Each heat flux sensor has a measurement area of 10 x 10 cm.

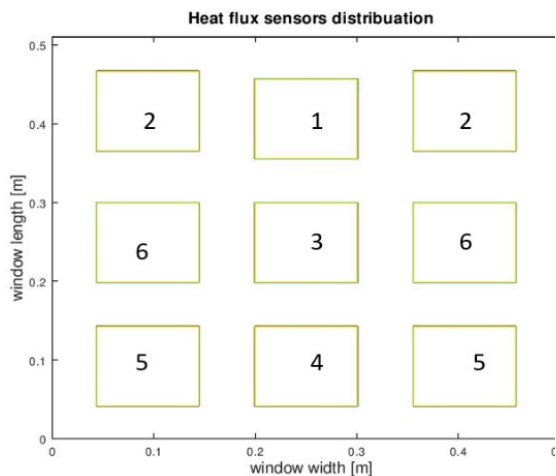


Figure 7: Heat flux sensors distribution over the glass

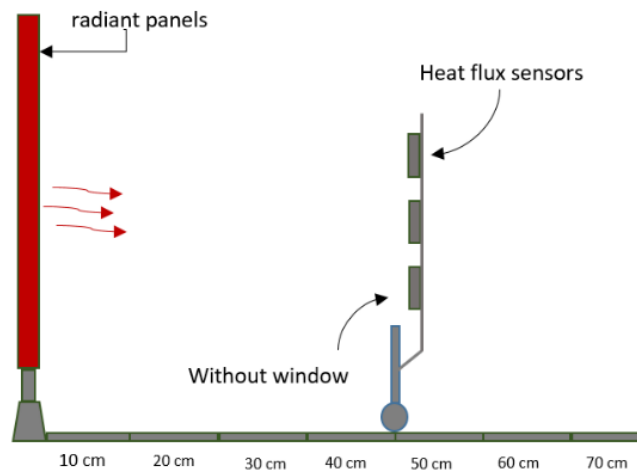


Figure 8: heat flux sensors installation

It is observed as given in Figure 9, that the glass receives a greater flux of heat on its lower part and its maximum value of 28 and 29 kW/m² for heat flux sensors 4 and 5. While the upper part corresponds to heat flux sensors 1 and 2, which receives the lowest heat flux with one of 20 kW/m² and the middle

part of the glass by heat flux sensors 3 and 6, presents with an average of 21 kW/m² of heat flux received.

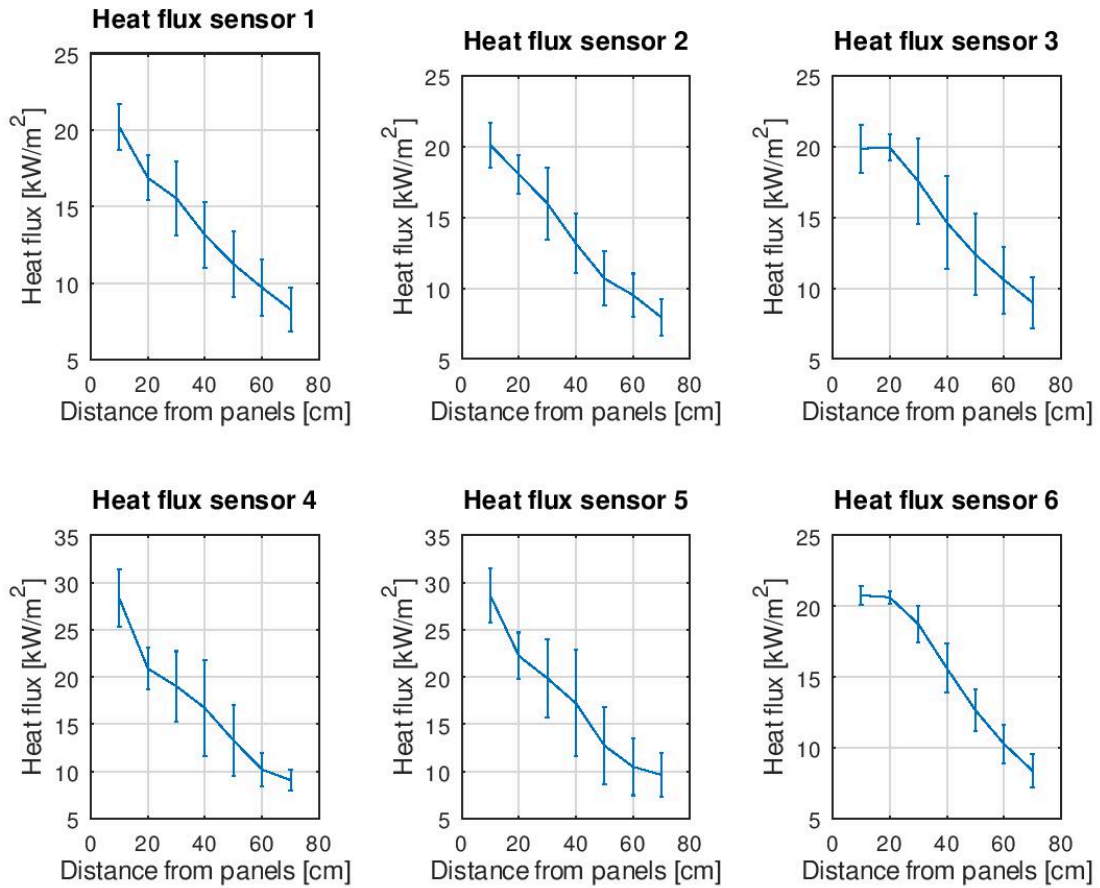


Figure 9: Heat flux sensors

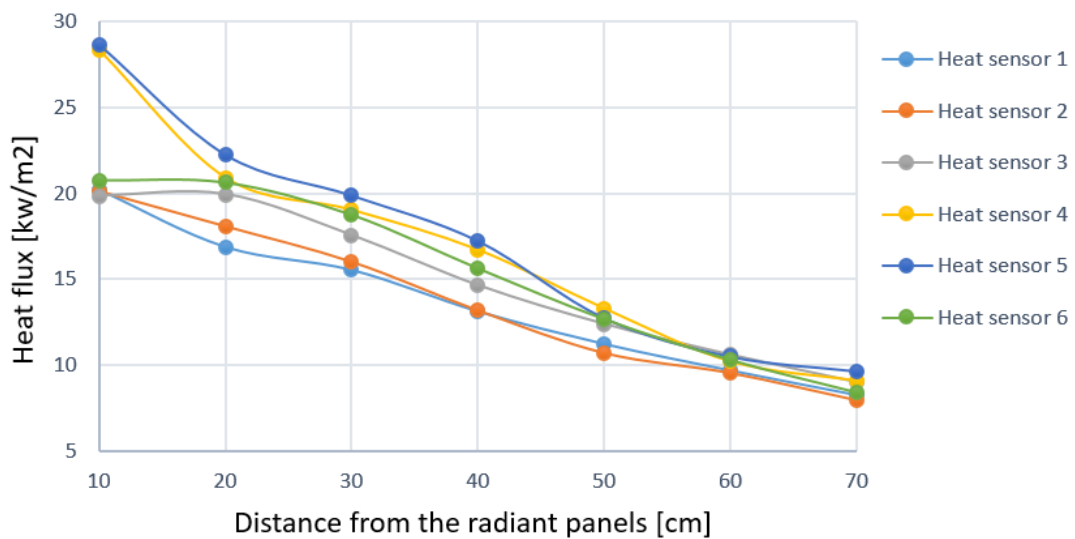


Figure 10: Heat flux sensors at different positions

Therefore, depending on the distance of radiant panels the heat flux received by the glass was recorded, as one can easily assume the flux increases by approaching the heat source with values

between 20 and 29 kW/m² at 10 cm; and values between 8 and 10 kW/m² for the most distant position at 70 cm.

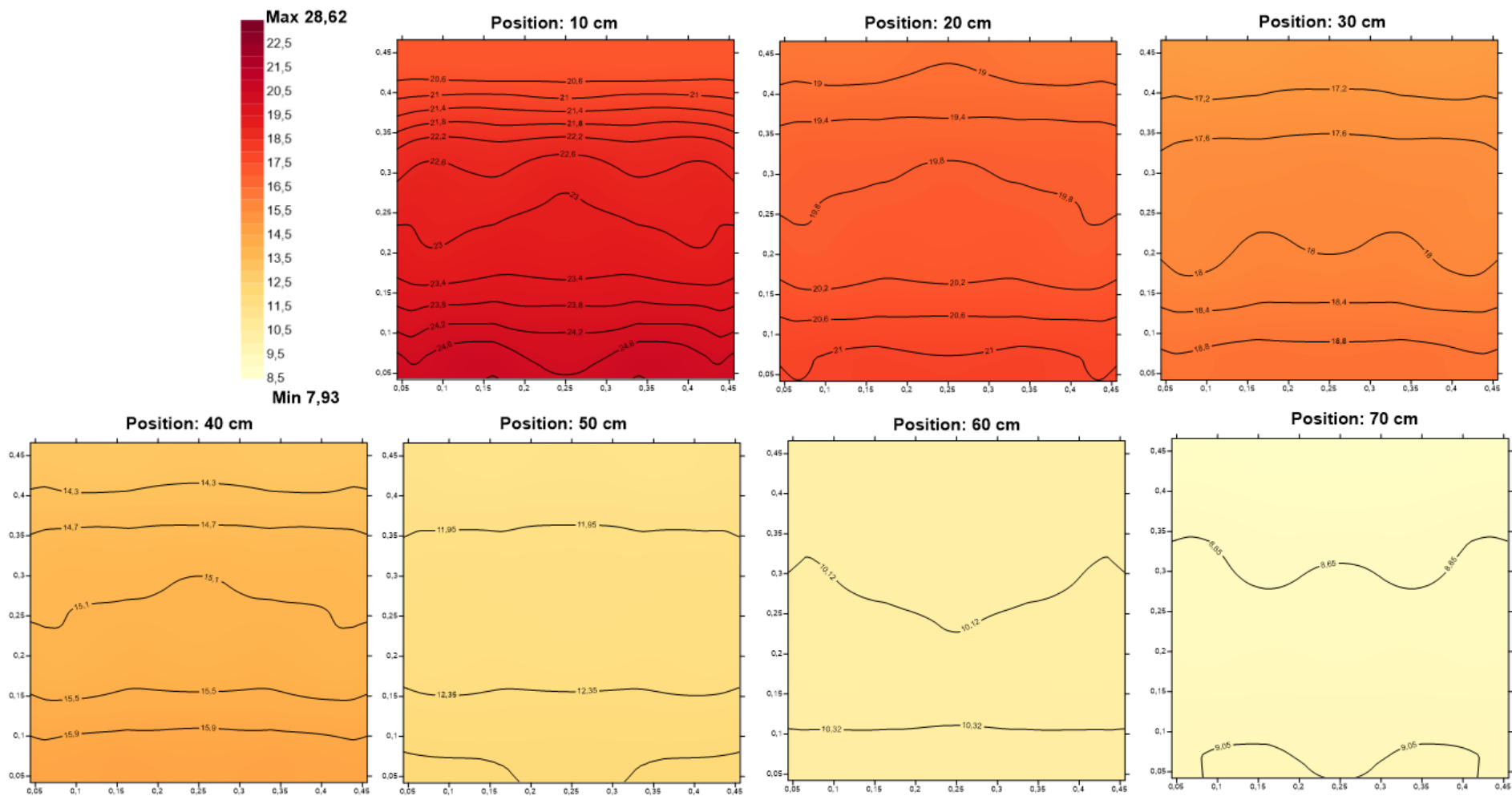


Figure 11: Heat flux received by the glass, spatial distribution

From the data measured locally by the heat flux sensors, we estimated the incident heat flux on the glass surface by a slippery average method. As can be seen in the figure above, as the glass moves away from the radiant panels, there is not only a decrease in the incident heat flux, but also a decrease in the special variability of incident heat flux on the glass surface.

At the 10 cm position, there is a greater spatial variability of 9 kW/m² in average, while the 60 cm and 70 cm positions have lowest variability of 2 kW/m². It is also noted that for a given position, the heat flux on the glass is greater on the lower part and weaker on its upper part.

2.2 Characterization of the exposure of the glass

In order to assess the heat flux transmitted through the glass (the heat flux that passes through the glass) and the heat flux emitted by the glass due to its high temperature, the glass is exposed to the heat flux radiated by the panels for a few minutes. The heat flux measured with and without the glazing system allows calculating the transmission of the window. To measure the emitted heat flux by the window, another method was employed. When the glass is sufficiently heated, the incident heat flux is completely cut off with an aluminum screen. The heat flux emitted by the glass is then measured on the not exposed fire glass face. The glass was placed at 40 cm of radiant panels, where the flux on the glass surface varies in average between 13.14 and 17.22 kW/m² with a single glazing glass 0.51 x 0.51 m and 6 mm thick.

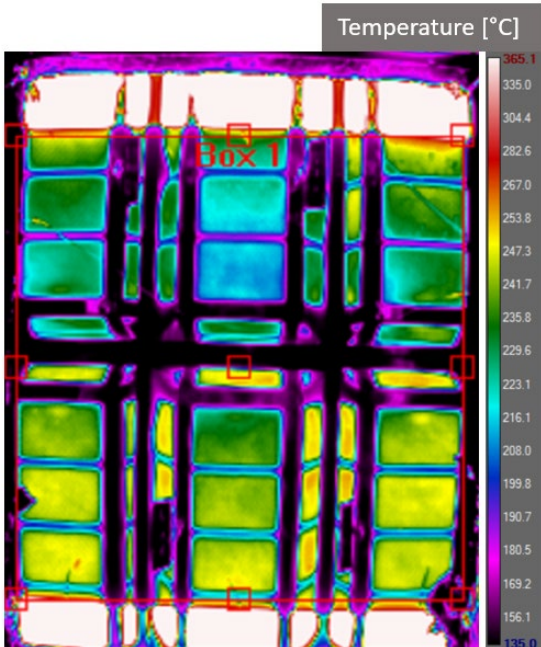


Figure 12: Emitted heat flux-thermal camera image

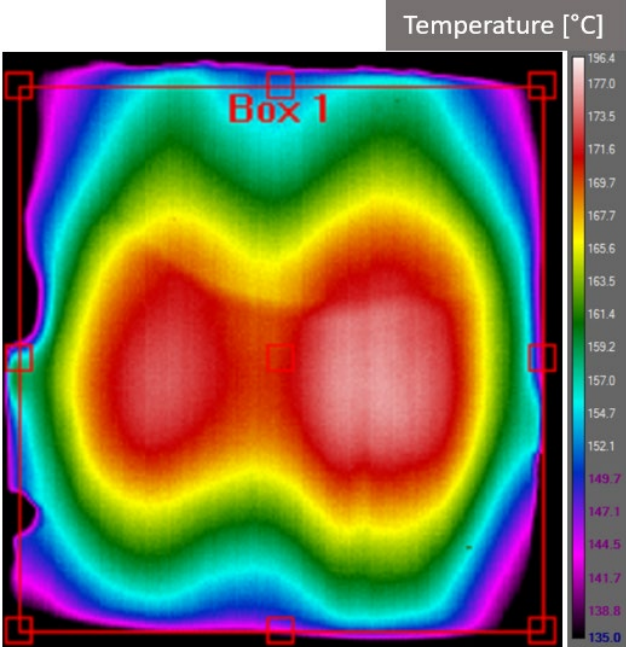


Figure 13: Emitted heat flux-thermal camera image

The heat flux transmitted by the ranges from 0.50 to 0.59 kW/m², making an average of 0.53 kW/m² as given in Table 2, the flux transmitted from the panels radiation exposed face to the unexposed face of the glass, represents 3.54% of the heat flux it receives (incident flux).

The heat flux emitted by the glass from its unexposed face varies from 0.10 to 0.73 kW/m² making an average of 0.37 kW/m², which represents 2.49% of the flux received by the glass. We notice that on the entire heat flux received by the glass, 2.49% is transmitted, 3.54% is emitted by the glass and most of the incident heat about 90% is therefore lost by convection and reflection.

Table 2: Thermal flux balance on the glass surface

[kw/m ²]	Heat flux sensor 1	Heat flux sensor 2	Heat flux sensor 3	Heat flux sensor 4	Heat flux sensor 5
Incident heat flux	13.14	13.15	14.63	16.7	17.22
Transmitted heat flux	0.59	0.52	0.50	0.51	0.53
Emitted heat flux	0.10	0.09	0.41	0.73	0.53

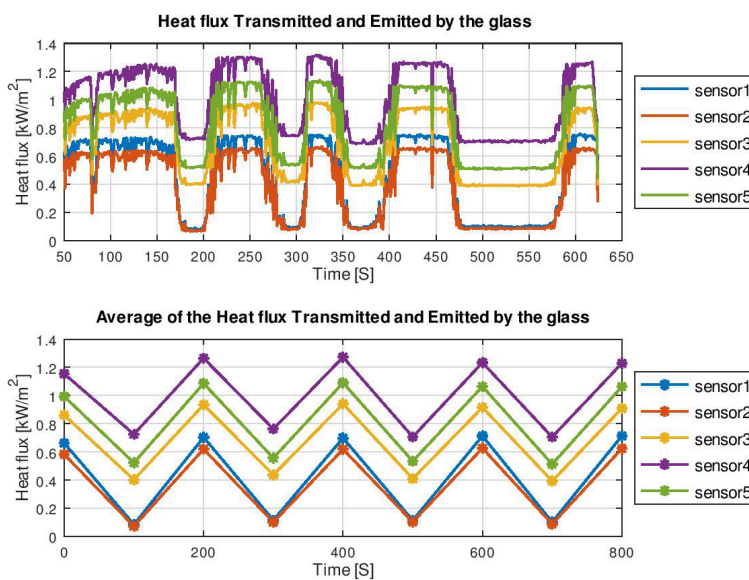


Figure 14: Transmitted and emitted heat flux for 6mm thin glass

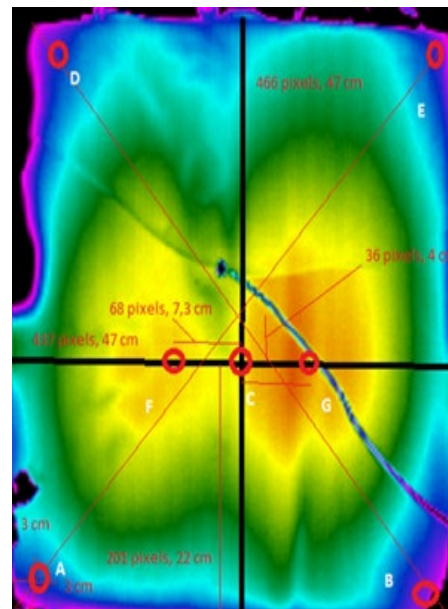


Figure 15: Temperature gradient on the glass, observed by the IR camera

2.3 Tests on 6 and 4 mm simple and double pane glass

2.3.1 Outcomes of the tests

The tests were carried out on a total of 16 windows, composed by single and double pane glass of 0.51 x 0.51 size, with 4 mm and 6 mm thickness. For this test we analyzed data such as the time of failure of the glass, the temperature difference between the heat flux-exposed glass face and the unexposed face ΔT_1 and the temperature difference between the middle of the glass and the edges ΔT_2 . The measurements were made by type K thermocouples placed in the middle and in the edges of both glass sides, as can be seen on the Figure 16 and Figure 17.

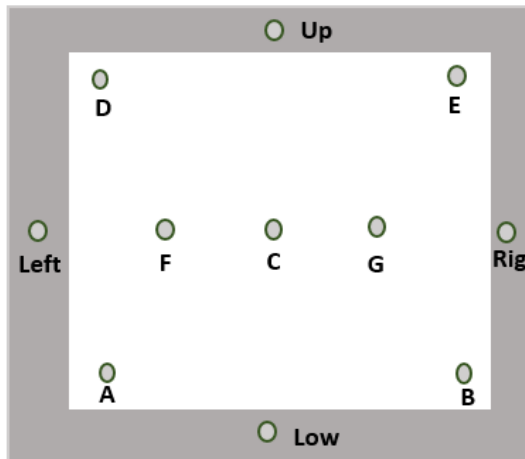


Figure 16: Thermocouples identity and location

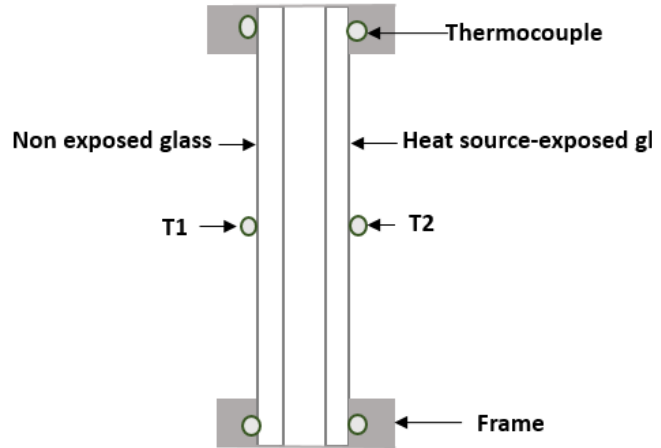


Figure 17: Glass installation and thermocouple distribution

The thermocouples position was chosen according to the gradient of temperature observed by the infrared thermal camera, as given in Figure 15. The thermocouples are named from A to G on each glass surface, and up, down, left and right on the frame (in contact with the glass, and therefore hidden from incident heat flux by the frame itself).

The first face of a window (impacted face) is named by 1, the second face (not impacted face) is named by 2. A and B can be located on a same glass for single pane window, and on two different panes for double pane windows.

2.4 Experimental results

A global view of windows breakage pattern is given in Figure 18, Figure 19 and Figure 20.

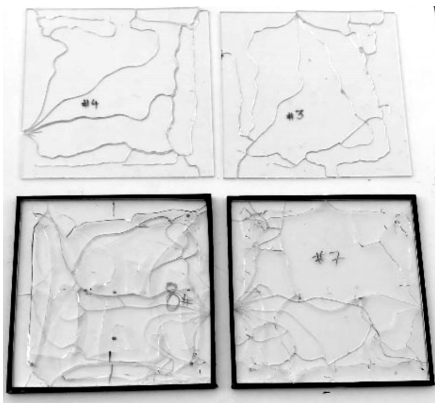


Figure 18: Single and double pane glass window Test 1,2,3,4

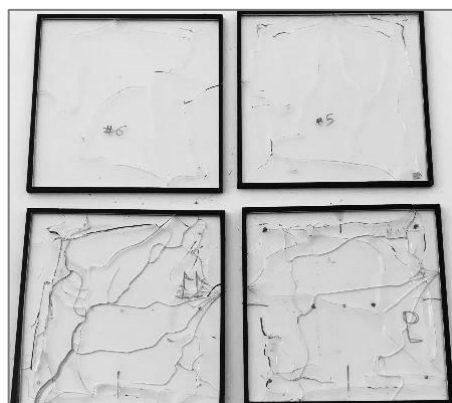


Figure 19: Single and double pane glass window Test 5,6,7,8

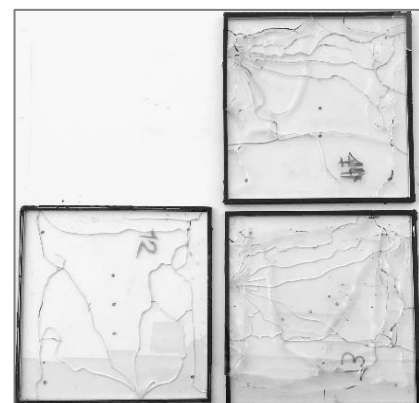


Figure 20: Single and double pane glass window Test 9, 10, 11

2.4.1 Test1, Test2, Test3

This test was carried out on a single pane of 6mm thickness at 60 cm distance from the radiant panels, where the pane is exposed to a heat flux of 10 kW/m², on the 3 panes used, the first glass broke at 9 min 44 s, the second at 2 min 43 s and the last at 1 min 41 s of heat flux exposure. This considerable difference in the breaking time of the first and the other two can be due to a fragility linked to a micro

defect in the internal structure of the first glass, we observe significant fallout of piece in the 3 test as given in the Figure 21, Figure 22 and Figure 23.

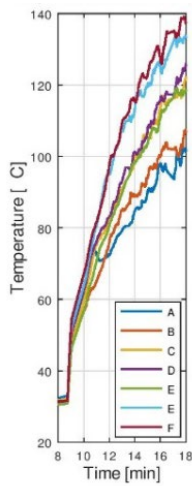


Figure 21: Test 1, single glass window 6mm at 60cm from the radiant panels

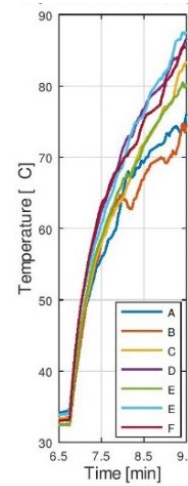
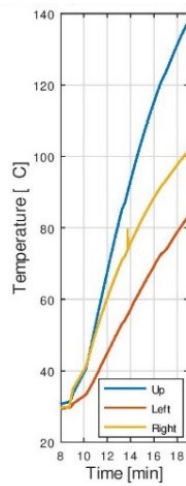


Figure 22: Test 2, single glass window 6mm at 60cm from the radiant panels

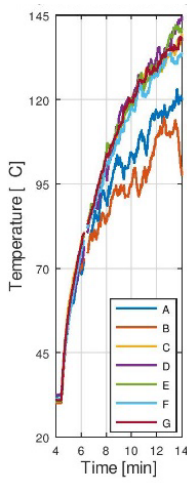
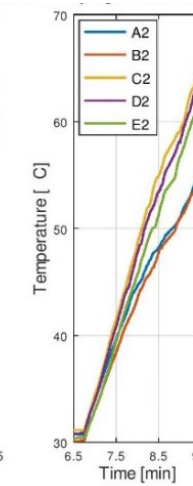
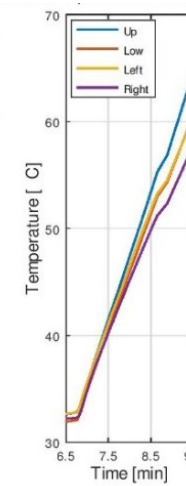


Figure 23: Test 3, double glass window 4mm at 60cm from the radiant panels

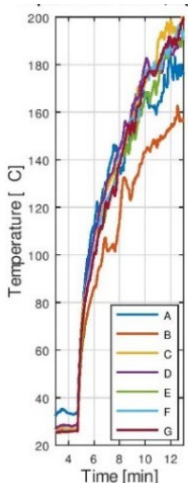
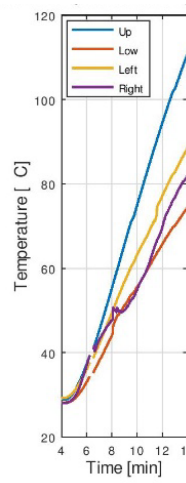
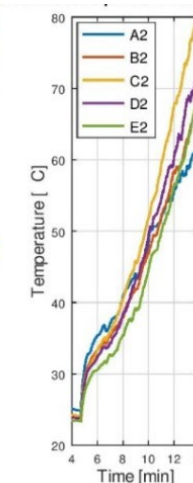
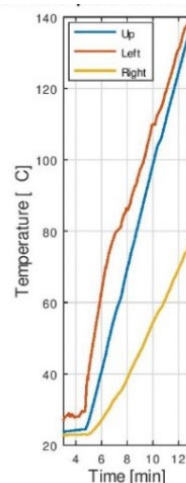


Figure 24: Test 4, double pane glass window 6-6-6mm at 30cm from the radiant panels



2.4.2 Test4, Test5, Test6, Test7

These tests were carried out on double pane glass window of 6mm thickness, where the pane is exposed to a heat flux of 18 kW/m² and 20 kW/m² at 30 and 20 cm respectively far from the radiant panels, for those 4 windows tested, the exposed glass broke at 1.1 min as can be seen in Figure 24, Figure 25, Figure 26 and Figure 27. The unexposed pane glass broke at 17 min in average at 20 cm and broke at 10 min at 30 cm distance from the radiant panels.

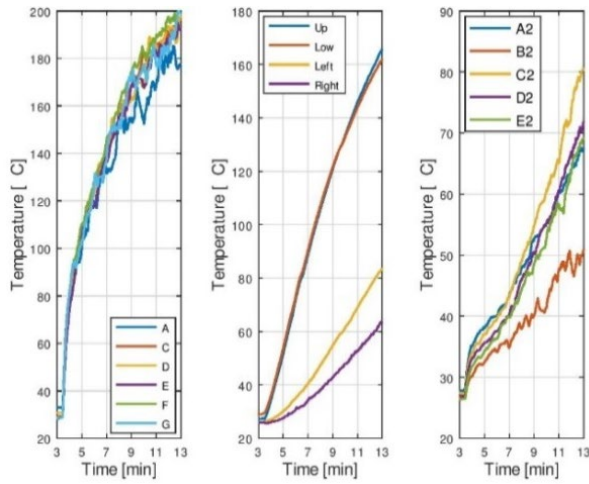


Figure 25: Test 5, double pane glass window 6-6-6mm at 30cm from radiant panels

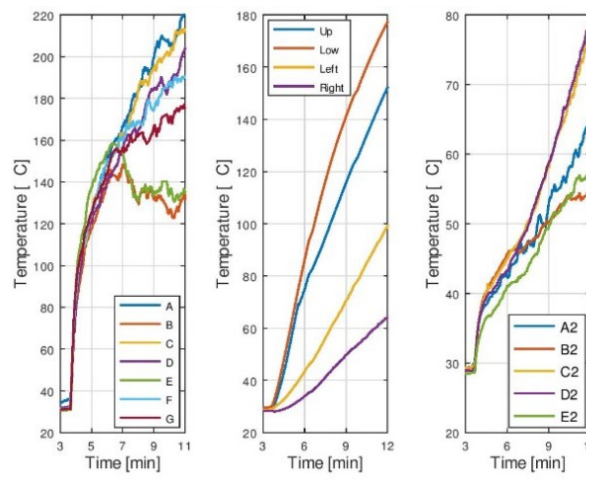


Figure 26: Test 6 double pane glass window 6-6-6 mm at 20cm from radiant panels

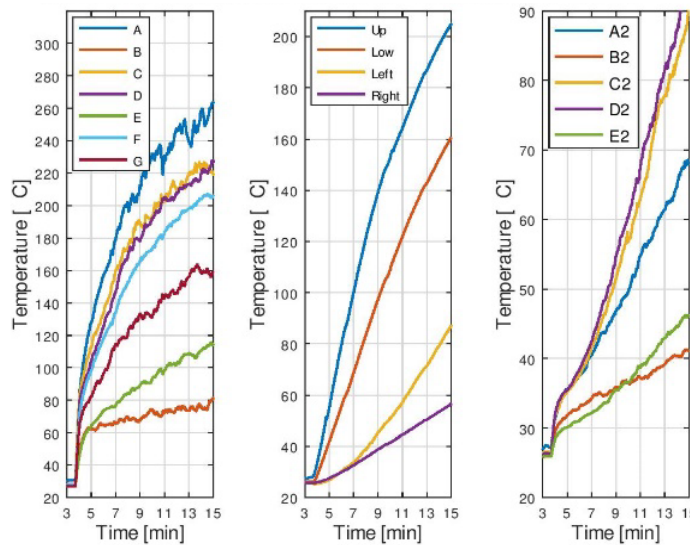


Figure 27: Test 7, double pane glass 6-6-6 mm at 20cm

2.4.3 Test8, Test9, Test10, Test11, Test12, Test13

This test was carried out on single and double pane glass windows of 4mm thickness and 4-4-4 mm at 60 cm and 30 cm distance from the radiant panels, where the pane is exposed to a heat flux of 18 and 10 kW/m². Results are given on Figure 28, Figure 29, Figure 30, Figure 31, Figure 32 and Figure 33.

We observe pour for this test very close time of breakage around 2 min 20 s, the unexposed pane glass broke at 10 min at 30 cm, but at 60 cm from the radiant panels the unexposed glass did not break even 20 min of heat flux exposure observe and significant all out of piece in the first pane glass in all tests. On The two single pane glass windows we measured a temperature gradient following the thickness of the glass of 13 degrees and to 30 degrees of temperature difference between the glass edges under frame and the center exposed.

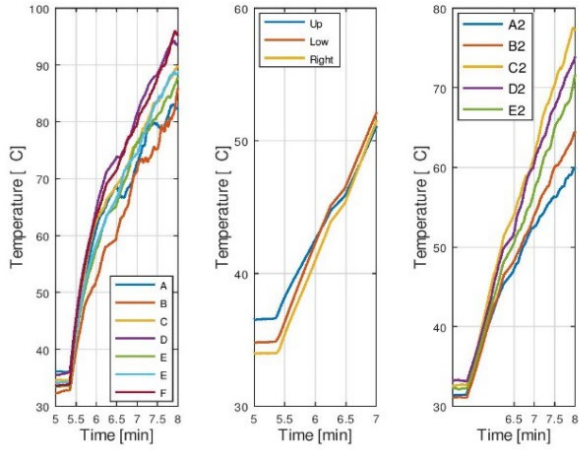


Figure 28: Test 8 single glass window 4mm at 60cm from radiant panels

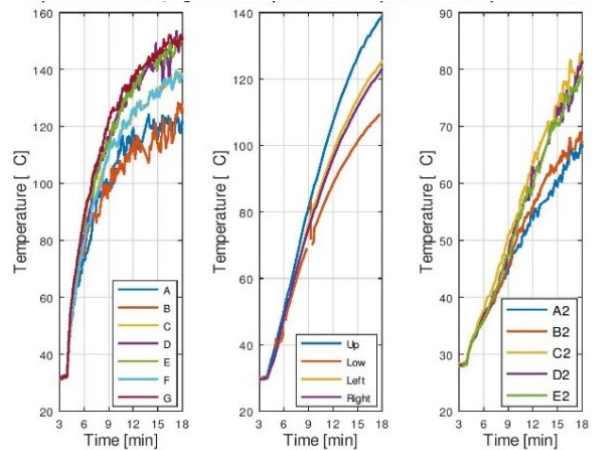


Figure 29: Test 10, double pane glass window 4-4-4mm at 60cm from radiant panels

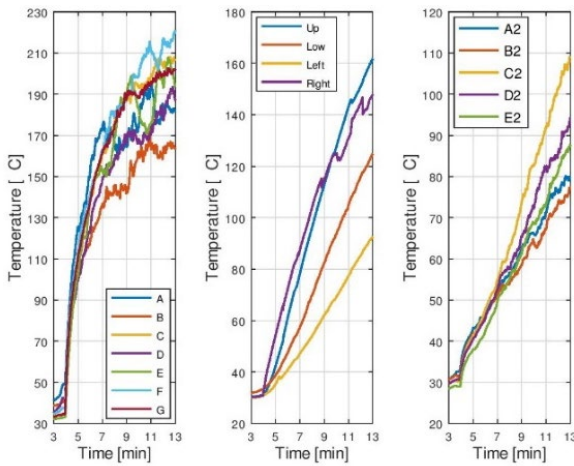


Figure 30: Test 12, double pane glass window 4-4-4mm at 30cm from radiant panels

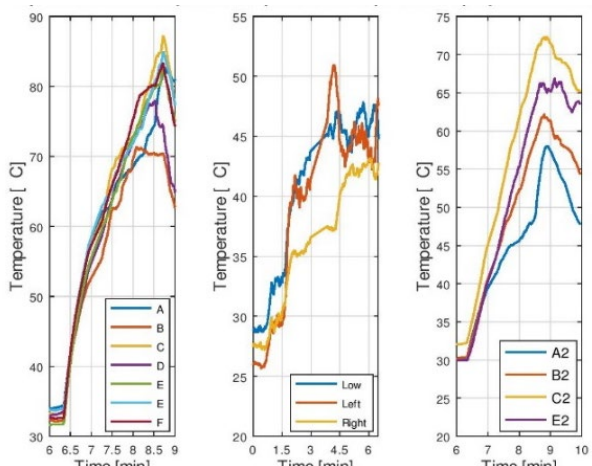


Figure 31: Test 9, single glass window 4mm at 60 cm from radiant panels

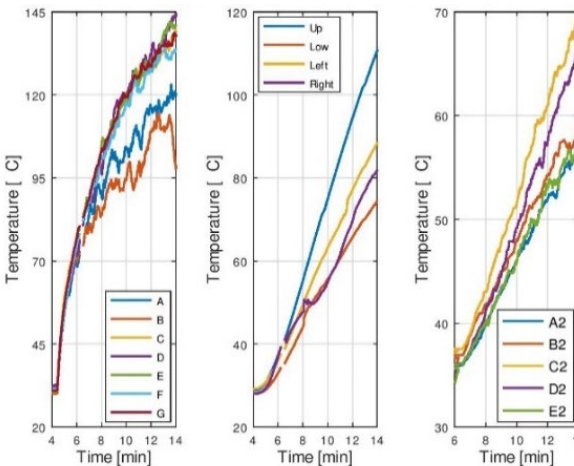


Figure 32: Test 11 double pane glass window 4-4-4mm at 60cm from radiant panels

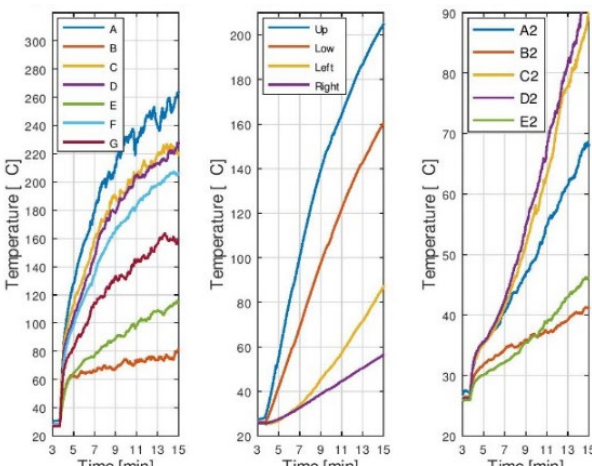


Figure 33: Test 13 double pane glass window 4-4-4mm at 30cm from radiant panels

2.4.4 Tests global results

A summary of the complete set of experiments is given in Table 3.

Table 3: Summary of results

6mm Double and Single glass window									
	Incident heat flux [kw/m ²]	$\Delta T1$	$\Delta T2$	$T_{breakage}$ [°C]	heat dose [(kw/m ²) ^{4/3}]	Time of failure[min]	Time of failure[S]	Distance from radiant panels [cm]	Glass thickness [mm]
Test 1	10	37	18	137	111514	9.7	584	60	6
Test2	10	21	16	85	2966	2.7	163	60	6
Test3	10	29	14	68	1715	1.7	101	60	6
Test 4	18	56	66	106	2784	1.0	60	30	6_6_6
Test 5	18	63	74	116	5290	1.2	69	30	6_6_6
Test 6	20	77	75	130	3755	1.2	74	20	6_6_6
Test 7	20	53	71	117	3242	1.0	60	20	6_6_6
4mm Double and Single glass window									
Test 8	10	28	13	91	2825	2.6	153	60	4
Test 9	10	34	13	82	2583	2.2	132	60	4
Test 10	10	32	44	90	2588	2.1	125	60	4_6_4
Test 11	10	42	47	84	2562	2.2	132	60	4_6_4
Test 12	18	54	52	105	1531	0.9	54	30	4_6_4
Test 13	18	42	43	79	1114	0.7	39	30	4_6_4

The single windows, 4 and 6mm thick at 60 cm, broke almost at the same maximum temperature T_{max} with an average temperature difference of 10°C, which is probably related to the temperature gradient following on the thickness of the glass, which is higher for the 6 mm than for the 4mm thick glass, as can be seen in the table above.

On single tests is double glazing of 4 mm thickness at 60 cm, we find that both present a break time very close to 2.14 min for simple glazing and 2.30 for double glazing, the single glazing windows breaks to a T_{max} on the exposed face of 87°C and 86.5°C for double glazing.

This suggests that the double glazing does not have a considerable influence in the breaking of the exposed glass, but it protects the second glass by delaying its exposure to heat flux, because for these tests the second glass broke an average of 9 minutes after the first glass broke.

The heat dose criteria is given in the literature only for the 3 mm thick glass [13], so we wanted to evaluate the reliability of these breaking criteria for other thickness of glass. We found that the glass breaks for the tests performed took place at heat dose greater than 2000 (kW/m²)^{4/3}s except for the double-glazed windows of 4-4-4 mm thick for which rupture occurred for heat dose of 1322 (kW/m²)^{4/3}s on average.

3 Conclusions

Generally, on the tests carried out, the middle of the glass is hotter than its edges covered by the aluminum frame. The gradient between the middle and the edges of the glass is more important than its gradient according to the thickness, which is reinforced by the conclusion drawn from the literature [1]. It explains that the breakage of the glass window would be linked to the mechanical stress on the glass created by the temperature difference between the edges of the framed window and the middle, directly exposed to the heat flux.

This could also explain the form of propagation of the breaks on the windows, which was observed in our tests: the breaks started at the borders of the glass for all the tests except one, these breaks propagate in the interface between the middle hot part and cold edges of the glass. However, we do not have yet enough data to be able to generalize its results.

We also noticed that for the same thicknesses and similar glass windows properties, panes glass broke at very low temperature in our tests compared to the data of the literature, which makes the criteria for the glass breakage such as ΔT_1 and T_{max} that were applied to our numerical simulations, more difficult to verify.

The difference between the failure criteria given by the literature and the results of our tests may be related to a difference in the specific properties of the glass, such as the conductivity of the material. We do believe that this difference in the failure criteria is essentially linked to the heat source (radiant panel) used.

If the heat source emitted is not spatially uniform, the temperature gradient on the glass will be greater even if the average temperature remains low. However, this could cause a faster glass breakage and on the other hand, under a spatially heat flux more homogeneous, the pane glass will break at a higher temperature and less quickly.

4 References

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