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Brahim Ismail, Paul Lardet, Seddik Sakji, Nicolas Pinoeau, Zoubir Acem, et al.. Experimental investigation on the fire behaviour of wooden facades. FSF, Jul 2024, Lund (Sweden), France. <hal-04773020>

HAL Id: hal-04773020

<https://hal.science/hal-04773020v1>

Submitted on 8 Nov 2024

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Experimental investigation on the fire behaviour of wooden facades

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ABSTRACT

The paper presents results of large-scale facade fire tests which were performed during “Firewall” research project. This project, funded by the French National Research Agency (ANR), aims to provide a better understanding of flame propagation mechanisms along vertical walls. Two large-scale fire tests were carried out on a non-combustible and combustible facade. The tests were conducted with a high fire power of approximately 950 kW, generated by a natural gas burner. Spruce wood was used as testing material in the case of combustible facade. The gas temperature, heat release rate, in-depth temperature, total and radiative heat flux and char depth were measured to evaluate the thermal actions and the influence of wood on the flame spread. These findings are presented in this publication and compared with the results of other works of literature.

KEYWORD: wooden facades ; non-combustible facades ; fire spread ; full-scale tests ; heat release rate; wood char depth

INTRODUCTION

Wooden facades are becoming increasingly popular in building design due to their low environmental impact, aesthetic appearance and favorable hygrothermal properties. However, they may lead to complicated and unpredictable behaviors in the case of external fire spread. Fire spread through the facade, particularly in the presence of combustible materials as wood, can lead to a disastrous consequence on the building structure and its occupants as in the Grenfell Tower fire in UK or the fire in Ulsan, South Korea. In the literature, several works have been carried out on facade fires in order to understand the spread mechanisms and to design for mitigation of the facade fire spread hazard. Most of these works focus on the study of the thermal impact on the facade of window-ejected fire plume [1], [2], [3], [4], [5]. Flames ejected through openings (windows/doors) are usually observed when the under-ventilated compartment fire is reached. The heat flux profile upon building facade, flame height and temperature profile are the most important parameters in heat transfer process which determine the scope of the facade fire hazard.

In the present work, large-scale tests were carried out on an inert and a wooden facade to assess the contribution of wood in terms of heat release rate (HRR), heat flux and temperature. A natural gas burner was set as the fuel source, placed at the bottom of the tested wall. The results will be used to calibrate and improve numerical models which is the subject of another paper at this conference.

EXPERIMENTS

Experimental setup

The tests were carried out on a non-combustible and combustible wall measuring 2.5 m wide, 5 m high and 0.04 m thick. The walls were placed under a calorimetric hood with a section of 4.9 m × 3.75 m. Fiberglass curtains with an aluminized face were added to the test bench in order to improve the collection of combustion effluents by the calorimetric hood. An opening of 0.4 m × 2.1 m was created on the left side to visualize the lateral profile flame. Spruce wood with a density of 440 kg/m³ and nominal moisture content of 11% was used as testing material in the case of combustible façade while in the case of a non-combustible façade, the test was carried out on calcium silicate with a density of 870 kg/m³. There is no cavity between the wooden wall and the calcium silicate in the case of combustible façade test.

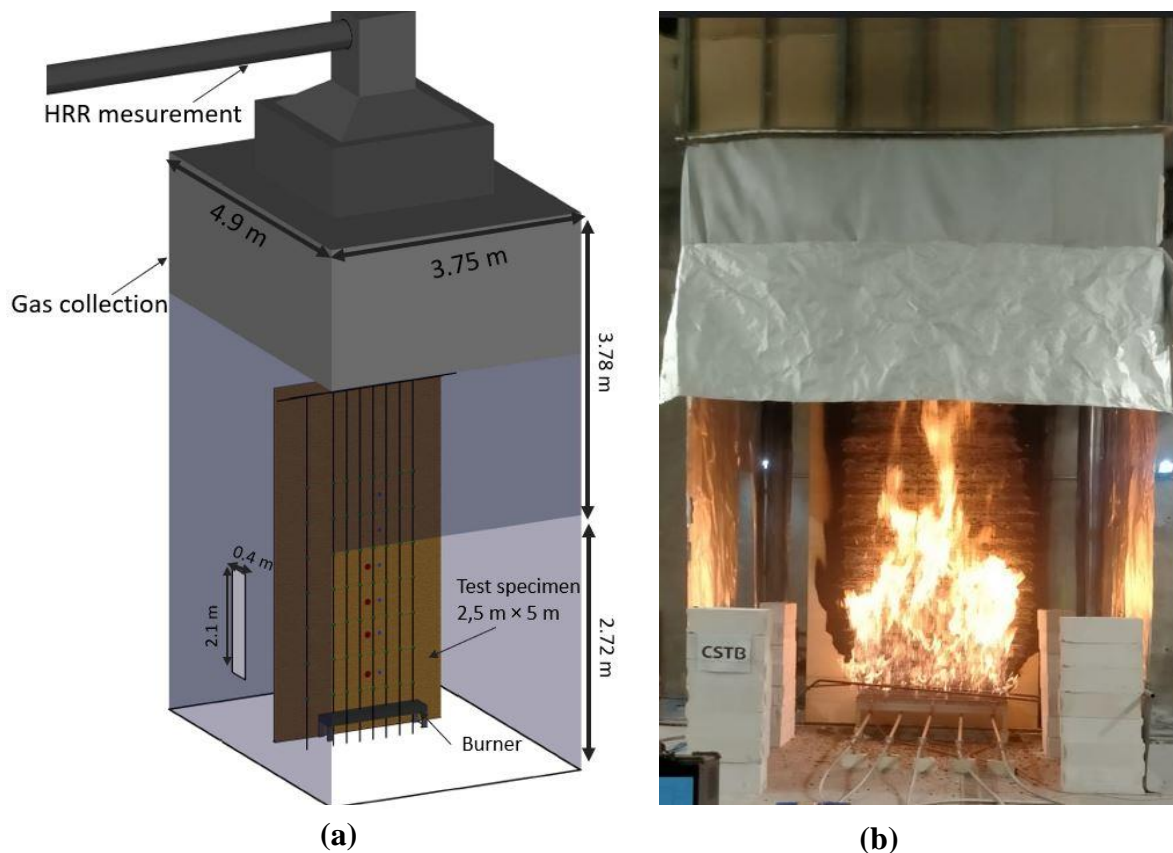


Figure 1 Experimental set-up (a) sketch of test bench (b) picture of a wooden facade test

Fire source

A natural gas burner of size 1.5 m × 0.3 m × 0.32 m (width × depth × height) was used as the fire source in these tests. It was placed along the lower edge of the specimen. The heat output of the burner was 950 kW in both tests, resulting in a flame height of approximately 2.5 m. The heat output of the burner was kept constant throughout the 30 min test. A digital mass-flowmeter was used to measure and control the natural gas flow rate.

Instrumentation and measurements

To measure the gas temperature near the wall, 56 K-type thermocouples of size 1.5 mm were used. A series of 35 TCs was installed 15 cm from the exposed face and another of 21 TCs was installed 40 cm

from the exposed face. Figure 2 shows a detailed overview of the positions of all thermocouples. In the case of a combustible facade, K-type thermocouples of size 0.6 mm were installed at 10 mm from the exposed face to evaluate the temperature development into the wood. The holes for thermocouples were drilled perpendicular to the isotherms. Figure 2 shows the positions of these sensors. The Total Heat Flux (THF) perceived by the walls was measured using water-cooled heat flux gauges (Hukseflux SBG01) with an external diameter of 25 mm, 10 mm sensor diameter and a measurement range from 0 to 200 kW/m². These heat flux sensors work on both Gardon and Schmidt–Boelter technology. Radiative Heat Flux (RHF) was measured with CAPTEC sensors that were placed in an enclosure with a Zinc Selenide (ZnSe) window to prevent measuring the convective heat flux. A slight breeze of air was blown on this window to prevent soot or other combustion products from settling on it. These sensors were calibrated with the ZnSe window to determine their sensitivity. Figure 2 shows the positions of the total heat flux sensors and those of the radiative heat flux sensors. All the sensors were set flush with the surface of the wall.

The heat release rate was measured using oxygen depletion method. A gas analyser was used to measure the oxygen (O₂), carbon monoxide (CO) and carbon dioxide (CO₂) concentrations in a sample of combustion gases extracted via the exhaust hood. The data measurements are recorded at a frequency of 1 Hz and then were used to estimate the heat release rate as described in ISO 5660-1:2015 [6].

After the test on the combustible facade, the wall was cut into five vertical parts and ten horizontal parts to measure the char depth. Each panel was scraped using a wire brush to remove the charred layer. Then the remaining thickness of the wood was measured using a digital caliper.

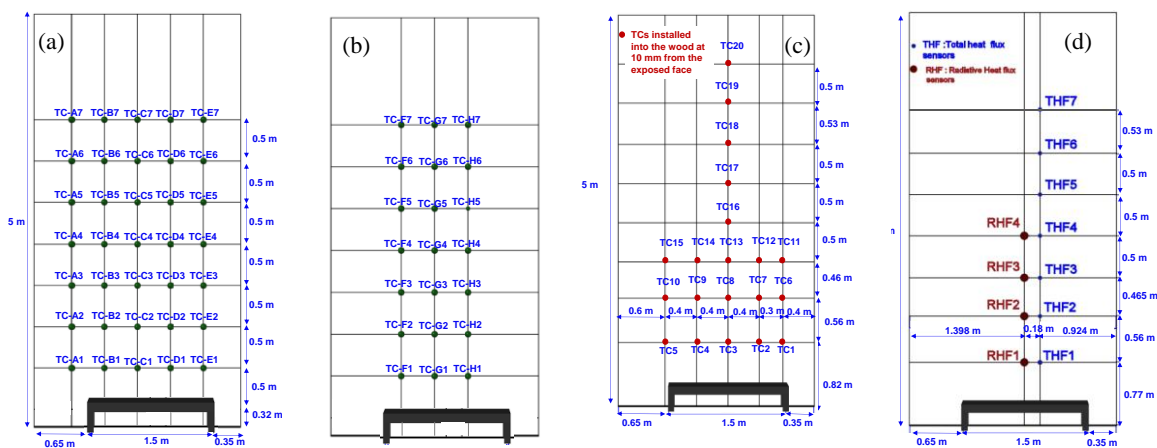


Figure 2 Positions of measurement sensors (a) and (b) thermocouples to measure gas temperatures (b) thermocouples to measure in-depth temperatures and (c) heat flux sensors

RESULTS AND DISCUSSIONS

Heat release rate

Figure 3 shows the temporal evolution of heat release rate estimated using the oxygen-depletion method and heat output of the burner in the case of inert facade and wooden facade test. The both facades were exposed to a heat output burner of 950 kW maintained constant throughout the duration of the test. The heat release rate in the case of inert facade is identical to the imposed heat output. This comparison makes it possible to validate the accuracy of the measurement method based on analysis of gaseous combustion products (collected via the exhaust hood). In the case of the wooden facade, a typical HRR curve of thermally thick charring materials was obtained [7]. A rapid increase in HRR was observed immediately after ignition. Indeed, a peak HRR value of 1530 kW is reached at about 2 min from the beginning of the test which is attributed to the ignition of volatile pyrolysis gases. Subsequently, the HRR decreased to a value of 1080 kW at around 13 min and then increased again slightly (by 35 kW) until the end of the test. This effect is related to the formation of the insulating char layer which limit the heat transfer to the in-depth virgin wood, thus wood pyrolysis decreases. The

comparison of the HRR curves obtained in the two tests clearly shows a significant contribution of the wooden facade which reaches a maximum value of around 580 kW.

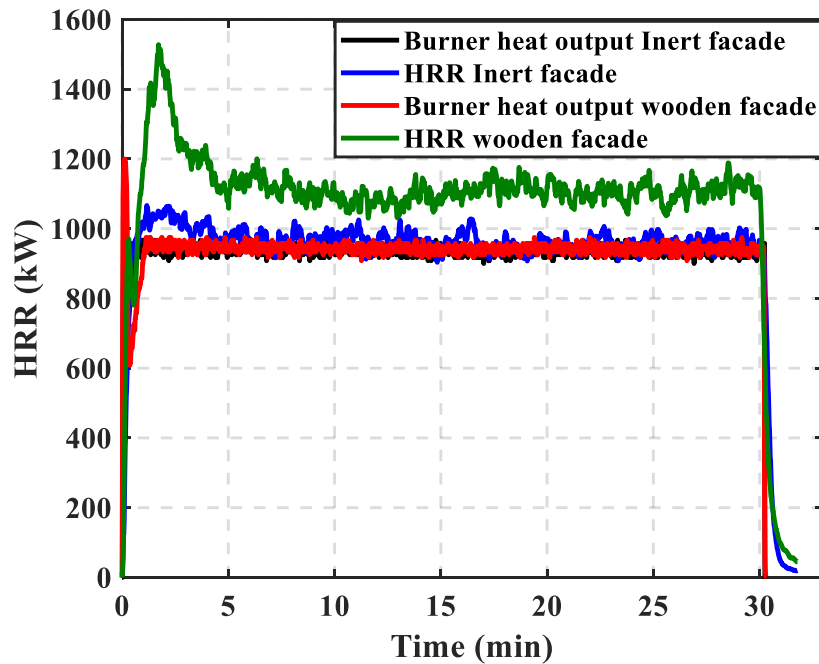


Figure 3 Temporal evolution of heat release rate

Total and radiative heat fluxes

Figure 4 illustrates the temporal evolution of the total heat and radiative heat fluxes received in the case of the inert facade and the wooden facade. The curves of total heat flux were filtered (smoothed) to minimize the effect of the signal noise. In the wooden facade, it can be noted that the curves obtained by FT5, FT6 and FT7 sensors, located respectively at 2.29 m, 2.79 m, 3.23 m from the bottom panel, show a trend similar to that of HRR (Figure 3). The three curves indicate a heat flux peak at 2 min followed by a drop and then a slight increase from around 13 min as observed in the HRR curve. In addition, the heat flux measured with the wooden panel is almost twice the heat flux with the inert panel. It is explained by the fact that the flame with the wooden panel is higher than with the inert panel, thus the heat flux in the upper part of the panel is more affected by the fact the panel burns or not. On the contrary, in the bottom part of the panel, for sensors from FT1 to FT4, the influence is not so large because the flame is present whether the panel is flammable or not, and its thickness and temperature are not very modified.

Heat fluxmeters in this zone are the least affected by any fire growth further away from the burner as mentioned by Zeinali et al. 2018 [8]. A continuous increase of the measured heat flux during the test is observed which can be explained by the deposit of soot, tar, and dust on the sensitive area of the sensors (we notice that total heat fluxmeter are not protected against deposits on their surface). This can cause a significant variation of the calibration constants and consequently of the measured heat flux. Bundy et al 2007 [9] reported that that the soot coating on the sensors could add an additional uncertainty of $\pm 10\%$ due to variations in surface emissivity, and soot agglomerates shadowing the surface of the sensors.

Figure 5 shows the evolution of total and radiative fluxes as a function of wall height. The values shown are averages over the last 15 minutes of the test. All curves show the same evolution. The heat flux increases up to a maximum value and then decreases linearly as a function of wall height. This trend is in agreement with that found in the literature, where the evolution of heat flux as a function of a vertical wall height is divided into three zones corresponding to the three flame regions (continuous flame, intermittent flame, and buoyant plume) [2].

It is clear that in the figure the total fluxes are much higher than the radiative fluxes for both inert and wooden facade. Maximum total flux values reached are 55 kW and 65 kW respectively for the inert

facade and the wooden facade. These values are recorded by the THF 3 located at 1.79 m from the bottom wall. Similarly, the maximum radiative fluxes were measured at the same position by RHF 3, the values reach 24 kW and 26 kW respectively for the inert facade and the wooden facade. These two values are quite similar because the flame in both cases is similar, just a bit more sooty and therefore emissive with the wooden panel.

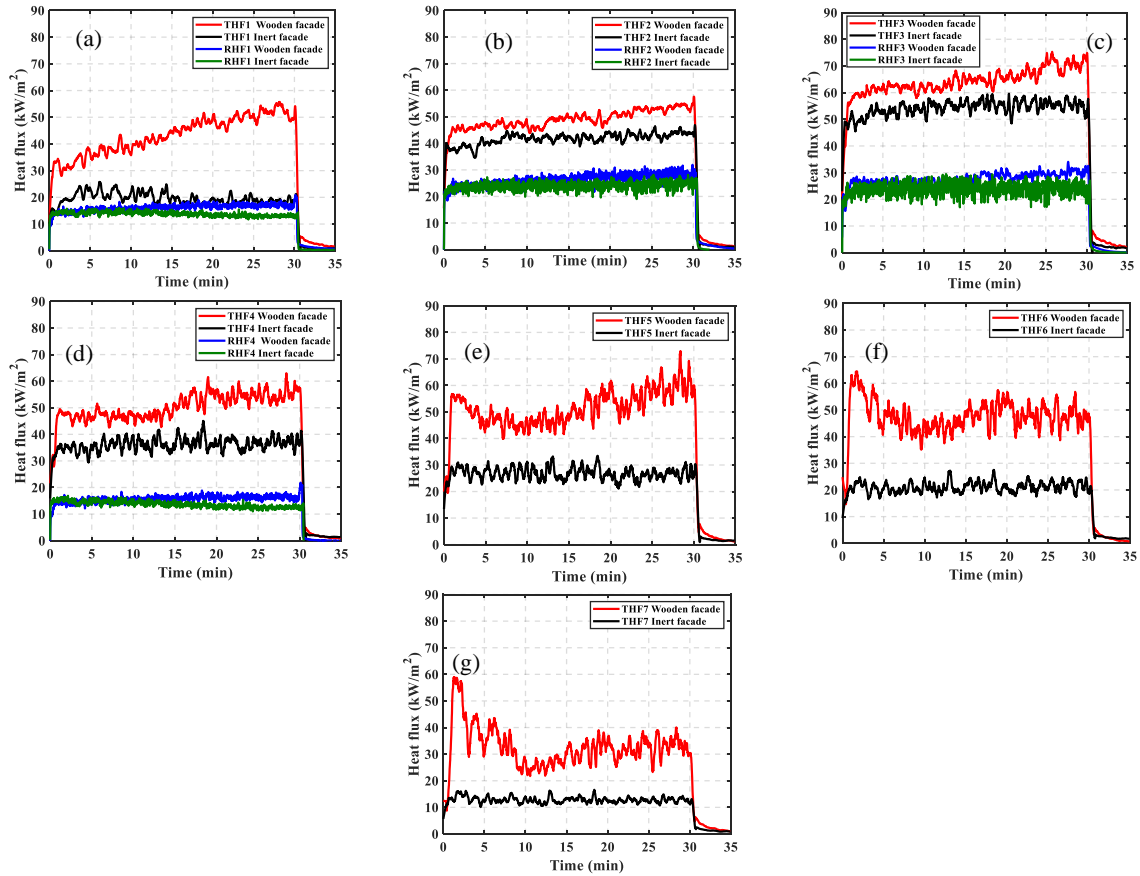


Figure 4 Temporal evolution of total and radiative heat flux (a) 0,5 m (b) 1 m (c) 1.5 m (d) 2 m (e) 2.5 m (f) 3 m (g) 3.5 m

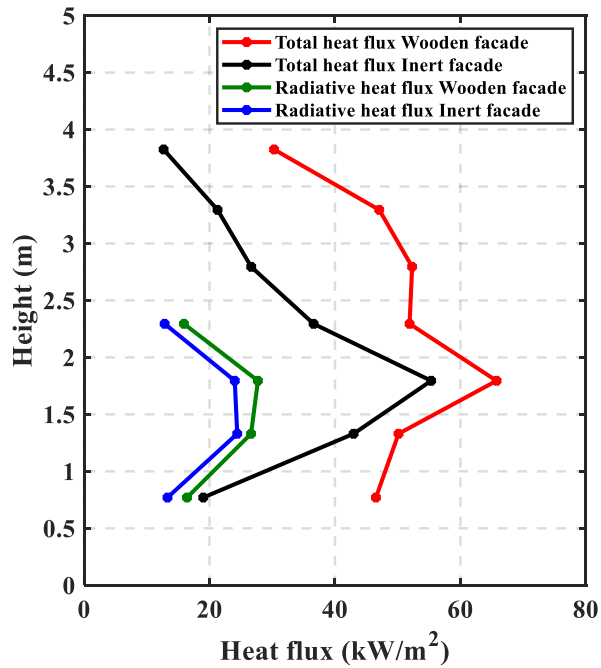


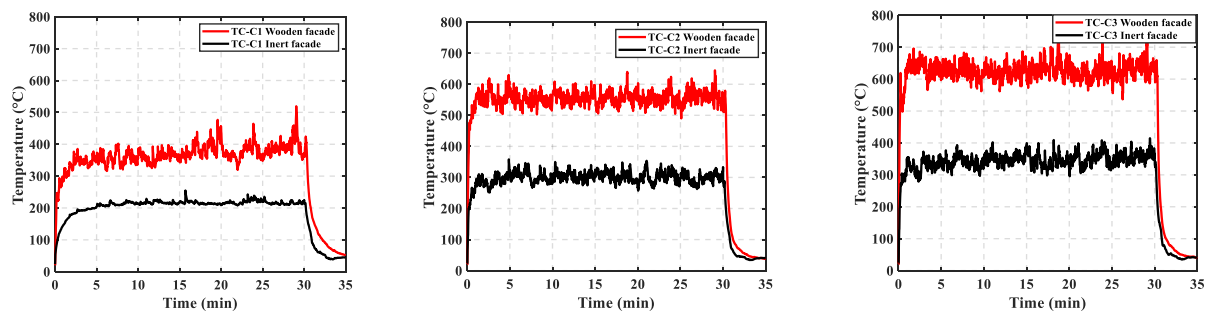
Figure 5 vertical profiles of total and radiative heat flux

Temperatures in the gas phase.

Figure 6 depicts the temporal evolution of gas temperatures recorded by a series of thermocouples along the centerline of the facade (TC-C tree), located 15 cm from the exposed face. Immediately after the start of test, temperatures increase rapidly and reach their maximum values. These temperatures remain almost stable throughout the duration of the test. Because the thermocouples have a large diameter and were not corrected from radiative losses, the measured temperatures are very significantly underestimated compared to the actual gas/flame temperature. The temperatures measured with wooden facade are much higher than those measured on the inert façade because the wood panel is much hotter than the inert panel and thus the thermocouples are also subjected to a higher radiative flux coming from the panel surface. The difference reaches 300 °C at 1.5 m (TC-C 3) in continuous flame region and around 170 °C at 3.5 m.

To better visualise the temperature variations in the facade, temperature distributions were obtained through bilinear interpolation from the thermocouples measurements. Figure 7 shows the temperature distribution maps at different times of test (5 min, 15 min and 30 min) for the wooden and the inert facade. As previously mentioned, the maps obtained show that the temperature field remains constant over time. The asymmetry observed is mainly due to the fact that the burner is offset to the right of the facade for technical reasons. We note that the highest temperatures are measured at the lower part of the facade (between 0.5 m and 2.5 m). The temperatures reached values of 675 °C and 520 °C respectively for the wooden and the inert facade and then decrease in the vertical direction. Indeed, the temperatures obtained with the wooden facade in the upper part of the wall (from 3 m) are around 400 °C and less than 300 °C with the inert facade.

This evolution of the temperature as a function of facade height is similar to that observed previously for the total flux and the radiative flux.



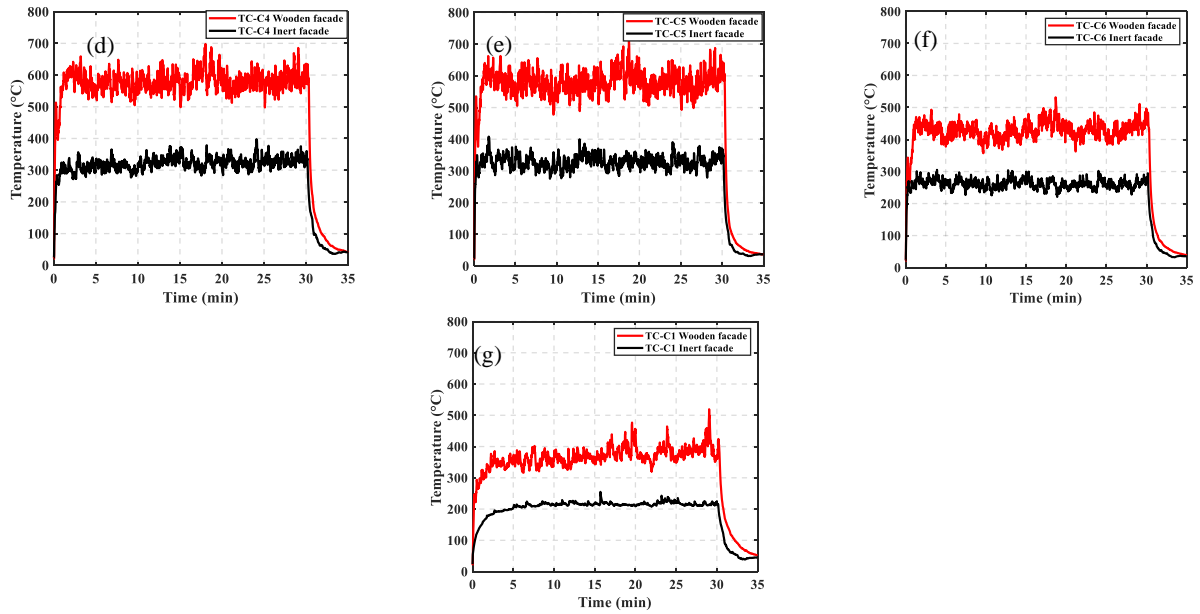


Figure 6 Gas temperatures along the centreline of façade (a) 0,5 m (b) 1 m (c) 1.5 m (d) 2 m (e) 2.5 m (f) 3 m (g) 3.5 m

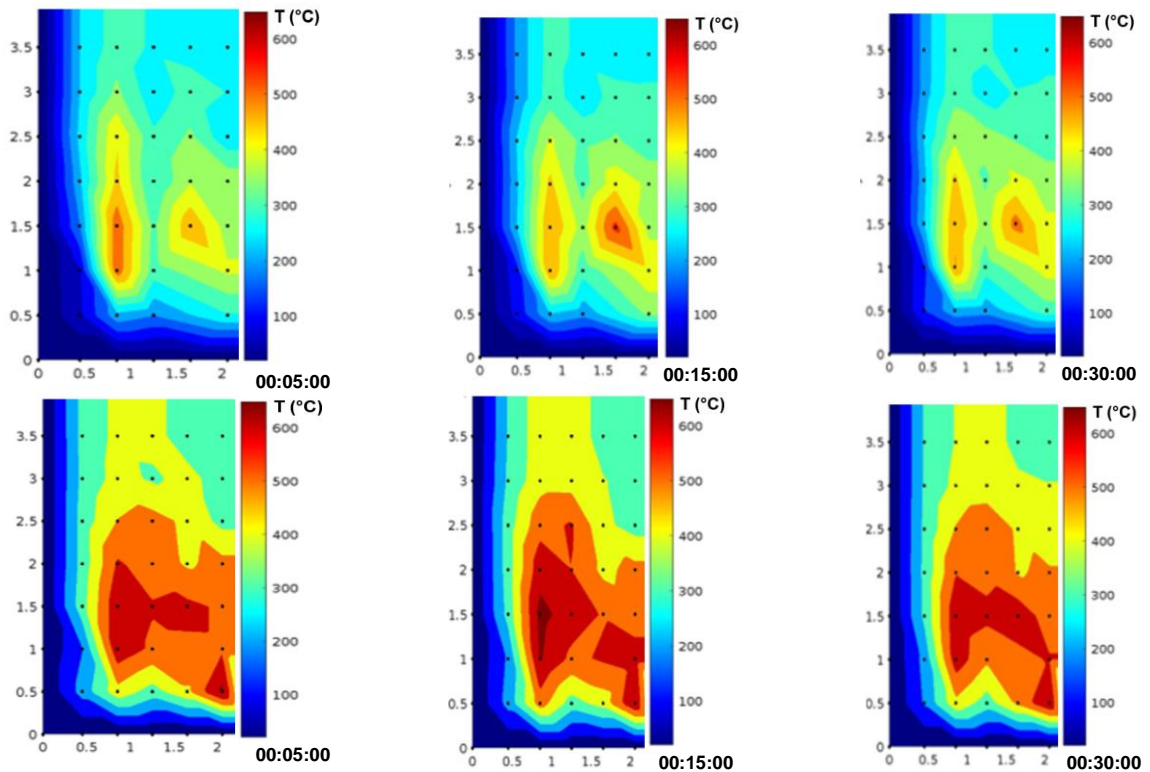


Figure 7 Maps of gas temperatures at different time after ignition , time is given as (hh:mm:ss).

Char depth

After the test, the char depth was measured according to the method explained previously. Figure 8-a

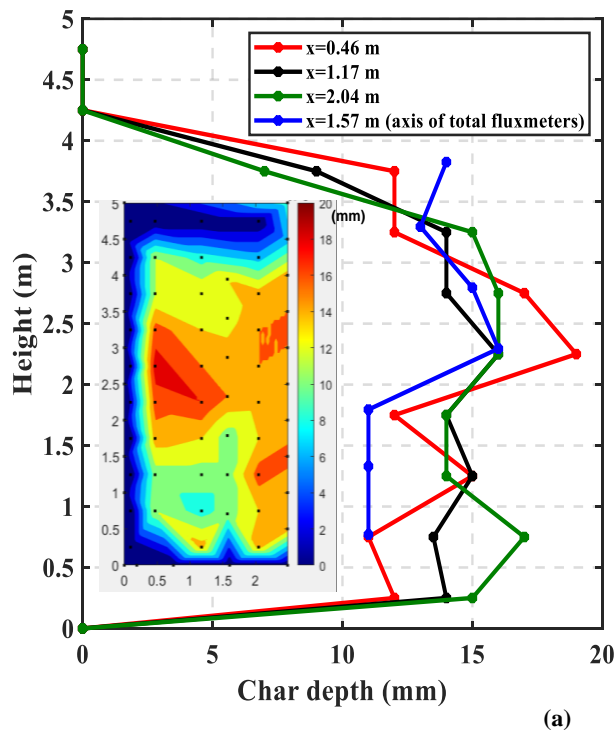


Figure 8 (a) picture after test (b) char depth distribution

shows the vertical profiles of the char depth with char depth map obtained through bilinear interpolation from measurements data as an indication. The most severe charring was found in the center right of the facade where the char depth reached approximately 18 mm. The average char depth was 11 mm corresponding to a charring rate of 0.33 mm/min. In the upper regions, char depths became negligible above a height of 4.5 m (between 0 and 1 mm). We note also that a part in the left end of the wall remained uncharred (figure 8-b) due to the position of the burner which is shifted to the right as mentioned previously.

Char depth can also be evaluated by the 300 °C isotherm [11]. Indeed, it is often assumed that the 300 °C isotherm is the location of the charring front. As shown in Figure 9, the temperatures recorded by the thermocouples installed into the wood 10 mm from the exposed face do not exceed 300°C except for two thermocouples. These results are therefore not in agreement with those obtained from direct measurements. This is explained by the fact that the thermocouples are installed perpendicular to the isotherms which leads to a significant underestimation of the temperature due to thermal bridging effect created by a thermocouple [12], [13], [14], [15]. It is strongly recommended that thermocouples must be embedded parallel to the isotherms to limit measurement errors. However, this technique is very difficult to implement in large panels.

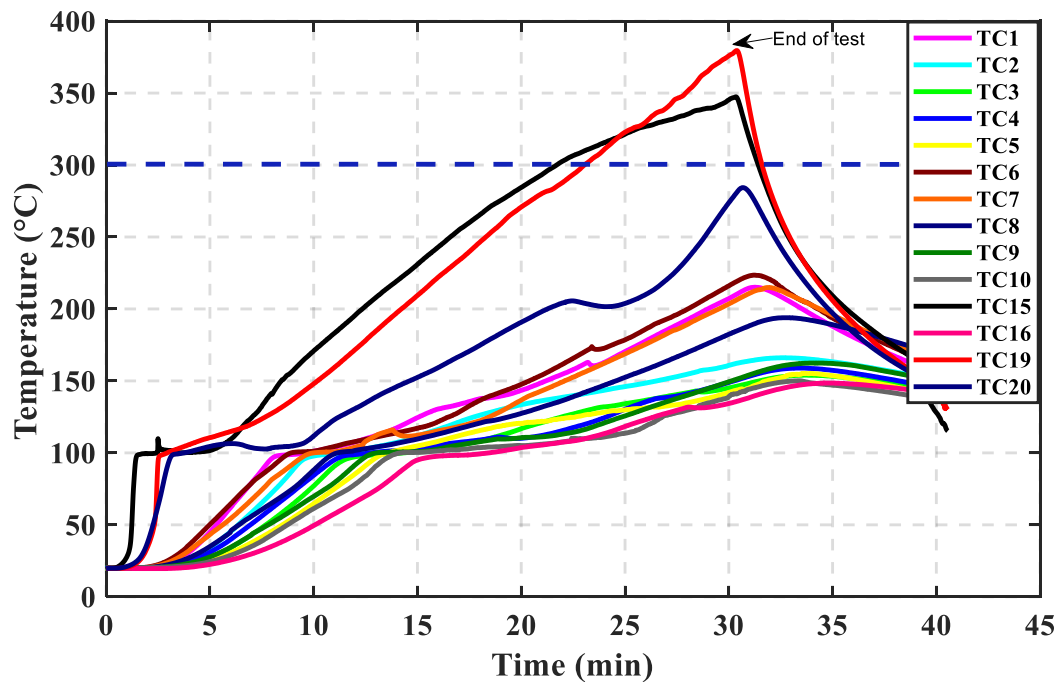


Figure 9 In-depth temperature measured by thermocouples located at 10 mm from the exposed face

CONCLUSIONS

The present study investigates experimentally fire behaviour of a wooden facade. The heat release rate (HRR), gas temperature profile, vertical heat flux profile upon the facade and the char depth were measured and compared from those with an inert facade. The following conclusions can be drawn from this investigation:

- The heat release rate increases considerably in the case of the wooden facade compared to the inert facade. The contribution reaches a peak of around 550 kW.
- The total heat flux measured with the wooden facade is 15 to 60% higher (depending on the height) than with the inert facade. For the radiative flux, a less significant difference (between 8 % and 19 %) was noticed.
- The vertical temperature profile near the façade was similar to that observed for the heat flux, a difference of about 300 °C was observed between the wooden and inert facade test.
- The maximum value of char depth was 20 mm in the most severe charring zone. The direct measurements are not in agreement with those obtained by the 300°C isotherm due to the errors related to thermocouples which were installed perpendicular to the isotherms.

These results were used to assess the ability of FDS code (Fire Dynamics Simulator) to simulate the flame propagation along a facade. The comparison between these experimental and numerical results is the subject of another paper at this conference.

ACKNOWLEDGEMENTS

The authors acknowledge the support of the French Agence Nationale de la Recherche (ANR), under grant ANR-20-CE22-0005 (project FIREWALL+).

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