Study of experiments on flame spread in corner configurations

Emma Vandemoortele

Supervisors: Prof. dr. ir. Bart Merci, Dr. Tarek Beji
Counsellor: Davood Zeinali

Master's dissertation submitted in order to obtain the academic degree of Master of Science in Fire Safety Engineering

Department of Flow, Heat and Combustion Mechanics
Chair: Prof. dr. ir. Jan Vierendeels
Faculty of Engineering and Architecture
Academic year 2016-2017
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June 2nd 2017

Emma Vandemoortele
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Abstract

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University of Ghent
Department of Flow, Heat and Combustion Mechanics
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The impact of corner fires on the flame spread and fire development in an enclosure is substantial in comparison with single wall fires. As this presents challenges related to the prediction of such fire behavior, the fire growth in a corner configuration is examined for medium density fiberboard (MDF) and plywood panels in the form of single burning item (SBI) tests. In addition, calcium silicate panels were used to examine the difference in fire growth behavior when only one of the panels in the corner is combustible. Furthermore, inert tests with calcium silicate panels at both a lower and higher heat release rate than the standard test (10 kW and 50 kW) were performed as well, in order to examine the impact on the parameters monitored. The tests performed in this thesis are part of a larger experimental campaign. A description on the SBI testing methodology, corner fire dynamics, material properties and experimental set-up is provided. The results of the flame spread, panel temperatures, total Heat Release Rate (HRR) and Smoke Production Rate (SPR) and total heat fluxes at characteristic locations are presented in this work. The MDF panels showed two peaks of different height in the HRR, whereas the plywood panels showed two peaks of equal height but further apart, when both panels are combustible. The short panel showed a faster temperature development near the corner if either both or no panels are combustible. In the plywood tests, more lateral flame spread on the short panel was observed. When only one of the panels is combustible, the peaks in the HRR are less pronounced, the lateral flame front propagation takes more time on the short panel and the average instantaneous flame height is higher in the case of only the short panel burning. The 10 kW inert test generated an average HRR of 11.1 kW with an average flame height of 0.51 m. In the 50 kW inert test, an average HRR of 54.5 kW with an average flame height of 1.34 m was observed.

Keywords: Flame spread, corner fire, single burning item test, medium density fiberboard, plywood
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Abstract: The impact of corner fires on the flame spread and fire development in an enclosure is substantial in comparison with single wall fires. As this presents challenges related to the prediction of such fire behavior, the fire growth in a corner configuration is examined for medium density fiberboard (MDF) and plywood panels in the form of single burning item (SBI) tests. In addition, calcium silicate panels were used to examine the difference in fire growth behavior when only one of the panels in the corner is combustible. Furthermore, inert tests with calcium silicate panels at both a lower and higher heat release rate than the standard test (10 kW and 50 kW) were performed as well, in order to examine the impact of the HRR delivered by the burner on the parameters monitored. The tests performed in this thesis are part of a larger experimental campaign. A description on the SBI testing methodology, corner fire dynamics, material properties and experimental set-up is provided. The results of the flame spread, panel temperatures, total Heat Release Rate (HRR) and Smoke Production Rate (SPR) and total heat fluxes at characteristic locations are presented in this work.

Keywords: Flame spread, corner fire, single burning item test, medium density fiberboard, plywood

I. INTRODUCTION

Due to the reduced air entrainment into the fire, flame heights are observed to be higher when a fire is located in a corner when compared to a single wall fire [1]. Therefore, the impact on flame spread in enclosure fires is more substantial. For this reason, a number of tests have been conducted in the past in order to characterize the fire growth behavior of such types of fires [eg. 2-5]. An additional goal of these tests was to provide suitable data for the evaluation of CFD models. For this purpose, several parameters were quantified: the heat release rate (HRR), smoke production rate (SPR), smoke layer temperature, surface temperature, heat fluxes, flame spread in several directions (front, height and length), time to flashover, etc. However, a certain number of parameters is yet to be quantified according to the authors of [6]: the backside panel temperatures, the evolution of the wall temperatures and the level of symmetry on the thermal attack on the walls. In order to investigate these parameters described above and to supply data for assessing pyrolysis and CFD model predictions, a set of Single Burning Item (SBI) tests are conducted using Medium Density Fiberboard (MDF), plywood and calcium silicate panels. The tests discussed here are part of a larger experimental campaign. As such, the discussion of the results focuses on the similarities and differences with the discussion of the previously conducted tests in [6-8].

II. EXPERIMENTAL SET-UP

Two panels of different dimensions are placed vertically in the SBI trolley perpendicular to each other to form a corner configuration. The long panel has a width of 1.00 m and a height of 1.50 m, whereas the short panel has a width of 0.50 m and a height of 1.50 m. The thickness and nominal density of the materials used in this set-up is given in Table 1.

Table 1 Properties of the materials used in the experiments

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness [m]</th>
<th>Nominal Bulk Density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDF</td>
<td>0.0182 ± 1%</td>
<td>585 ± 5%</td>
</tr>
<tr>
<td>Plywood</td>
<td>0.0169 ± 1%</td>
<td>560</td>
</tr>
<tr>
<td>Calcium silicate</td>
<td>0.0123 ± 0.001</td>
<td>1005 ± 5%</td>
</tr>
</tbody>
</table>

Different arrangements of the panels are considered when testing the three panel types used in the experiments (MDF, plywood and calcium silicate). Accordingly, the performed experiments include tests in which both panels are of the same material type, and tests in which one panel is calcium silicate while the other one is either MDF or plywood. In the latter case, two tests are performed, namely one where the calcium silicate panel serves as the short panel, and one where one where it serve as the long panel. Prior to the experiments, the panels have been conditioned at 21°C and 50% humidity as to reduce the variability of the initial conditions [6].

A triangular sandstone propane burner, with side dimensions of 0.25 m and a 30 kW HRR, is positioned at the bottom of the corner with a 0.04 m clearance, in order to represent the ignition source [9].

The combustion gasses, collected by a hood, are used to calculate the total HRR and total SPR by the application of the oxygen depletion technique and the obscuration concept [9].

The evolution of the panel temperatures is monitored by attaching a total of 110 thermocouples (K-type), both at the backside of the panels and through the thickness of the panels (see Figure 1). The latter is made possible by fixing the thermocouples in holes drilled from the backside of the panels with a ±0.1 mm accuracy, using thermal adhesive 940 HT-1 from Polytec PT. The conductivity of this paste (2.1 W/(m.K)) is over 40 times the conductivity of air at 400°C and over 10 times that of the panels [6]. Since the paste does not decompose at high temperatures and is electrically nonconductive, it is assumed that fixing the thermocouples in this manner will not interfere with the functioning of the thermocouples [6]. To ensure that the measurements are made precisely at the desired depth, the wires of the thermocouples are welded forming a bead at its end. The size of the bead is approximately 1.5 mm. [6] The through-thickness measurements are made at different depths at the same position. In order to do so, multiple holes are drilled with
sufficient spacing such that the influence from neighboring measurements is reduced and contact between the beads and the panels is better [3]. According to initial experiments conducted by the authors of [3], the holes can have a lateral spacing of 1 cm with respect to the position shown on Fout! 

In the case of MDF or plywood panels, through-thickness temperature measurements are made at 2 mm and 12 mm from the front surface whilst in the case of calcium silicate panels the measurements are made at 1 mm and 6 mm from the front surface instead.

Figure 1 Lay-out of the thermocouples on the long and short panel

Heat flux measurements are made using water-cooled Schmidt-Boelter heat flux sensors (working range up to 75 kW/m²) at three locations on the long panel as shown on X. The positions of these measurements correspond to the thermal attack calibration points described in Annex D.2 of EN 13823 [9]. In order to reduce the condensation errors on the water-cooled heat flux sensors, the temperature of the cooling water is set to 50°C [6]. The heat sensors are set flush with the surface of the panels. The positions of the heat flux sensors are indicated on Figure 2.

Finally, two cameras – pointed in different directions – are used to monitor the flame spread during the experiments. One camera faces the short panel and the other one faces the long panel. The instantaneous flame heights are obtained using Video Fire Analysis.

III. RESULTS AND DISCUSSION

In the experimental campaign, a total of 19 SBI experiments are to be conducted. Here, the results of the eight tests given in Table 2 are compared to the results obtained in [6-8].

<table>
<thead>
<tr>
<th>Test</th>
<th>HRR [kW]</th>
<th>Long panel</th>
<th>Short panel</th>
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<tr>
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<td>30</td>
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</tr>
<tr>
<td>CSP1</td>
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<td>plywood</td>
</tr>
<tr>
<td>PCS1</td>
<td>30</td>
<td>plywood</td>
<td>calcium silicate</td>
</tr>
<tr>
<td>PP1</td>
<td>30</td>
<td>plywood</td>
<td>Plywood</td>
</tr>
<tr>
<td>CSCS10</td>
<td>10</td>
<td>calcium silicate</td>
<td>calcium silicate</td>
</tr>
<tr>
<td>CSCS50</td>
<td>50</td>
<td>calcium silicate</td>
<td>calcium silicate</td>
</tr>
</tbody>
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A. Results of the HRR and SPR measurements

The heat release rate evolution of the tests in which both panels are combustible showed two peaks in the beginning of the test. In the case of the MDF tests, the second peak (158 kW) occurs 66 s after the first peak and is the highest of the two peaks. The first peak in the HRR is associated with the fast pyrolysis of the surface material. Afterwards, a char layer is formed, which reduces the heat transfer towards the panels, leading to a temporary decrease in the HRR. As more material is pyrolyzed (both in the lateral and vertical direction) whilst also the char layer shrinks and starts to delaminate, the second peak in the HRR manifests. For the plywood tests, the peaks are 224 s apart and are equal in height (70 kW). This difference between the initial burning behavior of MDF and plywood can be mainly attributed to the difference in manufacturing of the panels. As opposed to the plywood panels, the surface layer of the MDF panels has a much higher density compared to its inner core, tending to delaminate and crack rapidly as it chars. In the case of plywood, it takes much longer for the surface char to crack, with only minimal delamination. This explains why the HRR evolution between the two peaks in test PP1 is more gradual than that in test MM3, taking approximately 224 s versus 66 s, respectively.

If only one panel is combustible, the occurrence of peak values is less pronounced and can be better described as maximum values. A similar HRR evolution is seen for both
the case in which only the short panel is combustible as for when the long panel is the only combustible panel.

At the end of the test, a peak in the HRR is observed for tests PP1 and CSP1 as the fire penetrates the corner. In order to preserve the thermocouples, the tests were stopped prematurely which can be observed as a sudden drop in the HRR for test PP1. This is the case for both types of materials.

An average HRR value of 11.1 kW and 54.5 kW can be observed for test CSCS10 and CSCS50 respectively. In both inert tests, a slow rise in the HRR could be seen. As was described in [8], the gradual rise in the HRR is accredited to the slow pyrolysis of dust particulates on the surface of the panels.

For the MDF tests, a peak in the SPR occurs as the surface material of the panels pyrolyzes. This occurs at the same moment for all three types of tests performed. Afterwards, a gradual rise in the SPR towards the end of the test can be seen for test MCS1, MCS2 and CSM1. Test MM3 shows more efficient burning in the first half of the test as the SPR is the lowest of all tests. Towards the end of the test, the SPR rises fast as the fire starts penetrating through the material.

In the case of the plywood tests, no peak in the SPR is observed in the beginning of the test. Only a gradual rise of the SPR can be seen. This indicates that the burning of the panels is more efficient and gradual for plywood than for MDF. For test PP1, a sudden peak in the SPR occurs as the fire penetrates through the corner. In the case of test CSP1, the SPR drops somewhat before the end of the test as the fire starts to penetrate the corner. This might be related to the different shape of opening in the short panel after the fire has penetrated.

The overall average SPR of the inert tests was found to be 0.025 m²/s for test CSCS10 and 0.102 m²/s for test CSCS50.

B. Results of the panel temperatures

Both the temperatures measured near the surface and at the back of the panels show a plateau around 100°C. This is related to the moisture migration and evaporation of the panels [6-8]. At the back of the panels, it can be seen that this process takes a while to complete whilst near the surface of the panels, this phenomenon is observed for a shorter period of time. After the panels have dried near the surface, the temperatures of the combustible panels measured at 2 mm from the exposed surface start to rise rapidly. As a char layer is formed and delamination occurs, the rate at which the heat is transferred through the panels changes, causing the temperatures near the surface to drop before increasing at a slower rate. At locations further away from the corner, the peaks in the temperature profiles occur at progressively later times, as flames take some time to spread on the panel surface.

In case both or no panels are combustible, a faster temperature development can be observed near the bottom of the corner on the short panel. In the MDF tests performed, it was found that this was not the case when only one panel is combustible. This can be observed on Figure 8.
D. Results for the instantaneous flame heights

In the MDF tests, peaks in the instantaneous flame height can be observed in the beginning of the test, around the same time as the peaks in the HRR. This is not observed in the plywood tests. A second difference regarding the flame heights of the two materials is that for plywood, no significant increase in flame heights could be observed as the flames started to penetrate the panels. However, for both types of materials, higher instantaneous flame heights were monitored when only the short panel is combustible compared to only the long panel being combustible.

In the case of the inert tests, an average flame height of 0.51 m and of 1.34 m was found for the 10 kW and 50 kW tests respectively. Note, that the latter value is most likely to be an underestimation caused by the limitations of the apparatus height.

E. Results for the lateral flame spread

Monitoring the lateral flame spread shows that for MDF, the propagation of the flame front is halted early in the test when only one panel is combustible. Afterwards, only the propagation of a ‘delamination front’ was seen. In the case of plywood panels, this was observed for all types of tests performed. Moreover, similar positions of the flame front were seen at the end of the test when only one panel is combustible. However, the lateral flame spread continued to propagate long in the case of only the short panel being combustible. For plywood, it was seen that if both panels are combustible, the lateral flame front has advanced more on the short panel and for a long period of time.

IV. Conclusions

The MDF panels showed two peaks of different height in the HRR, whereas the plywood panels showed two peaks of equal height but further apart, for the tests in which both panels are combustible. A peak in the temperature evolution near the surface could be observed in the MDF tests after the panel has dried, whereas for plywood, this is not very noticeable. This is assumed to be related to less extensive char cracking and delamination. The short panel showed a faster temperature development near the corner if either both or no panels are combustible. In the plywood tests, more lateral flame spread continued to propagate long in the case of only the short panel being combustible. For plywood, it was seen that if both panels are combustible, the lateral flame front has advanced more on the short panel and for a long period of time.
height is higher. The 10 kW inert test generated an average HRR of 11.1 kW with an average flame height of 0.51 m. In the 50 kW inert test, an average HRR of 54.5 kW with an average flame height of 1.34 m was observed.

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List of Symbols

Bi  Biot number [-]
$c_p$  Heat capacity [J/kg.K]
C  Mass concentration of smoke particles [%]
E  Heat release rate per unit volume of oxygen consumed at 298 K (17 200 kJ/m³)
$f_v$  Particulate volume fraction [-]
$F_{1→2}$  Geometrical or configurational factor [-]
g  Gravitational acceleration constant (9.81 m/s²)
h  Convection coefficient [W/m².K]
$H_f$  Flame height [m]
$H_p$  Pyrolysis height [m]
I  Intensity of light [-]
$I_0$  Intensity of the light beam without smoke attenuation [-]
$I$  Signal from the light receiver [%]
$I(30s...90s)$  Average light intensity between 30s and 90s [%]
$I(\lambda,T)$  Spectral radiance [W/sr.m²]
k  Thermal conductivity of the fluid [W/m.K]
k  Thermal conductivity of the solid [W/m.K]
K  Effective emission coefficient [m⁻¹]
l  Characteristic length scale [m]
L  Flame thickness or the mean equivalent beam length [m]
L  Distance travelled by light [m]
$L_c$  Length of the pre-heat zone [m]
$L_v$  Latent heat of vaporization [J/kg]
Nu  Nusselt number [-]
$\dot{q}_{conv}$  Convective heat flux [kW/m²]
$\dot{q}_{rad}$  Radiative heat flux [kW/m²]
Distance between the two surfaces [m] (with regards to the geometrical factor)

Re
Reynolds number [-]

T
Temperature [K]

\( u_\infty \)
Free stream velocity [m/s]

V
Non-normalized volume flow in the exhaust duct [m³/s]

\( V_{298} \)
Volume flow of the exhaust system normalized at 298 K [m³/s]

\( X_{a,O2} \)
Ambient mole fraction of oxygen including water vapour [-]

**Greek symbols**

\( \alpha \)
Thermal diffusivity [m²/s]

\( \alpha_{eff} \)
Effective absorptivity [-]

\( \beta \)
Coefficient of expansion [K⁻¹]

\( \Delta T \)
Change in temperature [K]

\( \Delta H_{c,ox} \)
Heat of combustion per gram of oxygen consumed [J/kg]

\( \Delta Q_{pyr} \)
Latent heat of pyrolysis [J/kg]

\( \varepsilon \)
Emissivity [-]

\( \varepsilon_{eff} \)
Angle [°] (with regards to the geometrical factor)

\( \kappa \)
Extinction coefficient [-]

\( \lambda \)
Wavelength [µm]

\( \mu \)
Dynamic viscosity [kg/m.s]

\( \nu \)
Kinematic viscosity [m²/s]

\( \rho \)
Density [kg/m³]

\( \rho_\infty \)
Ambient density [kg/m³]

\( \sigma \)
Stefan-Boltzmann constant \((5.67 \times 10^{-8} \ W/m².K^4)\)

\( \phi \)
Oxygen depletion factor [-]
<table>
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<tr>
<td>CEN</td>
<td>Comité Européen de Normalisation</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>FPA</td>
<td>Fire Propagation Apparatus</td>
</tr>
<tr>
<td>HRR</td>
<td>Heat Release Rate</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>MDF</td>
<td>Medium Density Fiberboard</td>
</tr>
<tr>
<td>SBI</td>
<td>Single Burning Item</td>
</tr>
<tr>
<td>SPR</td>
<td>Smoke Production Rate</td>
</tr>
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Chapter 1  Introduction

A fire is mainly an exothermic oxidation reaction which requires three ingredients in order to occur: fuel, an oxidizer and heat. First, the heat is provided by the ignition source after which the heat produced by the exothermic reaction sustains the fire by transforming a solid or liquid fuel into a combustible gas. In case of a solid fuel, the amount of energy required to obtain such a phase change is called the latent heat of pyrolysis, whereas for a liquid fuel this is the latent heat of vaporization (Merci & Beji, 2017b). As of such, heat transfer is vital with regards to sustaining the fire and fire growth.

In an enclosure, the heat exchange between the fire and its surroundings is imperative in the fire growth process. In order for the fire to grow, enough heat must be produced to sustain the burning of the already ignited fuel area and to ignite additional ‘virgin’ combustible material. The most important source of heat are the flames. On the level of the fuel surface, part of the heat supplied by the flames through convection and radiation is used to transform the fuel surface into a combustible gas. Another part of this heat is lost to in-depth conduction into the solid or liquid fuel and/or to internal convection in case of a liquid fuel (Merci & Beji, 2017b). In addition to that, the fuel surface also radiates heat towards the surrounding environment (Merci & Beji, 2017b). However, a significant quantity of the heat produced by the fire is transferred to the smoke plume via radiation and convection. In enclosure fires, the walls and ceiling form a boundary to the smoke produced by the fire, keeping the smoke and a large portion of the heat contained. This causes a smoke layer to develop, which interacts with the smoke plume, the enclosure boundaries (ceiling and walls) and the cold lower layer. The interaction of all these heat transfer processes is shown on Figure 1.

![Figure 1 – Schematic representation of the heat transfer processes in enclosure fires (Redraw after figure 1.4 (Merci & Beji, 2017b))](image-url)
In case of enclosure fires, additional radiative feedback is supplied to the fuel surface by the smoke layer and the enclosure boundaries (Merci & Beji, 2017b). This is indicated by red arrows on Figure 1. Due to this additional incident radiation on the fuel surface, the pyrolysis and flame spread process is enhanced (Merci & Beji, 2017b). This causes the fire to develop more rapidly compared to free burning fires (Merci & Beji, 2017b).

The aforementioned demonstrates the importance of heat transfer and flame spread in enclosure fire scenarios. However, when a fire is located in a corner, flame heights are more extended and flame temperatures are higher than when the fire is located near a wall or in the center of the room (Drysdale, 2011d). Therefore, the impact of a corner fire in an enclosure is more substantial especially when the walls are made from combustible materials. An detailed explanation for this is given in the subsequent section.

1.1 Fire dynamics aspects of corner fires

In fires, the vertical movement of the hot gases due to buoyancy causes ambient air to be entrained from the surroundings into the fire plume. This entrained air not only causes the hot combustion products to dilute and cool down, but also provides air for the combustion process. The amount of air entrained depends on multiple factors such as the presence of an air conditioning system, the size of enclosure openings, etc. The configuration of the fire inside the enclosure (fire burning in the middle of the room, against a wall, in a corner, or similar) has an effect on the entrainment of air into the fire plume too (Drysdale, 2011a). If the fire is unconfined, no barriers are present to prevent the air from being entrained into the fire plume or to alter the flame height. In case the fire is located near a barrier such as a corner formed by the intersection of two walls, the area through which air may be entrained into the fire plume can be reduced as can be seen on Figure 2. This has an effect on the flame height and plume temperatures. (Drysdale, 2011a)

![Figure 2](image)
According to McCaffrey the fire plume consists of three distinct regimes shown on Figure 3:

1) The persistent flame: where the flaming is persistent and the flow of burning gasses is accelerating

2) The intermittent flame: where the flaming is intermittent and the flow velocity is almost constant

3) The buoyant plume: where no flaming is present and the flow velocity and plume temperature are decreasing with height

![Figure 3 – Schematic diagram of the three distinctive regimes of a fire plume, according to McCaffrey (Drysdale, 2011a)](image)

When the fire is located near a corner of walls, the same three regimes as shown on Figure 3 can be observed, but due to the reduced entrainment there is less mixing of cold air with hot combustion gasses in the buoyant plume. This causes the temperatures to decrease less rapidly as a function of height compared to the unbounded case. According to (Drysdale, 2011a), the flame height is higher when the fire is in a corner, provided there is no substantial gap between the fire source and the walls. If the gap between the sides of the burner and the vertical surfaces becomes greater than twice the characteristic burner dimension, the flames do not attach to the walls and the flame height is not increased compared to the unbounded case.

For corner fires, a simple model can be used to estimate the average flame height. This concept introduces an ‘imaginary mirror fire source’ as shown on Figure 4. The flame height is assumed to be equal to the flame height which would be produced by the combination of the actual and the imaginary fire source when applying Heskestad’s equations. However, evidence is found that this concept does
not provide accurate estimations for the average flame height for gas fires. According to (Drysdale, 2011a), it is reported that the average flame height for corner fires is doubled if there is no gap between the vertical surfaces and the burner. Still, the ‘imaginary mirror fire source’ concept is useful for estimating the maximum temperature as a function of the flame height.

![Figure 4 – Concept of the imaginary fire source (Drysdale, 2011a)](image)

Heat transfer towards the surfaces in the corner configuration and the rate at which the material will ignite, if combustible, must be considered as well when investigating the impact of the corner configuration on the fire dynamics. Heat is transferred from the fire to the walls by convection of the hot combustion gases and by radiation of the flames towards the walls. Whether or not the material will ignite depends on the characteristics of the material and on the rate of heat transferred. If the walls are made of a combustible material, the walls will also contribute to the fire growth process (Drysdale, 2011a).

The heat transfer mechanisms involved in corner fire configurations are convection and radiation in the gas phase, as mentioned above, as well as the conduction inside the walls (Drysdale, 2011c). Convection is described as a mode of heat transfer between a gas/liquid and a solid caused by the motion of that gas/liquid (Drysdale, 2011c). A distinction can be made between natural or forced convection. In the first case, the motion of the liquid is driven by buoyancy due to temperature gradients (Drysdale, 2011c). In the latter case, the motion is caused by an external force such as wind, a fan, etc (Drysdale, 2011c). Heat transfer caused by convection in fires (also in corner configurations) is in most of the cases natural. But it should be noted that convection plays a different role in an
unbounded free fire, than in a case such as a corner configuration where the solid walls are heated due to the convection created by the buoyant hot gases (Drysdale, 2011c). Quantitatively, the difference between natural and forced convection lies in the value of $h$, the convection coefficient. This coefficient is defined as (Drysdale, 2011c):

$$h = \frac{\dot{q}^{\text{conv}}}{\Delta T} \quad (7)$$

With:

- $\dot{q}^{\text{conv}}$: the convective heat flux [kW/m²]
- $\Delta T$: the temperature difference between the fluid and the solid [K]

The convective heat transfer process takes place in a thin layer of the fluid adjacent to the solid which is called the boundary layer (Drysdale, 2011c). This region of the fluid is characterized by a temperature and a velocity gradient. The steepness of this gradient increases if the flow becomes turbulent in this region (Drysdale, 2011c). However, it needs to be noted that a laminar sublayer will always remain close to the wall regardless of whether the flow is turbulent or laminar (Drysdale, 2011c). The structure of this boundary layer determines the value of $h$ (Drysdale, 2011c). Therefore, the value of $h$ depends on the fluid properties such as thermal conductivity, density and viscosity, but also on the geometry of the solid, whether it is forced or natural convection and the velocity of the flow (Drysdale, 2011c). Depending on the geometry and the nature of the flow, $h$ is expressed as a function of the Nusselt number ($Nu$) (Drysdale, 2011c).

$$Nu = \frac{h l}{k} \quad (8)$$

With:

- l: characteristic length scale [m]
- k: thermal conductivity of the fluid [W/m.K]

The Nusselt number can be expressed as a function of dimensionless numbers that take into account the flow velocity and the fluid properties. When the convection is (Drysdale, 2011c):

- forced: $Nu = f(Re, Pr)$ and $h$ ranges between $10 – 500$ W/m².K
- natural: $Nu = f(Re, Gr)$ and $h$ ranges between $5 – 25$ W/m².K

For further details regarding the correlations for the Nusselt number according to the nature of the flow and the geometry, the reader is referred to (Drysdale, 2011c). The Reynolds number, Prandtl number and Grashof number can be defined as (Drysdale, 2011c):

$$Re_l = \frac{lu_\infty \rho}{\mu} = \frac{\text{inertia forces}}{\text{viscous forces}} \quad (9)$$
With:

- \( u_\infty \): free stream velocity [m/s]
- \( \rho \): density of the fluid [kg/m³]
- \( \mu \): dynamic viscosity [kg/ms]
- \( l \): characteristic length on the surface [m]

\[
Pr = \frac{\nu}{\alpha} = \frac{\mu c_p}{k} = \frac{\text{momentum diffusivity}}{\text{thermal diffusivity}} \tag{10}
\]

With:

- \( \nu \): kinematic viscosity [m²/s]
- \( c_p \): heat capacity of the fluid [J/kg.K]
- \( \alpha \): thermal diffusivity (=\(k/\rho c\)) [m²/s]
- \( k \): thermal conductivity of the fluid [W/m.K]

\[
Gr = \frac{gl^3(\rho_\infty - \rho)}{\rho \nu^2} = \frac{gl^3 \beta \Delta T}{\nu^2} = \frac{\text{buoyancy forces} \cdot \text{inertia forces}}{(\text{viscous forces})^2} \tag{11}
\]

With:

- \( g \): gravitational acceleration constant (9.81 m/s²)
- \( l \): characteristic length [m]
- \( \rho_\infty \): ambient density [kg/m³]
- \( \rho \): density of the hot gasses [kg/m³]
- \( \nu \): kinematic viscosity [m²/s]
- \( \beta \): coefficient of expansion [K⁻¹]
- \( \Delta T \): temperature difference between the hot gasses and ambient air [K]

When a body is heated, a part of this heat will be lost to the surroundings by convection and also by radiation. Radiation can be defined as the transfer of heat by electromagnetic waves at wavelengths between 0.4 and 100 µm. This range of wavelengths comprises a part of the ultraviolet, visible light and infra-red spectrum (Drysdale, 2011c). The radiative heat flux (W/m²) or the total radiation emitted by unit area of a grey surface into the hemisphere above it can be defined as (Drysdale, 2011c):
\[ \dot{q}_{\text{rad}} = E = \varepsilon \sigma T^4 \] (12)

With:

- \( T \): flame temperature [K]
- \( \sigma \): the Stefan-Boltzmann constant \((5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4)\)
- \( \varepsilon \): emissivity [-] (taken here to be independent of the wavelength)

For a real surface, the emissivity lies between 0 and 1 and depends on the wavelength of the electromagnetic waves emitted. By defining the concept of a ‘grey body’ which is an ideal, non-black body, the emissivity can be defined as independent of the wavelength. Such emissivity values can be found in the literature and differ for different objects and temperatures. The equation above gives the total heat lost by radiation, but it does not take into account how much of that heat is received by another body such as for instance by a wall. In order to define the radiant intensity received at a certain location with respect to the radiation source, a geometrical or configuration factor is defined (Drysdale, 2011c). Specifically, the rate of radiative heat transfer from surface 1 \((A_1)\) to surface 2 \((A_2)\) can be defined as (Drysdale, 2011c):

\[ Q_{1 \rightarrow 2} = F_{1 \rightarrow 2} A_1 \varepsilon_1 \sigma T_1^4 \] (13)

\[ F_{1 \rightarrow 2} = \frac{1}{A_1} \int \cos \theta_1 \cos \theta_2 \frac{dA_1}{\pi r^2} dA_2 \] (14)

With:

- \( F_{1 \rightarrow 2} \): the geometrical or configurational factor [-]
- \( \theta_1, \theta_2 \): as shown on Figure 5 [°]
- \( r \): distance between the two surfaces [m]

\[ Figure 5 – Illustration of the configuration factor principle (Drysdale, 2011c) \]
This configuration factor $F_{1\rightarrow 2}$ is important in corner configurations since the fire heats up both walls which can in turn radiate onto each other. In order to calculate the configuration factor, three methods are applied:

- Charts
- Tables
- Analytical expression

To calculate the configuration factor for radiation between two surfaces which are perpendicular to each other, a chart is given by (Drysdale, 2011c). This can be used to calculate the view factor for radiation between two walls in a corner and can be seen on Figure 6.

![Chart for the configuration factor between perpendicular surfaces with a common edge (Drysdale, 2011c)](image)

The radiative flux emitted by the luminous flame depends on the flame temperature and on the emissivity of the flame which in turn depends on the concentration of soot and the thickness of the flame (Drysdale, 2011a). Soot is the name for the carbonaceous particles with a diameter in the range of 10 nm – 100 nm which are formed on the fuel-side of the reaction zone in the flame (Drysdale, 2011a). The radiation emitted by these particles in the flame causes the flame to have a ‘yellowish’ color (Drysdale, 2011a). Depending on the temperature of the flame, this color can change (Drysdale, 2011a). As long as the flame height is below its ‘smoke point’, the soot produced by the flame is consumed in the oxidative region of the reaction zone (Drysdale, 2011a). Once the flame height,
crosses this threshold soot escapes from the flame (Drysdale, 2011a). The relation below shows the correlation between the soot concentration and the emissivity (Drysdale, 2011c):

\[ \varepsilon = 1 - \exp(-KL) \] (15)

With:

- K: effective emission coefficient proportional to the soot particle concentration [m\(^{-1}\)]
- L: the flame thickness or the mean equivalent beam length (typically taken as the pool diameter) [m]

The effective emission coefficient \( K \) is proportional to the ‘particulate volume fraction’ \( f \), if the soot particle diameter is less than the radiation wavelength (Drysdale, 2011a). The particulate volume fraction is the proportion of the flame volume occupied by the soot particulates.

It has to be noted that for large fires, the flame does not have uniform temperatures and soot concentration. According to (Drysdale, 2011c), \( f \) has its maximum value near the fuel surface and decreases with height for horizontal slabs of burning PMMA. Due to this non-uniform temperature distribution, it is possible that cooler soot in the outer perimeter of the flame re-absorbs some of the emitted heat. As a consequence, simple formulas to calculate the radiative heat flux will tend to overestimate the fraction of radiative heat because the non-uniform temperature of the flame was not taken into account. For smaller fires, there can also be radiation coming from CO\(_2\)- and H\(_2\)O-molecules in addition to radiation coming from soot particles. For simplicity, the radiation coming from flames is sometimes assumed to behave as a ‘grey body’, although in the early stages of the fire the radiation coming from CO\(_2\)- and H\(_2\)O-molecules is dominant. More information can be found regarding this in (de Ris, 1979; Mudan, 1984; Moss, 1995; Tien et al, 2008; Yeoh and Yuen, 2009).

Based on relation (12), the radiative flux coming from the flame can be defined as:

\[ \dot{q}_{rad} = \sigma T^4 = \sigma T^4(1 - e^{-KL}) \] (16)

To estimate the radiative flux received by the walls in a corner configuration, a configuration factor needs to be defined. Since the flame has an irregular shape, the problem is simplified by assuming that the flame can be approximated by a simple geometrical shape. Chapter 2 of *An Introduction to Fire Dynamics* by Dougal Drysdale assumes a rectangle with a height of 1.5 to 2 times the fuel bed diameter as such a geometrical shape to represent the flame. The configuration factor can then be found using the charts or tables given in (Drysdale, 2011c).
Figure 7 – Upward flame spread; $H_f$ is the flame height, $H_p$ is the pyrolysis height and $L_c$ is the heating zone length. (Kwon, Dembsey & Lautenberger, 2007)

The combination of the radiative and convective heat coming from the fire is conducted through the material of the walls. Depending on the values of $\varepsilon$ and $h$, convection is the dominant mechanism at low temperatures (< 150°C – 200°C). Above 400°C, radiation becomes the more dominant mode of heat transfer (Drysdale, 2011c). If the heat flux coming from the fire is sufficient, it will cause the wall material to pyrolyze. The pyrolysis of a solid material is the endothermic degradation process in which the solid is transformed into a gas. This process is irreversible, meaning that once the gasses are formed, the solid material has decreased in mass and cannot be restored to its original form. The amount of heat needed for a solid material to pyrolyze is quantified as ‘heat of pyrolysis’ $\Delta Q_{pyr}$ similar to ‘heat of vaporization’ $L_v$ for liquid fuels and has the same unit J/kg. In contrast to $L_v$, the heat of pyrolysis is not a material property but a model parameter since it is a simplification of reality (Merci & Beji, 2017c).

Due to the buoyancy, the flames are aligned with and close to the virgin wall material as is shown on Figure 7. This causes the radiation to be more effective due to the high view factor. The specific configuration of the set-up also causes the hot combustion products to be in direct contact with the unburnt fuel, making the heat transfer by convection more effective as well. As discussed before, in a corner configuration the flame heights are elongated. Combined with the more effective heat transfer, this results in a faster flame spread. Flame spread is referred to as an “advancing ignition front” (Merci & Beji, 2017a) because the unburnt solid material releases combustible volatile - when it gets heated up to a certain ignition temperature - which start to burn once ignited by the flames. The flame spread is thus defined as the velocity at which the pyrolysis front moves. The amount of mass which starts to pyrolyze depends on the length of the pre-heat zone ($L_c$ in Figure 7) and on the in-depth thickness of the pre-heat zone. The vertical velocity at which the flames spread is not constant, but increases
exponentially due to the positive feedback loop (Merci & Beji, 2017a). Since the heat transfer increases with higher flame heights, more unburnt fuel is pre-heated. This increases the pyrolysis rate which in turn results in more fuel burnt, thus higher flame heights and more heat being transferred to unburnt fuel (Merci & Beji, 2017a). In addition to vertical flame spread, also lateral flame spread occurs but at a slower rate. This is due to the fact that the main mode of heat transfer in lateral flame spread is radiation from the flames (Merci & Beji, 2017a). Convection plays less of a role here (Merci & Beji, 2017a). In corner configurations, lateral flame spread is faster at the top of the corner than at the bottom due to the augmented effect of convection (Merci & Beji, 2017a).

With regards to the depth of the pre-heat zone through the thickness of the material, a distinction needs to be made between ‘thermally thin’ fuels and ‘thermally thick’ fuels. Thermally thin fuels are fuels in which the occurrence of a temperature gradient can be ignored (Drysdale, 2011c). Consequently, in thermally thick fuels the occurrence of a temperature gradient must be considered. To determine whether a solid material behaves as thermally thin or thermally thick, the Biot number is often used (Drysdale, 2011c).

\[
Bi = \frac{hL}{k} = \frac{L/k}{1/h} = \frac{\text{conductive resistance in the solid}}{\text{convective resistance in the fluid}}
\]

In general:

- Bi is less than approximately 0.1 : ‘thermally thin’ solid (Torero, 2008)
- Bi is bigger or not much less than 1 : ‘thermally thick’ solid (Torero, 2008)
- A transition region exists where ‘thermally thin’ and ‘thermally thick’ behavior overlaps (Lamorette & Candelier, 2015).

When the solid fuel is thermally thick, the heat is conducted through the solid ahead of the flame front. In case the fuel is thermally thin, then the heat is conducted through the gas phase. However, attention should be paid to thermally thick composite materials which have the potential to delaminate (Drysdale, 2011f). The fuel is initially thermally thick but due to the delamination process, the surface layer can detach and become thermally thin (Drysdale, 2011f). This detached layer is then more easily ignited and can increase the flame spread rate (Drysdale, 2011f).

1.2 Objectives

The impact of corner fires on the flame spread and fire development in an enclosure is substantial. This is mainly due to are more extended flame heights and higher flame temperatures than when the fire is located near a wall of in the center of the room as was illustrated previously in this chapter.
Subsequently, it is of interest for the fire safety community to accurately predict the fire growth behavior of corner fires using CFD models.

In the past, a number of corner fire studies have been conducted, often in the form of ISO Room Corner Tests (Zeinali et al., 2015; ISO 9703, 1993). In these previous experiments, parameters such as: the heat release rate (HRR), smoke layer temperatures, smoke production rate (SPR), surface temperatures, heat fluxes (e.g. onto the walls, onto the façade or onto the floor), flame spread (vertical, lateral and flame front), time to flashover, etc. were monitored (Zeinali et al., submitted March 2017a). However, the need for investigating a few other parameters which are of importance for assessing pyrolysis models predictions still exists (Zeinali et al., submitted March 2017a). An important parameter for characterizing the boundary conditions of the walls in corner fires are the backside wall temperatures (Zeinali et al., 2015). By monitoring these temperatures, heat losses from the backside of the walls can be quantified. It is also an important parameter when transitioning from small-scale Cone Calorimeter tests to intermediate or large scale tests (Hjolman & Andersson, 2008). Another parameter yet to be investigated is the evolution of through-thickness wall temperatures (Zeinali et al., 2015). As described in (Zeinali et al., submitted March 2017a), only surface temperatures have been measured in previous experiments. This type of measurement is known to incorporate errors due to for example radiation and convection exposure (Zeinali et al., 2015). Finally, another relevant subject to investigate is the symmetry of the temperature evolutions on the corner walls and the flame spread on the walls (Zeinali et al., submitted March 2017b).

In order to investigate these parameters described above and to supply data for assessing pyrolysis and CFD model predictions, a set of Single Burning Item (SBI) tests are conducted using Medium Density Fiberboard (MDF), plywood and calcium silicate panels. The SBI test is an intermediate-scale test used to classify the reaction to fire performance of construction products in Europe (EN 13823, 2002; van Mierlo & Sette, 2005). Other international standard test methods used to classify the reaction to fire performance of construction products are the small-scale Cone Calorimeter test described in ISO 5660 and the full-scale ISO 9705 Room Corner test (van Mierlo & Sette, 2005). This thesis will discuss the results of the SBI experiments, forming part of a larger experimental campaign for the study of corner fires.
Chapter 2  Experimental corner configuration

This chapter describes the type of tests which were conducted and characterizes the properties of the materials used in the experiments.

2.1  SBI test

2.1.1  Testing environment

The single burning item (SBI) test method has been developed by Technical Committee CEN/TC 127 to determine the reaction to fire of construction products excluding floorings when exposed to thermal attack by a single burning item (EN 13823, 2002). The test facility is composed of a test room which contains a trolley with a frame, burners and a hood, a smoke exhaust system and general measurement equipment. On the trolley, two test specimens can be installed perpendicular to each other. A triangular sandbox burner is placed at the bottom of the vertical corner. The fuel which is used in the experiments is commercial propane with a minimum purity of 95% (EN 13823, 2002). The trolley is positioned in a fixed frame which supports the hood that collects the combustion gasses. On this frame a secondary (auxiliary) burner is fixed. On top of the hood a collector is positioned with baffles and a horizontal outlet for the exhaust duct (EN 13823, 2002).

The test room has an inner height of 2.47 m and has horizontal dimensions of 3.01 m by 3.20 m (as shown on Figure 8). The trolley is entered into the testing room from the surrounding laboratory using the opening in one of the walls of the testing room with dimensions of at least 1.47 m wide and 2.45 m high (EN 13823, 2002). The testing specimens consist of two panels with different dimensions. On the one side, a long panel of (1.000 ± 0.005) m wide and (1.500 ± 0.005) m high is placed (EN 13823, 2002). Perpendicular to that panel, a short panel which is (0.495 ± 0.005) m wide and (1.500 ± 0.005) m high is positioned (EN 13823, 2002). The maximum allowed thickness of the specimens is 0.20 m (EN 13823, 2002). At the bottom of the trolley, air inlet is provided into the testing room through an opening with dimensions of 1.16 m by 0.32 m (Zeinali et al., 2015). In that opening perforated plates are placed (open area to total area is 40% to 60% and perforation holes of 8 mm to 12 mm diameter) in order to produce an evenly distributed flow along the floor of the testing room (EN 13823, 2002). The triangular burner, placed at the bottom corner of the panels, has two equal sides with a length of 0.25 m and a height of 0.05 m.
2.1.2 Principle

The principle of the test is that the testing specimens are exposed to the flames of the triangular propane burner with a heat output of (30.7 ± 2) kW (EN 13823, 2002). The behavior of the test products is monitored during a period of 20 minutes (EN 13823, 2002). This is done by monitoring the heat release rate (HRR), the smoke production rate (SPR), the lateral flame spread and the falling of flaming droplets and particles (EN 13823, 2002). The secondary (auxiliary) burner is used to measure the heat output and smoke development of only the burner by igniting this burner for a short period of time before igniting the primary burner (EN 13823, 2002). During the test the data acquisitioning system automatically records the following parameters every 3 seconds (EN 13823, 2002):

- time (seconds);
- mass flow rate of propane gas through the burner (milligrams per second);
- pressure difference at a bi-directional probe in the exhaust duct (pascals);
- relative light intensity in the exhaust duct (-);
- \(O_2\) concentration in the exhaust duct (in \(V_{O_2}/V_{air}\) %);
- \(CO_2\) concentration in the exhaust duct (in \(V_{CO_2}/V_{air}\) %);
- ambient air temperature at air inlet at the bottom of the trolley (kelvins);
- three temperatures in the exhaust duct (kelvins).

The quantities described above are used to calculate the volume flow, the heat release rate (HRR) and the smoke production rate (SPR), while the lateral flame spread and the falling of flaming droplets is monitored visually (EN 13823, 2002). The exhaust extracts a volume flow rate of 0.60 m\(^3\)/s at 298K on average (EN 13823, 2002).

Calculating the HRR is based on the oxygen depletion concept. It relies on the fact that the heat of combustion for most fuels is constant when expressed in terms of oxygen or air consumption. According to (Drysdale, 2011b), the heat of combustion per gram of oxygen consumed (\(\Delta H_{c,ox}\)) is approximately -12.72 ± 3% kJ/g for organic liquids and gasses and -13.02 ± 4% kJ/g for polymers (Drysdale, 2011b). Based on this principle, the HRR can be calculated if the oxygen consumption is known. The following equation is be used to determine the total HRR of the burner and the test specimen [kW] based on the amount of oxygen consumed (EN 13823, 2002):

\[
HRR_{total}(t) = E \cdot V_{298}(t) \cdot x_{a, O_2} \cdot \left( \frac{\phi(t)}{1 + 0.105 \phi(t)} \right) \tag{1}
\]

Where:
- \(E\): the heat release rate per unit volume of oxygen consumed at 298 K (17 200 kJ/m\(^3\))
- \(V_{298}(t)\): the volume flow of the exhaust system normalized at 298 K [m\(^3\)/s]
- \(x_{a, O_2}\): the ambient mole fraction of oxygen including water vapour [-]
- \(\phi(t)\): the oxygen depletion factor [-]

According to (Williamson & Dembsey, 1993), the oxygen depletion factor is defined as:

\[
\phi = \frac{\left[ (\text{molar flow rate of oxygen in air entering the control volume}) \right]}{\left[ (\text{molar flow rate of oxygen in the exhaust ducts}) \right]} \tag{2}
\]

The control volume mentioned in (2) is in the case of an SBI test, the testing environment. For more details about how the parameters used in formula (1) are calculated, the reader is referred to (EN 13823, 2002).
In order to obtain the smoke production rate, the concept of light attenuation is used (EN 13823, 2002). In the experiments, a light attenuation system of the white light type is connected to the side ducts of the exhaust duct (EN 13823, 2002). This system contains a lamp, a lens to align the light to a parallel beam and a detector (EN 13823, 2002). Using this system, a beam of light is passed through the smoke in the duct. If there is no smoke present in the duct, the beam of light maintains its intensity $I_0$ (EN 13823, 2002). However, if smoke is present in the duct, the intensity of the light beam reaching the detector will be reduced.

![Figure 9 – Schematic representation of the device used to measure the light attenuation (Drysdale, 2011e)](image)

The reduced intensity of the light beam, travelling a distance $L$ through the smoke, is given by the Lambert-Beer law (Drysdale, 2011e):

$$I = I_0 e^{-\kappa CL} \quad (2)$$

With:
- $I_0$: intensity of the light beam without smoke attenuation
- $\kappa$: the extinction coefficient [-]
- $C$: the mass concentration of smoke particles [%]
- $L$: the distance of the beam of light passing through the smoke [m]

The total smoke production rate of the test specimen and the burner [$m^2/s$] can be determined as (EN 13823, 2002):

$$SPR_{total}(t) = \frac{V(t)}{L} \ln \left[ \frac{I(30s \ldots 90s)}{I(t)} \right] \quad (3)$$

Where:
- $V(t)$: the non-normalized volume flow in the exhaust duct [$m^3/s$]
- $L$: the length of the beam of light through the duct taken as the duct diameter [m]
- $I(t)$: the signal from the light receiver [%]
2.2 Material properties of MDF, Plywood and Calcium Silicate panels

In this section, the material properties of the panels used in the SBI experiments is given as well as how they were obtained. A short illustration of how the panels are manufactured is also provided here.

2.2.1 Introduction

The materials which are used to investigate the flame spread in corner configuration using SBI tests are Medium Density Fiberboard (MDF) panels, plywood and inert calcium silicate panels. MDF and plywood are both engineered wood products. This means that both products are man-made wood products specifically engineered for the desired mechanical properties by binding wood fibers with a wax/resin under high temperature and pressure.

MDF is made from lignocellulosic fibers which are bonded together with a synthetic resin under high temperature and pressure into a homogeneous board (Ye et al., 2007). The fibers are usually a combination of sawmill residues and chips obtained from roundwood (Moore & Cown, 2015). The most common resins used for manufacturing MDF panels are urea-formaldehyde, phenolic resins, melamine resins and isocyanates (AP-42, 1995b). The density of MDF panels typically lies between 500 kg/m³ and 1000 kg/m³ (ANSI A208.2, 2002).

In contrast to MDF that is made from wood fibers, plywood is made from multiple thin layers of wood veneer known as ‘ply’ which are glued together, hence the name plywood. The thin layers of wood are obtained by peeling or slicing wood logs (Moore & Cown, 2015). The resins most commonly used to glue the veneer layers are urea-formaldehyde and phenol-formaldehyde as are also used in the manufacturing process of MDF (AP-42, 1995a). In the manufacturing process, each successive layer is rotated 90° with respect to the previous layer, so that the wood grain of the successive layers is...
perpendicular (AP-42, 1995a). Due to the manufacturing process, the composition of the plywood panels is not homogeneous (AP-42, 1995a).

![Sample of plywood panel using in the experiments](image)

**Figure 11 – Sample of plywood panel using in the experiments**

Inert calcium silicate boards used to be made by dewatering a slurry of asbestos-fibers and a calcium silicate matrix (Harper, 1982). Due to the health hazard associated with asbestos, cellulosic fibers are nowadays used to manufacture calcium silicate panels (Harper, 1982). In the manufacturing process, the boards are cured in autoclaves under saturated steam conditions with pressures up to 1.4 MPa and temperatures up to 200°C (Harper, 1982). The calcium silicate matrix is obtained by autoclaving Portland cement with silica flour (Harper, 1982). By using a calcium silicate matrix as a hydraulic binder for the cellulosic fibers, a higher strength to weight ratio is obtained, better stability to moisture and better thermal stability, particularly at temperatures between 750°C and 1000°C (Harper, 1982). The type of calcium silicate boards intended for fire resistant applications usually contain less than 5% and high levels of mineral fillers such as vermiculite (Harper, 1982).

### 2.2.2 Experiments

The pyrolysis properties of the MDF and plywood panels used in the experiments, described in (Agarwal et al., 2016), were obtained experimentally by FM Global. More specifically, the material properties for pyrolysis of these panels were obtained by inverse modeling using FireFOAM pyrolysis code to correspond to the experimental data (Agarwal et al., 2016). It should be noted that the properties obtained in this manner are “model-effective” and are sensitive to both the accuracy of the experimental data as well as the physical processes included in the model (Chaos et al., 2011). In addition to the properties obtained in (Agarwal et al., 2016), the nominal bulk density of the MDF panels used in the experiments was determined by the authors of (Zeinali et al., submitted March 2017a) and the nominal moisture content is obtained by the supplier of the MDF panels (Zeinali et al., submitted March 2017a).

The experimental pyrolysis data from the panels was obtained by performing Fire Propagation Apparatus (FPA) pyrolysis tests in which test samples are exposed to transient heater irradiation. The
tests were conducted in a controlled nitrogen atmosphere at multiple heat fluxes (25, 50 and 100 kW/m²). During the tests, the sample mass loss, surface temperature and sample back-side temperature were measured (Agarwal et al., 2016). In order to measure these parameters, the insulated sample – illustrated on Figure 13 – was placed on the load cell of the FPA, shown on Figure 12. This load cell continuously records the weight of the sample during the pyrolysis process. While the heaters stabilize at the specific heat flux setting, the sample is shielded from exposure by water-cooled shields. The quartz tube shown in Figure 12 is used to shield the sample and the pyrolysis gasses from room air entrainment. The downstream instrumentation is used to analyze the pyrolysis products and determine the smoke generation, the CO, CO₂ and unburned hydrocarbon yields. The surface temperature is measured using an infrared pyrometer (Chaos et al., 2011). In order to measure the backside temperature, an unsheathed wireless thermocouple was attached to the back-side of the sample, enclosed with aluminum tape while keeping the front surface exposed (Agarwal et al., 2016). The experimental data is obtained by taking the average of three experiments conducted for each heat flux (Agarwal et al., 2016).

**Figure 12 – Schematic of the Fire Propagation Apparatus (Chaos et al., 2011)**

**Figure 13 – Schematic of the insulated sample holder for pyrolysis experiments (Agarwal et al., 2016)**
2.2.3 Inverse numerical modelling

The model-specific material properties of the panels have been obtained by optimizing the numerical results, corresponding with the experimental results. In this approach, it has been assumed that only three forms of the material exist: virgin material, char and pyrolysis gas. Therefore, a single heterogeneous \( n \)-th-order Arrhenius-type reaction is assumed in which the virgin solid material decomposes to char and/or gas (Chaos et al., 2011). A 1-D pyrolysis model is used consistent with the pyrolysis code of FireFOAM 2.2.x. In order to optimize the pyrolysis model results, a Shuffled Complex Evolution (SCE) approach has been used due to its high accuracy, efficiency and robustness (Agarwal et al., 2016). For more detailed information about this approach, the reader is referred to [10,17].

In addition to what is described above, the effective material emissivity and absorptivity have been determined during the experiments with the use of spectrophotometers. These were determined because the pyrolysis model requires these parameters to accurately represent the heat transfer boundary conditions at the sample surface. The values of the effective emissivity and absorptivity refer to the net integrated fraction of radiation a material absorbs (when the radiation source/heater has a \( T_{\text{source}} \)) or emits (when its surface is at a temperature equal to \( T_{\text{sample}} \)). These values are calculated as per the following equations (Agarwal et al., 2016):

\[
\alpha_{\text{eff}}(T_{\text{source}}) = \frac{\int \alpha(\lambda) I(\lambda, T_{\text{source}}) d\lambda}{\int I(\lambda, T_{\text{source}}) d\lambda} \quad (18)
\]

\[
\varepsilon_{\text{eff}}(T_{\text{sample}}) = \frac{\int \varepsilon(\lambda) I(\lambda, T_{\text{sample}}) d\lambda}{\int I(\lambda, T_{\text{sample}}) d\lambda} \quad (19)
\]

In these formulations, \( I(\lambda, T) \) is the spectral radiance based on either the radiation source temperature \( T_{\text{source}} \) or on the sample surface temperature \( T_{\text{sample}} \). It has to be noted that for char, it is found that the effective emissivity and absorptivity are relatively independent of temperature over a wide range (300K – 3000K) (Agarwal et al., 2016). Therefore, only the average value is given in Table 1. From this table it can be seen that for the MDF panels, two sets of material properties is given, namely assuming the panel density to be either uniform or non-uniform. The reason for this is that authors of (Agarwal et al., 2016) have established that the density distribution through the thickness of the MDF panels is in fact parabolic by nature, with the density being the highest near the surface of the panels.
**Figure 14** – Illustration of the non-uniform density. The thickness of the surface material with a higher density amounts to 2.27 mm.

**Table 1** – Material properties for the panels used in the SBI tests, as determined in (Agarwal et al., 2016). The calcium silicate material properties were obtained from the source supplier.

<table>
<thead>
<tr>
<th></th>
<th>MDF (Uniform density)</th>
<th>MDF (Non-uniform density)</th>
<th>Plywood</th>
<th>Calcium Silicate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness [m]</td>
<td>0.0182 ± 1%</td>
<td>0.018 ± 1%</td>
<td>0.0169 ± 1%</td>
<td>0.0123 ± 0.001</td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td>605a</td>
<td>ρ_V(x)b</td>
<td>560</td>
<td>1005 ± 5%</td>
</tr>
<tr>
<td>Moisture content [%]</td>
<td>6 – 10c</td>
<td>6 – 10c</td>
<td>10.2c</td>
<td>5 – 10c</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.18</td>
<td>0.18</td>
<td>0.12</td>
<td>0.17d</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>1580</td>
<td>1576</td>
<td>1330</td>
<td></td>
</tr>
<tr>
<td>Emissivity [-]</td>
<td>ε(T_MDF)g</td>
<td>ε(T_MDF)g</td>
<td>ε(T_Plywood)h</td>
<td></td>
</tr>
<tr>
<td>Absorptivity [-]</td>
<td>α(T_source)l</td>
<td>α(T_source)l</td>
<td>α(T_source)l</td>
<td></td>
</tr>
<tr>
<td>Pyrolysis reaction</td>
<td>Virgin material → Char + Pyrolysate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat of pyrolysis [J/kg]</td>
<td>1.05 × 10⁵k</td>
<td>−1.02 × 10⁵k</td>
<td>−2.15 × 10⁵k</td>
<td></td>
</tr>
<tr>
<td>Net (lower) heating value [J/kg]</td>
<td>18.2 × 10⁶l</td>
<td>18.2 × 10⁶l</td>
<td>19.61 × 10⁶l</td>
<td></td>
</tr>
<tr>
<td>Effective heat of combustion [J/kg]</td>
<td>9.54 × 10⁶m</td>
<td>9.54 × 10⁶m</td>
<td>10.20 × 10⁶m</td>
<td></td>
</tr>
<tr>
<td>Reaction order [-]</td>
<td>0.66</td>
<td>1.04</td>
<td>2.94</td>
<td></td>
</tr>
<tr>
<td>Activation energy [J/mol]</td>
<td>7.19 × 10⁴n</td>
<td>8.02 × 10⁴n</td>
<td>8.01 × 10⁴n</td>
<td></td>
</tr>
<tr>
<td>Pre-exponential factor [s⁻¹]</td>
<td>1.47 × 10⁴n</td>
<td>9.03 × 10⁴n</td>
<td>6.30 × 10⁴n</td>
<td></td>
</tr>
<tr>
<td>Char emissivity [-]</td>
<td>0.86i</td>
<td>0.86i</td>
<td>0.85i</td>
<td></td>
</tr>
<tr>
<td>Char absorptivity [-]</td>
<td>0.86i</td>
<td>0.86i</td>
<td>0.85i</td>
<td></td>
</tr>
<tr>
<td>Char thermal conductivity [W/(m.K)]</td>
<td>0.21</td>
<td>0.18</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>Char specific heat capacity [J/(kg.K)]</td>
<td>1450°</td>
<td>1450°</td>
<td>1450°</td>
<td></td>
</tr>
<tr>
<td>Char density [kg/m³]</td>
<td>125</td>
<td>142</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>Char fraction by mass [-]</td>
<td>0.21</td>
<td>0.24</td>
<td>0.15</td>
<td></td>
</tr>
</tbody>
</table>
The nominal bulk density of the MDF panels is 585 ± 5%. The value of 605 kg/m³ was settled on as a representative value during the process of material properties estimation. The bulk density for the non-uniform density set is the same as for the uniform density set. (Agarwal et al., 2016)

\[ \rho_v(x) = ax^2 + bx + c \] with \( a = 3.62 \times 10^6 \text{ kg/m}^5, b = 0.21 \text{ kg/m}^4, c = 502.8 \text{ kg/m}^3 \)

where \( \rho_v(x) \) is the virgin material density profile through the panel’s thickness in kg/m³, with \( x \) denoting the distance from the center in meters (ranging from -0.0092 to 0.0092 m). (Agarwal et al., 2016)

The nominal value at 293K, available from the technical specification sheet from the material supplier.

The nominal value of thermal conductivity is 0.17, 0.19 and 0.21 W/(m.K) at temperatures of 293K, 373K and 473K respectively (available from the technical specification sheet from the material supplier).

The nominal value at 673K, available from the technical specification sheet from the material supplier.

Obtained in reference (Agarwal et al., 2016) for the MDF and plywood samples used in the SBI experiments.

\[ \epsilon(T_{MDF}) = aT_{MDF}^6 + bT_{MDF}^5 + cT_{MDF}^4 + dT_{MDF}^3 + eT_{MDF}^2 + fT_{MDF} + g, \] where \( a = 7.17\times10^{-21}, b = -7.90\times10^{-17}, c = 3.23\times10^{-13}, d = -5.65\times10^{-10}, e = 3.26\times10^{-7}, f = -1.28\times10^{-4}, g = 9.34\times10^{-1} \) (Agarwal et al., 2016)

\[ \epsilon(T_{Plywood}) = aT_{Plywood}^6 + bT_{Plywood}^5 + cT_{Plywood}^4 + dT_{Plywood}^3 + eT_{Plywood}^2 + fT_{Plywood} + g, \] where \( a = 6.65\times10^{-21}, b = -7.57\times10^{-17}, c = 3.22\times10^{-13}, d = -5.98\times10^{-10}, e = 3.85\times10^{-7}, f = -1.49\times10^{-4}, g = 9.44\times10^{-1} \) (Agarwal et al., 2016)

\[ \alpha(T_{source}) = aT_{source}^6 + bT_{source}^5 + cT_{source}^4 + dT_{source}^3 + eT_{source}^2 + fT_{source} + g, \] where \( a = 7.17\times10^{-21}, b = -7.90\times10^{-17}, c = 3.23\times10^{-13}, d = -5.65\times10^{-10}, e = 3.26\times10^{-7}, f = -1.28\times10^{-4}, g = 9.34\times10^{-1} \) (Agarwal et al., 2016)

\[ \alpha(T_{source}) = aT_{source}^6 + bT_{source}^5 + cT_{source}^4 + dT_{source}^3 + eT_{source}^2 + fT_{source} + g, \] where \( a = 6.65\times10^{-21}, b = -7.57\times10^{-17}, c = 3.22\times10^{-13}, d = -5.98\times10^{-10}, e = 3.85\times10^{-7}, f = -1.49\times10^{-4}, g = 9.44\times10^{-1} \) (Agarwal et al., 2016)

A positive sign denotes an endothermic reaction, whilst a negative sign denotes an exothermic reaction.(Agarwal et al., 2016)

Determined via bomb calorimetry of the sample MDF and plywood material used in the SBI tests by the authors of (Agarwal et al., 2016).

Determined via a combustion test performed on the sample MDF material in the FPA at 50 kW/m² by the authors of (Agarwal et al., 2016). As the final char fraction was 18%, this effective heat of combustion must mainly be attributed to the pyrolysate.

Reaction kinetic parameter in the Arrhenius equation. (Laidler, 1987)

Taken as the specific heat capacity of carbon graphite. (Chaos, 2014)
Chapter 3 Experimental set-up

This chapter discusses the set-up of the experiments conducted as part of this thesis. This includes discussing similarities and differences between the experiments conducted and standard SBI tests as discussed in section 2.1. It also includes specifics on the preparation of the experiments as well as how long it takes to prepare for one experiment.

3.1 General

In the experiments, two panels of different dimensions are placed vertically in the SBI trolley perpendicular to each other to form a corner configuration. The long panel has a width of 1.00 m and a height of 1.50 m, whereas the short panel has a width of 0.50 m and a height of 1.50 m. The thickness and properties of the panels used in the experiments have been discussed in section 2.2. Different arrangements of the panels are considered when testing the three panel types used in the experiments (MDF, plywood and calcium silicate). Accordingly, the performed experiments include tests in which both panels are of the same material type, and tests in which one panel is calcium silicate while the other one is either MDF or plywood. In the latter case, two tests are performed, namely one where the calcium silicate panel serves as the short panel, and one where one where it serve as the long panel. Prior to the experiments, the panels have been conditioned at 21°C and 50% humidity as to reduce the variability of the initial conditions (Zeinali et al., 2015; Zeinali et al., submitted March 2017a).

To represent the corner fire source, a triangular propane sandstone burner with a standard HRR of 30 kW is placed in the bottom corner with a 4 cm clearance from the panels (Zeinali et al., 2015). The peak HRR is attained in less than 30 s after the ignition of the burner (Zeinali et al., submitted March 2017a). In one of the tests performed during the writing of this thesis, the HRR delivered by the burner is reduced to 10 kW, which was attained 10 to 15 s after ignition. In another test, the HRR delivered by the burner was increased to 50 kW, which was attained about 60 s after ignition. The sides of the burner, parallel to the panels have a length of 25 cm (Zeinali et al., 2015; Zeinali et al., submitted March 2017a). In addition to this burner, a second identical, auxiliary burner is fixed on the frame in which the trolley is positioned in order to measure the heat output and the smoke development of the burner only (without the possible contribution of the panels) (EN 13823, 2002).

The lay-out and dimensions of the SBI testing environment are the same as discussed in section 2.1. However it has to be noted, that there is a 30 cm wide gap of air between the long panel and the frame (in which the trolley is placed) and a 28 cm wide gap of air between the short panel and the frame (Zeinali et al., 2015; Zeinali et al., submitted March 2017a). The bottom sides of the trolley are also covered with perforated steel plates (50% open area), to produce a more uniform air flow. This set-up can also be seen on Figure 15.
Figure 15 – The geometry of the SBI enclosure used in the experiments (units in m) (Zeinali et al., 2015; Zeinali et al., submitted March 2017a)

As can be seen on Figure 15 and as was described in section 2.1, the combustion gasses are collected by a hood placed above the frame enclosing the trolley. A duct is connected to this hood, equipped to obtain certain parameters described in the previous chapter. The volume flow of the exhaust is set to 0.60 Nm³/s (normal cubic meter per second at 298 K) (Zeinali et al., 2015; Zeinali et al., submitted March 2017a) The main parameters which are of interest are the HRR and the SPR. These parameters are calculated using the oxygen depletion and the smoke obscuration concept respectively (Zeinali et al., 2015; Zeinali et al., submitted March 2017a).

In addition to these parameters, the evolution of the panel temperatures is monitored by attaching a total of 110 thermocouples (K-type), both at the backside of the panels and through the thickness of the panels. The latter is made possible by fixing the thermocouples in holes drilled from the backside of the panels with a ±0.1 mm accuracy (Zeinali et al., 2015). The fixing of the thermocouples inside the holes is done using thermal adhesive 940 HT-1 from Polytec PT. The conductivity of this paste
(2.1 W/(m.K)) is over 40 times the conductivity of air at 400°C and over 10 times that of the panels (Zeinali et al., 2015). Since the paste does not decompose at high temperatures and is electrically nonconductive, it is assumed that fixing the thermocouples in this manner will not interfere with the functioning of the thermocouples (Zeinali et al., 2015). To ensure that the measurements are made precisely at the desired depth, the wires of the thermocouples are welded forming a bead at its end. The size of the bead is approximately 1.5 mm (Zeinali et al., 2015; Zeinali et al., submitted March 2017a).

As shown on Figure 16, the through-thickness measurements are made at different depths at the same position. In order to do so, multiple holes are drilled with sufficient spacing such that the influence from neighboring measurements is reduced and contact between the beads and the panels is better (Zeinali et al., submitted March 2017a). According to initial experiments conducted by the authors of (Zeinali et al., submitted March 2017a), the holes can have a lateral spacing of 1 cm with respect to the position shown on Figure 16 without it having a substantial impact on the temperature measurements.

Figure 16 also shows that the through-thickness measurements are made at different depths for the calcium silicate panels compared to the MDF or plywood panels. In the case of MDF or plywood panels, measurements are made at 2 mm and 12 mm from the front surface whilst in the case of calcium silicate panels the measurements are made at 1 mm and 6 mm from the front surface instead.
This is due to the fact that the surface fiber material of MDF delaminates whilst pyrolyzing, causing the thermocouples to become exposed at some point during the experiment (Zeinali et al., submitted March 2017b). As the char layer which is formed during the test oxidizes and shrinks as well, locally, the thermocouples become exposed to flames and possibly blocked by the delaminated fiber material (Zeinali et al., submitted March 2017b).

![Diagram of heat flux measurements on panels](image)

*Figure 17 – Positions of the heat flux measurements on the panels (Zeinali et al., 2015; Zeinali et al., submitted March 2017a)*

Heat flux measurements are made using water-cooled Schmidt-Boelter heat flux sensors (working range up to 75 kW/m²) at three locations on the long panel as shown on Figure 17 (Zeinali et al., 2015; Zeinali et al., submitted March 2017a). The positions of these measurements correspond to the thermal attack calibration points described in Annex D.2 of EN 13823 (EN 13823, 2002). The water used for the cooling of the heat flux sensors is maintained at 50°C during the experiments to prevent the condensation of water vapor produced by the burner onto the sensors (Zeinali et al., 2015; Zeinali et al., submitted March 2017a). The surface of the heat flux sensors is positioned in the same plane as the surface of the long panel, in such a manner that the transition from one surface to the other occurs smoothly (Zeinali et al., 2015; Zeinali et al., submitted March 2017a).

Finally, two cameras – pointed in different directions – are used to monitor the flame spread during the experiments. One camera faces the short panel and the other one faces the long panel (Zeinali et al., 2015; Zeinali et al., submitted March 2017a; Zeinali et al., submitted March 2017b).

### 3.2 Preparation details

Before the actual experiments can be conducted, some preparation work must be done. As described earlier, the HRR, SPR, flame spread, heat fluxes and panel temperatures are monitored during the
experiments. Since the HRR and SPR are automatically monitored upon collection of the combustion gasses, their quantification requires no special prior measures. However, being able to monitor the remaining parameters requires some extra efforts.

3.2.1 Initial test

To be able to monitor the panel temperatures, thermocouples need to be attached to the panels. In order to do so, the wires need to be cut to the right length first. In total 110 thermocouples are used in the experiments which are cut to a length of approximately 5 m each. Afterwards the protective coat of the thermocouples is stripped at both ends of the wire over 1 to 1.5 cm, uncovering two separate wires of which the protective layer is also removed. At one end of the thermocouple, the two bare wires are welded together to form a bead with a diameter of approximately 1.5 mm. This enables monitoring the temperatures at a distinct depth through the thickness of the panels. At the other end, the two bare wires are connected to a socket, which will be used to connect the thermocouples to databoxes collecting the panel temperatures. Once this is done, the wires are insulated for protection against exposure to high temperatures during the experiments since the wires are recuperated and re-used for each experiment. Finally, a voltmeter is used to label and check the functioning of the thermocouples.

![Figure 18 – The thermocouple wire](image1.png)  
![Figure 19 – The sockets used to attach the thermocouples to the databoxes](image2.png)

The next step in the preparation process is to cut the panels to the right size and drill holes, for attaching the thermocouples and heat flux sensors, to the right depth. For the MDF and plywood panels, holes with a diameter of 3.24 mm are drilled in such a way so that the distance between the hole and the exposed surface is 2 mm or 12 mm, depending on the desired measurement at a particular position on the panel (see Figure 16). For the calcium silicate panels, holes are drilled up until 1 mm and 6 mm from the exposed surface. In the long panel, holes with a diameter of 25.4 mm are made so that the heat flux sensors can be positioned in the panel.
Now the thermocouples can be attached to the panels. This is done by first stapling the thermocouples to the panel and later fixing the beads both in the holes and to the panels using the thermal adhesive.

The final step in preparing for the first experiment is to attach the heat flux sensors to the long panel. Since the thickness of the heat flux sensors is longer than the thickness of the panels, a calcium silicate template is made to be able to set the surface of the heat flux sensors flush with the surface of the long panel. Once all of the preparations are complete, the panels, with the thermocouples and heat flux sensors attached, are put in the conditioning room until the day of the experiment. The minimum amount of time the panels spend in the conditioning room after they are prepared and before performing the test is 2 days. In total, the panels will have been placed in the conditioning room for minimum 2 weeks before performing the test. The amount of time spent on performing the preparation tasks described above can be found in Table 2.

![Figure 20 – Stapling and gluing the thermocouples to the panels. The thermocouples are protected from thermal attack by separating them from the panels with glasswool insulation. However, the amount of insulation used is limited so that the boundary conditions at the back of the panels are not altered.](image1)

![Figure 21 – The thermocouples attached to the short panel](image2)
### Table 2 – Time schedule of the preparation tasks

<table>
<thead>
<tr>
<th>Task</th>
<th>Time spent on performing the task</th>
<th>No. of people performing the task</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting the thermocouples to the right size</td>
<td>6 hours</td>
<td>2</td>
</tr>
<tr>
<td>Attaching the thermocouples to the sockets</td>
<td>7 hours</td>
<td>2</td>
</tr>
<tr>
<td>Welding the beads</td>
<td>4 hours</td>
<td>1</td>
</tr>
<tr>
<td>Checking the functioning of the thermocouples</td>
<td>3 hours</td>
<td>2</td>
</tr>
<tr>
<td>Insulating the thermocouples</td>
<td>7 – 8 hours</td>
<td>2</td>
</tr>
<tr>
<td>Labeling the thermocouples</td>
<td>5 hours</td>
<td>2</td>
</tr>
<tr>
<td>Drilling the holes in the panels</td>
<td>2 hours</td>
<td>1</td>
</tr>
<tr>
<td>Attaching the thermocouples to the panels</td>
<td>5 – 6 hours</td>
<td>1</td>
</tr>
<tr>
<td>Insulating the heat flux meters</td>
<td>3 – 4 hours</td>
<td>1</td>
</tr>
<tr>
<td>Attaching the heat flux meters to the panels</td>
<td>1 hour</td>
<td>1</td>
</tr>
</tbody>
</table>

### 3.2.2 Other tests

The preparation work for the tests following the first tests is less extensive and takes between 14 to 16 hours. The following actions usually do not have to be repeated for the other tests:

- Cutting the thermocouples to the right length;
- Attaching the sockets to the thermocouples;
- Welding the beads;
- Labelling the thermocouples;
- Insulating the thermocouples.

However, it has to be noted that if the thermocouples are damaged during the test, they may have to be re-welded, re-labelled or re-insulated. If any of the previous mentioned actions is required, this will result in at least an extra 8 hours of preparation time before the test.

Since each test requires new panels, the drilling of the panels and attaching of the thermocouples needs to be repeated. Before attaching the thermocouples to the panels, the functioning is checked using a voltmeter. The heat flux meters also need to be cleaned before attaching them to the new panels, due to the soot deposition on the surface during the test.
Schmidt-Boelter heat flux sensors measure a temperature difference across a thin insulating material (Bundy et al., 2007). A voltage is then generated from the small temperature difference using a thermopile (Bundy et al., 2007). The calibration constant is used to transform the signal generated by the heat flux sensors from mV to kW/m². This constant is calculated using linear regression to fit to the sensor’s output signal for different known values of incident heat flux (Zeinali et al., submitted March 2017b). After performing a test, the calibration constant of the heat flux meters might have changed. As reported in (Bundy et al., 2007), the calibration constant is one of the main sources of uncertainty related to heat flux measurements. Therefore, in order to maintain a high level of accuracy for the future heat flux measurements, the heat flux meters have to be re-calibrated after performing a test.

### 3.2.3 Setting up the experiment

On the day of the SBI test, a few tasks need to be performed prior to the starting of the test:

- The panels are positioned in the SBI trolley;
- The thermocouples are attached to the databoxes;
- The heat flux meters are attached to the voltmeters;
- The water for the cooling of the heat flux meters is heated to 50°C;
- The plastic tubes which contain the water for cooling the heat flux meters are attached;
- The databoxes are attached to acquisitioning system which records the temperatures from each thermocouple;
- The two cameras facing the panels are installed in the testing room;
- The gas supply is attached to the SBI frame containing the two burners.

The amount of time spent on performing the tasks described above for two people is approximately 2 to 3 hours.
Figure 22 – Positioning the panels in the SBI trolley

Figure 23 – Attaching the thermocouples to the databoxes
Chapter 4  Results and discussion

As discussed in chapter 1, the experiments discussed in this thesis are part of a larger experimental campaign which aims to characterize the behavior of corner fires and provide data for the evaluation of fire modelling codes. In this campaign, a total of 19 SBI tests are to be performed. Table 3 gives an oversight of all the tests in this experimental campaign and indicates which tests were performed in the timeframe in which this thesis was written.

Table 3 – Tests comprised in the experimental campaign and thesis

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Test name</th>
<th>HRR [kW]</th>
<th>Long panel material</th>
<th>Short panel material</th>
<th>Performed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CSCS</td>
<td>30</td>
<td>Calcium Silicate</td>
<td>Calcium Silicate</td>
<td>Before thesis*</td>
</tr>
<tr>
<td>2</td>
<td>CSCS10</td>
<td>10</td>
<td>Calcium Silicate</td>
<td>Calcium Silicate</td>
<td>During thesis</td>
</tr>
<tr>
<td>3</td>
<td>CSCS50</td>
<td>50</td>
<td>Calcium Silicate</td>
<td>Calcium Silicate</td>
<td>During thesis</td>
</tr>
<tr>
<td>4</td>
<td>MM1</td>
<td>30</td>
<td>MDF</td>
<td>MDF</td>
<td>Before thesis*</td>
</tr>
<tr>
<td>5</td>
<td>MM2</td>
<td>30</td>
<td>MDF</td>
<td>MDF</td>
<td>Before thesis*</td>
</tr>
<tr>
<td>6</td>
<td>MM3</td>
<td>30</td>
<td>MDF</td>
<td>MDF</td>
<td>Before thesis*</td>
</tr>
<tr>
<td>7</td>
<td>MM10</td>
<td>10</td>
<td>MDF</td>
<td>MDF</td>
<td>Not yet</td>
</tr>
<tr>
<td>8</td>
<td>MM50</td>
<td>50</td>
<td>MDF</td>
<td>MDF</td>
<td>Not yet</td>
</tr>
<tr>
<td>9</td>
<td>MCS1</td>
<td>30</td>
<td>MDF</td>
<td>Calcium Silicate</td>
<td>During thesis</td>
</tr>
<tr>
<td>10</td>
<td>MCS2</td>
<td>30</td>
<td>MDF</td>
<td>Calcium Silicate</td>
<td>During thesis</td>
</tr>
<tr>
<td>11</td>
<td>CSM1</td>
<td>30</td>
<td>Calcium Silicate</td>
<td>MDF</td>
<td>During thesis</td>
</tr>
<tr>
<td>12</td>
<td>PP1</td>
<td>30</td>
<td>Plywood</td>
<td>Plywood</td>
<td>During thesis</td>
</tr>
<tr>
<td>13</td>
<td>PP2</td>
<td>30</td>
<td>Plywood</td>
<td>Plywood</td>
<td>Not yet</td>
</tr>
<tr>
<td>14</td>
<td>PP3</td>
<td>30</td>
<td>Plywood</td>
<td>Plywood</td>
<td>Not yet</td>
</tr>
<tr>
<td>15</td>
<td>PP10</td>
<td>10</td>
<td>Plywood</td>
<td>Plywood</td>
<td>Not yet</td>
</tr>
<tr>
<td>16</td>
<td>PP50</td>
<td>50</td>
<td>Plywood</td>
<td>Plywood</td>
<td>Not yet</td>
</tr>
<tr>
<td>17</td>
<td>PCS1</td>
<td>30</td>
<td>Plywood</td>
<td>Calcium Silicate</td>
<td>During thesis</td>
</tr>
<tr>
<td>18</td>
<td>PCS2</td>
<td>30</td>
<td>Plywood</td>
<td>Calcium Silicate</td>
<td>Not yet</td>
</tr>
<tr>
<td>19</td>
<td>CSP1</td>
<td>30</td>
<td>Calcium Silicate</td>
<td>Plywood</td>
<td>During thesis</td>
</tr>
</tbody>
</table>

*Test conducted before and not as part of this thesis.
The names of the tests are composed of letters and numbers having a specific meaning. The name of the long panel material makes up the first letter(s) and short panel material used in that particular test. The calcium silicate panels are denoted with the letters CS, the plywood panels with the letter P and the MDF panels with the letter M. The order in which the letters are placed is also not random. The first letters or letter refers to the long panel material and the name of the short panel material makes up the second half. When a test is indicated with the number 1, 2 or 3 it is because a standard HRR of 30 kW is used and multiple identical tests are (to be) performed. This means that 1 refers to the first test of this type performed, 2 to the second of that same type of test and so on. If, however, the letter portion is followed by the number 10 or 50, it means that a HRR different from 30 kW is used and the number refers to the alternative HRR used in the test. Thus, CSCS 50 refers to a test where both panels are calcium silicate panels and the HRR in the test is 50 kW.

As can be seen in Table 3, only 8 of the 19 tests were performed during the timespan of this thesis in total. Four tests had already been conducted prior to this thesis and the results of those tests are described in (Zeinali et al., 2015; Zeinali et al., submitted March 2017a; Zeinali et al., submitted March 2017b). Thus, seven tests still remain to be conducted in the future.

As described in chapter 3 and in (Zeinali et al., 2015; Zeinali et al., submitted March 2017a; Zeinali et al., submitted March 2017b), the parameters which were monitored during the tests are the HRR, the SPR, the flame spread, the through-thickness and backside panel temperatures and the heat fluxes. This chapter will discuss the results of tests 2, 3, 9 to 12, 17 and 19 in a similar manner as was done in (Zeinali et al., 2015; Zeinali et al., submitted March 2017a; Zeinali et al., submitted March 2017b). The results of the tests discussed in this chapter will also be compared to the results found in (Zeinali et al., 2015; Zeinali et al., submitted March 2017a; Zeinali et al., submitted March 2017b), where it is deemed needed.

4.1 Total Heat Release Rate (HRR) and Smoke Production Rate (SPR)

In this section, an oversight of the HRR evolution and SPR evolution during the different tests performed will be given and discussed. Note that the HRR and SPR discussed here are the total HRR and SPR, i.e. including the HRR and SPR produced by both the burner and the panels.

4.1.1 MDF tests

On Figure 24, the HRR evolution is shown for the MDF tests MCS1, MCS2, CSM1 and MM3. The first 60 s of the tests, the HRR has the same evolution in all four tests similar to test CSCS shown on Figure 32 (section 4.1.3). After that first minute, the HRR increases rapidly until it reaches a peak HRR around 90 s. As was explained in (Zeinali et al., 2015; Zeinali et al., submitted March 2017b), this fast increase in HRR is caused by rapid pyrolysis of the surface fiber material directly above the burner. Since tests MCS1, MCS2 and CSM1 are all composed of only one MDF panel, it is to be
expected that the HRR is lower than for test MM3 due to less combustible material being available for pyrolysis in those tests.

Table 4 – HRR values at characteristic times for the MDF tests performed

<table>
<thead>
<tr>
<th>Test</th>
<th>Test MSC1</th>
<th>Test MSC2</th>
<th>Test CSM1</th>
</tr>
</thead>
<tbody>
<tr>
<td>First peak HRR</td>
<td>68 kW @ t = 87 s</td>
<td>65 kW @ t = 96 s</td>
<td>52 kW @ t = 90 s</td>
</tr>
<tr>
<td>Second peak HRR</td>
<td>80 kW @ t = 180 s</td>
<td>72 kW @ t = 174 s</td>
<td>75 kW @ t = 225 s</td>
</tr>
<tr>
<td>Midway HRR</td>
<td>50 kW @ t = 600 s</td>
<td>53 kW @ t = 600 s</td>
<td>46 kW @ t = 600 s</td>
</tr>
<tr>
<td>Final HRR</td>
<td>45 kW @ t = 1200 s</td>
<td>46 kW @ t = 1200 s</td>
<td>43 kW @ t = 1200 s</td>
</tr>
</tbody>
</table>

For the tests in which the long panel is composed of MDF (test MM3, MCS1 and MCS2), it can be seen that the first peak in the HRR occurs at almost the same time, namely at $t = 87$ s in tests MM3 and MCS1 (as high as 123 kW versus 68 kW), and at $t = 93$ s in test MCS2 (as high as 65 kW). Afterwards, the HRR drops but peaks again at 156 s for test MM3 (158 kW). For tests the other tests, the HRR reaches a maximum value after the initial peak at around 180 s for tests MCS1 and MCS2. The decay after the first peak is caused by a char layer which is formed upon pyrolysis. This layer reduces the heat transfer to the virgin material and therefore impedes the pyrolysis process reduces the HRR (Zeinali et al., submitted March 2017b). The second peak in the HRR is caused by the combination of char cracking and the fact that over time more material pyrolyzes as the pyrolysis region spreads over the surface, both vertically and laterally. When only the long panel is composed of MDF instead of both panels (test MCS1 and MCS2), the decay after the first peak and the second peak are less pronounced. The second peak occurs later in both tests (approximately 20 s) compared to MM3 as is shown on Table 4. It is noteworthy to mention that both peaks for tests MCS1 and MCS2 occur at approximately half of the HRR of test MM3. By excluding the burner’s contribution (30 kW) and integrating the area under the HRR curves, one can determine the total amount of energy release as 25,621 kJ and 24,012 kJ in test MCS1 and MCS2, and 67 360 kJ in test MM3. This signifies that when only one test panel is made of combustible material, the final amount of burnt material is approximately 37% of the test in which both panels are combustible (assuming that the effective heat of combustion remains the same among the tests).

When only the short panel is composed of MDF (test CSM1), the pyrolysis of the combustible panel in the beginning of the test is slower than the other tests, even from tests MCS1 and MCS2 where only the long panel is MDF. This can be observed in terms of a first peak HRR in test CSM1 that is lower than that of MCS1 and MCS2 (52 kW versus 68 kW and 65 kW, respectively, all occurring at about $t = 90$ s). In addition, there is a delay in the occurrence of the second main peak (happening at $t = 225$ s, versus approximately $t = 180$ s in tests MCS1 and MCS2) with a HRR of 75 kW which is similar to that in tests MCS1 and MCS2 (80 kW and 72 kW, respectively). From 300 s until the end of the test, no large differences can be seen in the evolution of HRR in tests CSM1, MCS1 and MCS2. Overall, this shows that there is a great similarity among the tests in which only one panel is made from MDF, regardless of whether that is the short or the long panel.
In test MM3, the decay after the second peak in HRR lasts for nearly 800 s after which the HRR rises again because the fire starts to penetrate through the corner, eventually involving the backside of the panels into the fire as well (Zeinali et al., submitted March 2017b). If the corner is composed of only one combustible wall, the decay is shorter and the HRR levels off more rapidly. Since in this case, less material is involved and consumed in the fire. Therefore, the HRR does not rise again at the end of the test since the fire does not penetrate through the panels giving access to uncharred material at the backside.

![Figure 24 – Total HRR evolution profiles of the MDF tests](image)

On Figure 25, the total SPR is shown for the MDF tests MCS1, MCS2, CSM1 and MM3. During the first 100 s – 120 s of the test, the SPR evolves in a similar manner as the HRR. The first 60 s, the SPR levels off at a value which is the same as produced solely by the burner, namely 0.05 m²/s. Later, the SPR increases until it reaches a peak value around 90 s, as high as 0.11 – 0.16 m²/s. Up to this time, all four tests show the same behavior in terms of SPR. The early peak in the SPR profiles coincides with the rapid burning and pyrolysis of the surface fiber material, suggesting more extensive production of smoke and lower combustion efficiency during this period. After this peak SPR has occurred, the SPR drops to approximately 0.05 m²/s which is comparable with the SPR produced by the burner itself. This indicates that the burning of the panels does not contribute much to the smoke production. At approximately 170 s, at approximately $t = 170$ s, which is comparable with the SPR produced by the burner itself. This indicates that the burning of the panels becomes more efficient at this stage, not contributing much to the smoke production. Subsequently, SPR continuously increases until the end of the test and reaches a value. This constant increase in SPR is due to a growing char layer which is formed at the exposed surface, reducing the burning efficiency and therefore increasing the smoke production (Zeinali et al., submitted March 2017b). The final SPR value in tests MCS1 and MCS2, approximately 0.21 m²/s, is nearly three times higher than the initial peak SPR (0.05 m²/s). Test CSM1 shows an evolution profile similar to that of MCS1 and MCS2, but after 180 s the SPR is predominantly lower in test CSM1, by about 0.05 m²/s.
In test MM3 where both panels are composed of MDF, burning is more efficient in the first half of the test when compared to the other tests, considering that the SPR is predominantly lower. The SPR in the first half of test MM3 drops to approximately 0.031 m²/s which is even lower than that produced solely by the burner. After $t = 600$ s, however, the SPR increases rapidly and surpasses that of tests MCS1, MCS2 and CSM1. This is most likely due to a more rapid and widespread formation of char than in the other tests since the HRR and is higher and the flame spread is faster in test MM3. Due to this char formation, combustion becomes less efficient and the SPR increases (Zeinali et al., 2015; Zeinali et al., submitted March 2017b). In test MM3, the fire eventually penetrates the panels in the final 300 s of the experiments involving the backside of the panels as well (Zeinali et al., submitted March 2017b). The fire becomes larger again and burns more efficiently, reducing the SPR (Zeinali et al., submitted March 2017b). This can be seen in terms of SPR as a sudden drop around 960 s. This coincides with an increase in HRR in the final 300 s of the experiment.

**Figure 25 – Total SPR evolution profiles of the MDF tests**

### 4.1.2 Plywood tests

The HRR evolution of the plywood tests PP1, PCS1 and CSP1 is shown on Figure 27. Similar to the MDF tests, test PP1 shows two peaks in the HRR in the beginning of the test. The first peak (72 kW), relating to the pyrolysis and burning of the surface material, occurs at 105 s. A second peak in the HRR of 71 kW manifests at 339 s, because of char cracking and delamination at the surface. In contrast to the MDF tests, both peaks are almost equal in height and are further apart from each other. This difference between the initial burning behavior of MDF and plywood can be mainly attributed to the difference in manufacturing of the panels. As opposed to the plywood panels, the surface layer of the MDF panels has a much higher density compared to its inner core (see section 2.2), tending to delaminate and crack rapidly as it chars. In the case of plywood, it takes much longer for the surface char to crack, with only minimal delamination (illustrated on Figure 26). This explains why the HRR evolution between the two peaks in test PP1 is more gradual than that in test MM3, taking approximately 224 s versus 66 s, respectively. After the HRR has peaked a second time, the HRR
decays again but showing a slight increase halfway through the test before stabilizing at 52 kW. At 1020 s, the fire starts to penetrate the panels in the corner. This is associated with a strong increase in HRR reaching a peak value of 85 kW at 1065 s. At this time, the gas supply to the burner is stopped prematurely to stop the flames from damaging the thermocouples at the back of the panels. This reflects in the HRR curve as a sudden drop in HRR. After this drop, a second smaller peak in the HRR can be observed since the fire is still growing even though the burner has been turned off. The final drop in HRR is caused by the trolley being removed from the SBI testing environment, so that the panels could be extinguished.

Figure 26 – Illustration of the char cracking and delamination for tests MM3 and PP1. The first two images are MM3 (left) and PP1 (right) at t = 156 s. The two images at the right are MM3 (left) and PP1 (right) at t = 339 s.

In tests PCS1 and CSP1, where only one of the panels is made of plywood and the other panel is inert, the HRR in the first 30 s rises to 30 kW in the same manner as in test PP1. This follows the expected burner start-up time observed in the inert tests (section 4.1.3). In comparison with test PP1, the HRR increase and the peaks after t = 30 s are less pronounced in tests PCS1 and CSP1, as less material is available for pyrolysis (only one panel is plywood). In test PCS1, the first peak is as high as 41 kW, happening at t = 80 s, after which the HRR stays more or less constant for approximately 40 s before dropping slightly. The second peak HRR is as high as 44 kW and happens at t = 306 s. Later, the HRR drops to 37 kW (t = 360 s) but remains more or less constant afterwards until the end of the test. The average HRR over the final 800 s of the test is 36 kW. In case of test CSP1, the HRR values are in the
same order of magnitude as test PCS1, but the HRR profiles of the two tests sometimes show deviations, namely as high as 9 kW, with the HRR in test CSP1 being predominantly higher. The initial HRR rise in test CSP1 is slightly slower than that of PCS1, as was also the case for test CSM1 in comparison with test MCS1. After reaching approximately 40 kW at $t = 95$ s, the HRR in test CSP1 remains constant for nearly 120 seconds, before reaching a peak value of 45 kW at $t = 225$ s. After levelling off at this value for 60 s, the HRR starts to decay. Around $t = 700$ s, the HRR peaks again. This is when the HRR profile of test CSP1 collapses on that of PCS1. In the final 200 s of test CSP1, the fire penetrates through the short panel, leading to a significant increase in HRR. At the end of the experiment, the HRR is as high as 93 kW. This is because the test was not stopped prematurely, as opposed to test PCS1.

![Figure 27 – Total HRR evolution profiles of the plywood tests](image)

Similar to the HRR evolution profiles, the SPR curves more or less collapse in the first 30 s of the tests. As was pointed out earlier, the reason for this is that the panels do not contribute yet to the fire. Afterwards, the SPR gradually rises at a similar rate for all three tests during the first 600 s. Unlike for MDF, no peak in the SPR at the same time as the peak in HRR is shown for the plywood tests. This indicates that the burning of the panels is more efficient and gradual for plywood than for MDF. In the second half of the test, the three curves show more deviation with respect to each other. In test PCS1, the smoke production keeps on gradually rising until the end of the test without any drops or peaks in the SPR. In test CSP1, the SPR evolution is very similar to that of test PCS1, although it remains predominantly lower than that of test PCS1. Together with the fact that the HRR profile of test CSP1 is higher than that of test PCS1, this suggests that burning is more efficient when plywood is the short panel instead of the long panel.

In the final 200 s of test CSP1, the fire penetrates the short panel corresponding with a drop in the SPR. This would mean that the fire burns more efficiently after the flames have penetrated the panel. In terms of HRR, this can be observed as a peak in the HRR in the final 200 s of the test as shown on Figure 27. In the case of test PP1, the fire also penetrates the panels near the end of the test. However,
here this corresponds to a peak in the SPR instead of a drop. On Figure 28, it can be observed that at 1080 s the highest peak in SPR occurs (0.4 m²/s). This is the moment in the test when the gas supply to the burner was switched off, but the trolley is still inside the SBI testing environment.

![SPR evolution profiles](image)

**Figure 28 – Total SPR evolution profiles of the plywood tests**

In order to explain this opposite behavior in SPR evolution of tests CSP1 and PP1 in the final 200 s, the photographs of the panels after finishing the test were observed. As shown in Figure 30 and Figure 31, the fire only penetrates the short panel in both tests CSP1 and PP1. However, it can be noticed...
from those figures that the opening made by the fire in the short panel is much larger in test CSP1 than in test PP1. This might explain why the SPR drops for test CSP1 and rises in test PP1. Additionally, it is remarkable in Figure 31 that the short plywood panel is somewhat bent in test CSP1. Hence, the exposed surface might have been under tension and facilitated delamination of the char layers, enabling the flames to penetrate the panel more efficiently in the end of the test.

4.1.3 Inert tests

Figure 32 shows the evolution of the total HRR for the inert tests CSCS, CSCS10 and CSCS50. A tabulated summary is also presented in Table 5. As explained in (Zeinali et al., submitted March 2017a), the standard 30 kW test CSCS reaches 30 kW after approximately 20 s before levelling off with a gradual rise towards the end of the test. This is confirmed in Table 5, the overall average HRR is 31.4 kW, with minimal fluctuations (±1 kW). This slight increase in HRR is accompanied by an increase in SPR which can be seen on Figure 33. The increase in both parameters described is due to the pyrolysis of surface particulates and dust (Zeinali et al., submitted March 2017a). Nevertheless, the overall average HRR (31.4 kW) stays within the limits for the stability requirements of the average burner HRR of 30.7 kW ± 2 kW (EN 13823, 2002).

When the operating HRR is set to 10 kW, a HRR of 10 kW is attained after 10 to 15 s and then stabilizes. Similar to the 30 kW test, the HRR rises towards the end of the test with an average increase of 0.3 kW. This can again be explained by the slow pyrolysis of dust and surface particulates increasing the heat being released and the smoke being produced. Increasing the operating HRR to 50 kW, shows that the average HRR does not vary much throughout the experiment as the average HRR in the final 100 s is lower than the average HRR halfway through the test. It also takes longer (approximately 60 s) than in the other two tests (10 s – 20 s) for the HRR to stabilize. At a higher operating HRR, the pyrolysis of dust and surface particulates might be faster.

![Figure 32 – Total HRR evolution profiles of the inert tests](image-url)
When comparing the standard deviations, it appears that the higher the HRR, the harder for the system to maintain a constant HRR. In a short interval of only 100 s, the standard deviations are in the same order of magnitude for all three tests. However, the standard deviations calculated over 1200 s show larger differences between the three tests. The standard deviation for test CSCS10 amounts to 44% of the overall standard deviation found in test CSCS. For test CSCS50, the standard deviation found is 66% higher than the one found in test CSCS. These large differences in standard deviations are partially caused by the fact that since each HRR curve starts at 0 kW, in case of the 50 kW the HRR has to rise more in the start-up phase of the test than in the other two tests. This causes the overall standard deviation to be the highest for test CSCS 50.

**Table 5 – Average HRR and standard deviations for the inert tests**

<table>
<thead>
<tr>
<th>Test</th>
<th>Average total test</th>
<th>Standard deviation total test</th>
<th>Average mid 100 s</th>
<th>Standard deviation mid 100 s</th>
<th>Average final 100 s</th>
<th>Standard deviation final 100 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSCS</td>
<td>31.4 kW</td>
<td>1.7 kW</td>
<td>31.4 kW</td>
<td>0.4 kW</td>
<td>31.9 kW</td>
<td>0.4 kW</td>
</tr>
<tr>
<td>CSCS10</td>
<td>11.1 kW</td>
<td>0.8 kW</td>
<td>11.1 kW</td>
<td>0.3 kW</td>
<td>11.4 kW</td>
<td>0.3 kW</td>
</tr>
<tr>
<td>CSCS50</td>
<td>54.5 kW</td>
<td>2.9 kW</td>
<td>55.0 kW</td>
<td>0.3 kW</td>
<td>54.7 kW</td>
<td>0.5 kW</td>
</tr>
</tbody>
</table>

The total smoke production rate shows a similar evolution for all three tests with the main difference that the higher the HRR, the higher the SPR. The overall average SPR for tests CSCS10, CSCS and CSCS50 were found to be 0.025 m²/s, 0.084 m²/s and 0.102 m²/s respectively. For test CSCS, the SPR is 74% higher at the end of the test than at 60 s. For tests CSCS10 and CSCS50, that percentage is 107% and 65 % respectively. Graphically it can be seen that the SPR fluctuates more as the HRR becomes higher. The standard deviation found for test CSCS10 is 0.006 m²/s whilst the standard deviations for tests CSCS and CSCS50 are 0.015 m²/s and 0.016 m²/s respectively.

![Figure 33 – Total SPR evolution profiles of the inert tests](image)
4.2 Panel temperatures

As explained in Chapter 3, the panel temperatures are measured by fixing a total of 110 K-type thermocouples through the thickness and on the backside of panels. For the MDF and plywood panels, the through-thickness measurements are made at 0.002 and 0.012 m from the fire-exposed surface, with pilot holes drilled from the backside. For the inert panels, through-thickness measurements are made at 0.001 and 0.006 m from the exposed surface.

Note that the through-thickness measurements made very near the surface are primarily useful for tracking ignition times in the beginning of the test (before 120 s) (Zeinali et al., submitted March 2017b) and evaluating the overall repeatability of the thermal attack and its symmetry on the two panels (Zeinali et al., submitted March 2017b). This is because at some point, as explained in (Zeinali et al., submitted March 2017b), the panel surface delaminates as it pyrolyzes and the char layer oxidizes and shrinks, causing the near-surface thermocouples to become exposed or get covered by the delaminated material. Measurements made further through the thickness or on the backside of the panels are not affected by delamination or char shrinkage.

The panel temperatures are displayed using contour plots as shown on Figure 34. As in (Zeinali et al., 2015; Zeinali et al., submitted March 2017a; Zeinali et al., submitted March 2017b), the contour plots are obtained by using an interpolation scheme that combines bilinear and polynomial least-square fitting utilizing the QR decomposition technique. First, using the measurements made at every 0.2 m height, polynomial functions of the form $aX^5+bX^4+cX^3+dX^2+eX+f$ are estimated for each height. In the polynomial functions, parameters $a$ to $f$ represent constant coefficients, while $X$ represents the horizontal distance from the corner. Next, the polynomial functions are used to estimate the temperatures in the horizontal direction of the panels at every 5 cm between the measured temperatures (made at 5, 15, 30, 50 and 75 cm from the corner). Finally, using all the temperatures determined thus far, the temperatures in the other areas are estimated using bilinear interpolation in both the vertical and horizontal direction. The contour plots are made at the positions of the through-thickness measurements and for the measurements at the backside.

4.2.1 MDF tests

This section discusses and compares the results for tests MM3, MCS1, MCS2 and CSM1. As is to be expected, the regions on the panel near and above the burner show the highest temperatures. Figure 34 compares the through-thickness temperature evolution for the long panel for tests MCS1 and MCS2. In the region near the corner, between 0.05 m and 0.15 m, temperature differences up to 300°C can be observed. Moving further away from the corner, the agreement between the two tests is better although temperature differences of 100°C can be seen as well. In this regard, it must be noted that since the legend intervals of the contour plots are as large as 100°C, it is possible that the exact local temperature differences are much smaller (as for example a point at 95°C and another at 105°C will
fall within two different legend intervals). Even though local differences exist between the panel temperatures in tests MCS1 and MCS2, the overall agreement between the tests is considered reasonable.

![Temperature profiles for tests MCS1 and MCS2](image)

Figure 34 – Long panel through-thickness temperatures for tests MCS1 and MCS2. The X-axis denotes the horizontal distance from the corner as the Y-axis denotes the height from the bottom of the panels.

Noting the temperature evolution profiles of test MCS1 (Figure 35 to Figure 38), some effects can be inferred from the moisture content in the long panel. In (Zeinali et al., 2015; Zeinali et al., submitted March 2017a; Zeinali et al., submitted March 2017b), it is illustrated that the temperatures level off before reaching 100°C, similar to what can be observed in Figure 35 to Figure 38. This is due to the evaporation of the moisture content in the panels, requiring a substantial amount of energy that brings about a temperature plateau at about 100°C. As this behavior is more pronounced in the backside temperature evolution profiles (Figure 35 and Figure 36), it can be concluded that part of the moisture
content migrates towards the backside of the panels. The other part of the water vapor will exit through the exposed side of the panels.

**Figure 35 – Backside temperature profiles for test MCS1 at X = 0.05 m**

At heights below 60 cm, the evaporation of the moisture starts and finishes earliest (this is shown on Figure 37 and Figure 38). This indicates that the drying of the panels is more efficient at heights below 60 cm. In addition, considering the water evaporation plateau in the backside temperature profiles (Figure 35 and Figure 36), it can also be concluded that the moisture migration process is slower at higher heights. This is expected, as the higher panel regions are not in the persistent zone of the flames from the burner (Zeinali et al., submitted March 2017b).
Figure 37 – Temperature profiles near the surface at X = 0.05 m for test MCS1

Figure 38 – Temperature profiles near the surface at X = 0.15 m for test MCS1

Figure 37 and Figure 38 show the temperature profiles for test MCS1 near the surface in the vicinity of the corner. It can be seen that around 100°C, the temperatures level off momentarily as the moisture content migrates and evaporates. When the panels are dry, the panel temperature starts increasing rapidly. Roughly at the same time as the first peak HRR, a temperature peak followed by a drop can be observed in the through-thickness temperature profiles (Figure 37 and Figure 38). This peak in the temperature profiles occurs about 10 to 75 s after the moisture has evaporated (the exact time depends on the distance from the burner). Between \( t = 90 \) s to \( 240 \) s into the test, however, a char layer starts forming and delamination occurs, causing the temperatures to drop temporarily as heat transfer rate suddenly changes. Afterwards, the rate at which the temperatures increase is slower than before the occurrence of the peak. At locations further away from the corner, the peaks in the temperature profiles occur at progressively later times, as flames take some time to spread on the panel surface. Similarly, at higher panel regions, the peak in the temperature profiles occurs at later times, as these regions are away from the persistent zone of the flames from the burner.
At 20 cm from the bottom of the panels, there is no peak in the temperature curve and it takes much longer than at other positions for the moisture content to evaporate as the curve levels off at 100°C for a longer period (Figure 37). At a higher position, the panels might have dried to some extent already before being directly exposed to flames. Figure 39 shows that 20 cm higher on the panel, a clear peak in the temperatures can be observed. As there is also more lateral flame spread at this height, it could be that due to better mixing of the fuel with oxygen, the heat flux is higher at 40 cm above the bottom of the panels. However, this is just an assumption as no evidence could be found to support this theory.

In the second half of the experiment, the temperature curves show more fluctuations. This is expected to be due to the fact that the thermocouples become fully exposed to fire. These fluctuations are accompanied by high temperatures at the backside of the panels in the same region.

Approaching the end of the test, the fire has burnt through the panel in the vicinity of the corner. This is shown on Figure 40.

At 12 mm distance from the surface of the panels (Figure 39), a similar temperature evolution as for the backside of the panels can be seen. Around 75 s, the temperature starts to increase rapidly as the pyrolysis front reaches at this depth, until at 90 s into the test the fast temperature rise stops and more or less levels off. As the panel dries at the surface and the temperature starts to climb over 100°C, the temperature at $Z = 0.012$ m starts to rise rapidly. The temperature at 12 mm from the surface levels off due to the moisture migration and evaporation process. The reason why the temperature is not yet at 100°C when the temperature at $Z = 0.012$ m levels off, is that the migration of moisture and water vapor towards the back of the panels gets harder further into the material.

![Figure 39](image-url)  
*Figure 39 – Comparison of the through-thickness and backside temperature profiles for test MCS1 at the position of $X = 0.05$ m, $Y = 0.4$ m*
In (Zeinali et al., submitted March 2017b), it was established that the evolution of the through-thickness temperatures is faster on the short panel than the long panel for both the inert test and the MDF tests. This indicates that the panels are heated up in a non-uniform manner as a result of the set-up. However, when one of the two panels is combustible and the other is inert, the contour plots of both the backside and near surface (Z = 0.002 m) demonstrate quite a symmetric evolution of the panel temperatures as shown on Figure 41. In the vicinity of the corner, the lateral evolution of the temperatures is faster on the long panel than on the short panel which can be seen most clearly on Figure 41. This indicates that the set-up specific phenomenon, where the temperatures are noticeably higher on the short panel than on the long panel as discussed in (Zeinali et al., submitted March 2017b), is more likely to occur when both panels are made of combustible material. A possible explanation for this phenomenon is given in (Zeinali et al., submitted March 2017a) where it was stated that the ambient air supplied at the vent below the trolley, flows first towards the front of the trolley before flowing back towards the short panel. However, as this is not observed when only one panel is combustible, no firm conclusions can be drawn yet.
Figure 41 – Comparison of the near surface and backside temperature evolutions between the long panel of test MCS1 and the short panel of test CSM1. The X-axis denotes the horizontal distance from the corner as the Y-axis denotes the height from the bottom of the panels.

Figure 42 and Figure 43 show the temperature profiles at the positions where the long panel temperatures are higher than the short panel temperatures, in the case only one panel is combustible. The temperature difference at 40 cm above the bottom of the panels between the tests in which the long panel is composed of MDF and test CSM1 starts to develop around 90 s into the test in the vicinity of the corner. At a height of 80 cm, it can be observed that the short panel temperatures are
higher for a large part of the test, but near the end of the test the long panel temperatures become higher at this position.

**Figure 42 – Comparison of the near surface temperature profiles in the vicinity of the corner for tests MCS1 and CSM1**

Comparing the temperatures on the short panel of test CSM1 to those of test MM3 (contour plots in Figure 44) shows that good agreement exists at the backside of the panels in the first 900 s. The highest level of agreement can be seen at heights between 40 cm and 60 cm near the corner (X = 0.05 m). The near-surface temperatures in test MM3 are the highest near the bottom of the corner, whilst at the back they are higher at an upper position in the vicinity of the corner. In general, nevertheless, the temperature evolution in test MM3 is faster than in test CSM1. This is to be expected, because both panels are MDF in test MM3. Thus, more material is pyrolyzed and more heat is produced, leading to higher panel temperatures.
Figure 44 – Comparison of the short panel temperature evolutions between test CSM1 and test MM3. The X-axis denotes the distance horizontal from the corner as the Y-axis denotes the height from the bottom of the panels.

Both for tests CSM1 and MM3, it is found that the near-surface temperatures close to the corner are the highest at a height of 40 cm, indicating that the heat flux is the highest in that region. This can be observed both from Figure 44 and Figure 45. On Figure 45, it can also be seen that for up to $t = 90$ s, nearly all the temperature profiles of test MM3 and CSM1 from near the bottom corner match each other. This indicates that the temperature behavior in this early development stage depends mostly on the heat being produced by the burner itself. After reaching a peak value of about 164°C, a clear
difference in temperature profiles can be seen on Figure 45. The temperatures near the bottom of the corner in test MM3 follow an exponential course whilst the temperatures in the same region in test CSM1 develop linearly. The difference in manner of the temperature evolution is caused by the difference in rate at which heat is transferred into the panel, depending primarily on the external heat fluxes and thus the combustion in the gas phase, the local flames spread and the total HRR. In test MM3 with both panels being MDF, the HRR is higher, as more material pyrolyzes and more extensive flame spread follows. However, it is expected that the heat fluxes on each individual panel are lower than those observed in a test where only one panel is MDF. This can be because of a shortage of air supply when both the panels are burning, leading to less efficient combustion with lower heat fluxes on each individual panel. In other words, combustion on the short panel of CSM1 is expected to be more efficient than that on the short panel of MM3 simply because the supplied air is used for combustion of pyrolysate gases from only one panel in test CSM1. A final remark to be made regarding Figure 45 and Figure 46 is that near the end of the test, the near surface-temperatures at a height of 40 cm for test CSM1 become greater than or equal to those at the same location found for test MM3. This confirms similar levels of heating at this height in both the tests.

Figure 45 – Profiles of near-surface temperature evolution near the bottom of the short panel for tests CSM1 and MM3 at X = 0.05 m

In the upper regions of the panel near the corner, as Figure 46 indicates, the temperatures develop in a similar manner for both tests CSM1 and MM3, namely in an exponential manner. The expectation is that better mixing and convection at the upper regions of the panel cause the combustion to become more efficient, such that there is no significant air supply effects in these regions, irrespective of whether only one panel is MDF or both panels. Hence, external heat fluxes from combustion in both tests CSM1 and MM3 are in the same order of magnitude near the top of the panels, causing the short panel temperatures to develop in the same exponential manner. A final remark to be made regarding Figure 45 and Figure 46 is that near the end of the test, the near surface temperatures at a height of 40 cm for test CSM1 become equal and at the final seconds even higher than those at the same location found for test MM3.
4.2.2 Plywood tests

This section discusses and compares results for tests PP1, PCS1 and CSP1. On the contour plots for test PP1, presented on Figure 47, it can be seen that no contour plots were made at 1200 s but 1070 s instead. This is due to the fact that the test was stopped prematurely as the fire started penetrating the panels, which was already pointed out in section 4.1.2. This premature termination of the test can be observed as a sudden drop in the temperature profiles.

The contour plots at 0.002 m, show that the temperature evolution near the corner is faster on the long panel than the short panel in the beginning of test PP1. However, as the test progresses, higher temperatures can be found near the bottom of the corner on the short panel. This evolution can also be seen at the backside of the panels, shown as well on Figure 47. What is peculiar is that at a higher position on the corner it would appear from the near-surface temperature measurements that the temperature is lower on the short panel than on the long panel. However, at the backside, the opposite of what is seen at 0.002 m depth can be observed.
Test PP1 @ 0.002 m depth
Long panel
Short panel
Test PP1 @ backside
Long panel
Short panel

Figure 47 – Panel temperature evolutions for test PP1 near the surface and at the backside. The X-axis denotes the horizontal distance from the corner as the Y-axis denotes the height from the bottom of the panels.

Figure 48 shows that the short panel temperatures near the surface are only higher than the long panel temperatures at a height of 40 cm. At a height of 20 cm, the temperature difference is less than 1% at 1070 s, whilst at 80 cm the temperature on the short panel remains lower throughout the test. This might be explained by looking at Figure 30 which shows the panels after termination of the test. The opening in the short panel does not reach the bottom. It is likely that the fire has not reached the backside of the panels at a height of 20 cm, explaining why the temperatures are so similar at that location.
Figure 48 – Temperature profiles of the long and short panel near the surface of test PP1

At the backside, the temperature difference between the long and short panel is more pronounced. Notice that during the first half of the test, the temperatures are similar for the long and short panel. Halfway through the test, the temperatures start climbing higher than 100°C. From this point onward, the short panel temperatures start increasing faster with the temperatures at 20 cm and 40 cm being nearly identical. Around 1020 s into the test, the fire starts burning through the short panel. This is observed in terms of a peak in the backside temperatures for the short panel. As the fire does not burn through the long panel (this can be observed on Figure 30), no peaks in the backside temperature profiles are seen on Figure 49.

Backside temperatures in test PP1 start increasing at around $t = 120$ s, similar to the MDF panels (Zeinali et al., 2015; Zeinali et al., submitted March 2017b). In the inert panel tests, the backside temperatures started to increase as soon as 60 s in the region near the burner due to its lower thermal penetration time (Zeinali et al., submitted March 2017a). Another similarity between the tests is that the temperatures level off at 100°C as well due to the evaporation of the moisture content of the panels. This process takes equally long for the long and short panel.

Figure 49 – Backside temperature profiles of the long and short panel of test PP1
On the temperature profiles for the MDF tests, a peak could be observed in the beginning of the tests in the same time frame of the occurrence of the peaks in the HRR, because of the delamination of surface fiber layers and formation of char at this time. This occurs after the moisture in the material has evaporated. For the plywood tests, such a peak followed by a drop is not very noticeable. Only near the bottom of the corner such peak can be seen on the long panel, as Figure 50 shows at $t = 120$ s. This is expected, as there is minimal delamination and char cracking in the plywood tests (see Figure 26).

Moving further away from the corner, two peak values in the temperature curve can be seen at 20 cm above the bottom of the panel (Figure 51). A first smaller and shorter peak occurs at 135 s, whilst the second larger and longer peak occurs at 265 s. The first peak in the HRR for test PP1 occurred at 105 s, 30 s before the first peak in the temperature curve. The second peak in the HRR occurred at 336 s, 71 s after the second peak in the temperature curve. This means that the peaks in the temperature curve are located in between the HRR peaks, suggesting that it takes longer for a char layer to form in case of plywood than MDF. At 40 cm from the bottom of the panel, a larger peak which seems to envelop the two peaks at 20 cm, is shown. Although the temperature is initially higher at this height, after the occurrence of the temperature peak, the rise in temperature is slower at 40 cm than at 20 cm. This is expected to be because of the different local flame spread behavior at these locations. The peak in the temperature curve at 15 cm away from the corner also occurs later and is stretched over a longer period in time than at 5 cm. At the top of the corner, no peaks in the temperature curve can be found, neither at 5 cm nor at 15 cm away from the corner. The sudden drop in the temperature profiles after 1080 s on Figure 51 are because the burner is turned off prematurely in test PP1 and the panels are extinguished with water.

**Figure 50 – Temperature profiles of the long panel near the surface at X = 0.05 m of test PP1**

![Temperature profiles](image)
Comparing the near-surface and backside temperatures for the long panel of test PCS1 and the short panel of test CSP1, shows that the temperature development is quite symmetric in the beginning of the test. It is only in the last 300 s of the test that the short panel temperatures start to rise much faster. As pointed out before in section 4.1.2, the short panel is bent towards the exposed side. This causes the exposed side of the panel to be under tension. When wood under tension is exposed to fire, more than 75% of its initial tensile strength is lost when the wood temperature reaches 300°C (Harper, 2004). Combining this with the knowledge that over time the char layer is exposed to high temperatures causing the formation of cracks and fissures due to thermal stresses, the fire is able to penetrate the short panel faster than the long panel. Therefore, the results of these tests cannot be used to verify the temperature difference between the long and short panel if only one panel is combustible. Notice how at the end of the test, the temperatures at the backside of the short panel are higher in the region between 5 cm and 15 cm away from the corner than the near surface temperatures in the same region. This is expected to be because of flame exposure at the backside of the panel after fire has consumed the corner.
Comparing the short panel temperatures for tests PP1 and CSP1 shows that initially the temperatures develop at a similar rate, but as the test progresses the temperatures for the short panel in the test where both panels are combustible increase faster than when only the short panel is combustible. This behavior is to be expected. Comparing the backside temperatures for the short panel at 1070 s shows that at this point in time the flames have not yet penetrated the panel in test CSP1 as the temperatures near the burner are 200°C to 300°C lower than in test PP1 for which this was the case at 1070 s. When now comparing the temperatures for the short panel of test CSP1 at 1070 s (Figure 53) and at 1200 s...
(Figure 52), a very fast temperature increase can be observed. The temperatures near the corner have increased 400°C to 500°C in a period of 130 s.

![Temperature distribution diagram](image)

**Figure 53 – Comparison of the temperature evolutions between the short panels of test PP1 and test CSP1. The X-axis denotes the horizontal distance from the corner as the Y-axis denotes the height from the bottom of the panels.**

### 4.2.3 Inert tests

This section discusses the results for the inert tests CSCS, CSCS10 and CSCS50. In case both panels are inert, it was established in test CSCS that the through-thickness temperature evolution is faster on the short panel (Zeinali et al., submitted March 2017a). As both panels do not contribute to the fire, the cause of this was assumed to be a set-up specific phenomenon most likely to do with the air flow.
being directed more towards the short panel (Zeinali et al., submitted March 2017a). As explained before, this phenomenon was also observed in the MDF and plywood tests when both panels are combustible. When the HRR in the test is lowered from 30 kW to 10 kW, again a slightly faster temperature development can be seen for the short panel as Figure 54 shows.

Comparing the long and short panel temperatures near the corner in a quantitative way, shows that the temperature at 20 cm above the bottom of the panels is 50% higher near the surface for the short panel at the end of test CSCS10. As can be seen on Figure 55, the temperature difference at this position
keeps progressively increasing until the end of the test. When the height increases, the temperature difference in the vicinity of the corner between the long and short panel decreases. At a height of 40 cm, the short panel temperature is 10% higher whilst at 80 cm, the short panel temperature is 15% lower. Comparing the backside temperatures near the corner shows a more uniform temperature evolution between both panels. At a height of 20 cm, the temperature difference at the end of the test is reduced to 20%, whilst at higher positions the temperature profiles collapse.

Figure 55 – Temperatures for long and short panel near the corner at Z = 0.001 m for test CSCS10

Figure 56 – Backside temperatures for long and short panel near the corner for test CSCS10

In case the HRR is increased from 30 kW to 50 kW in the inert test, again a slight asymmetric temperature evolution can be graphically observed on Figure 57. Identical to test CSCS, the higher temperature evolution occurs predominantly near the corner on the short panel. However, regardless of this fact, the overall symmetry between both panels is good for all the inert tests.
In test CSCS50, the temperature difference between the long and short panel is not that high as the temperature at a height of 20 cm is only 15% higher for the short panel unlike in test CSCS10 where the temperature here was 50% higher. As the height on the panels increases, the temperature difference becomes smaller as was also the case in test CSCS10. At 40 cm, the difference in temperature is reduced to 12% (similar to test CSCS10), whilst at 80 cm, the temperature curves collapse for the majority of the test. What is interesting to observe is that in test CSCS10 the temperatures at a height of 20 cm were the highest, whilst in test CSCS50 the temperature are the highest at $Y = 0.4$ m. This
can be observed both at near the surface (Figure 58) and at the back of the panels (Figure 59). Similar to test CSCS10, the backside temperature at $Y = 0.2$ m differ the most (24%) whilst at higher positions on the panels the panel temperatures are almost identical for both panels.

![Figure 58 – Temperatures for long and short panel near the corner at $Z = 0.001$ m for test CSCS50](image)

![Figure 59 – Backside temperatures for long and short panel near the corner for test CSCS50](image)

### 4.3 Total heat fluxes

Figure 17 shows the positions of the heat flux sensors used to measure the total heat fluxes since the sensors are in direct contact with the flames. This causes the heat flux sensors to become exposed to both convective and radiative heat transfer. As described in literature (Bryant et al., 2003), the incident radiative heat flux is the main component in the total heat flux measurement. As this is the case, the heat flux measurement is primarily of function of $T^4$ difference between the temperature of the hot black core of the heat flux sensors and the water-cooled outer region of the heat flux sensors (Zeinali et al., 2015; Zeinali et al., submitted March 2017a). As described in section 3.1, the temperature of the water used to cool the heat flux sensors, is increased from 20°C to 50°C. As the heat flux sensors were calibrated at 20°C, it was investigated in (Zeinali et al., 2015; Zeinali et al., submitted March 2017a) if increasing the temperature of the water to 50°C during the tests could have a significant impact on the
uncertainty of the measurements. In order to do this, a ratio of $T^4$ differences between the assumed black-body temperature at the core and the cooling water temperature was calculated for the calibration temperature and the water-cooling temperature. This calculation showed that increasing the temperature of the cooling water from 20°C to 50°C would cause a relative change in heat flux measurement of less than 0.16%, which is insignificant compared to other potential sources of uncertainty associated with the type of heat flux measurements performed in the tests. The main sources of uncertainty according to (Bryant et al., 2003) are: the change in calibration constant and soot and dust deposition on the sensors during the test (less than 10%). Although the calibration constant is the main source for uncertainties, it was confirmed to change only slightly among several different tests (Zeinali et al., submitted March 2017a: Zeinali et al., submitted 2017b). Hence, due to the short preparation times between two consecutive tests in this work, it was decided not to recalibrate the heat flux sensors after each test.

Another challenge with the heat flux measurements is the method for obtaining the heat flux values which was used in these tests. During the tests, the heat flux sensors are connected to voltmeters which give a signal in mV. The output of these voltmeters was filmed during the tests so that afterwards the footage could be watched and paused every 5 seconds to note the signal in mV given by the voltmeters. Finally the values in mV are converted to kW/m², by multiplying with a factor obtained after calibration, to obtain the heat flux measurements at each 5 s during the total length of the test. However, due to the rapid changes of the values given by the voltmeters, combined with human interpretation errors, secondary uncertainties could be introduced into the accuracy of the values obtained in mV. By converting this mV signal to total heat fluxes in kW/m², the fluctuations in the values get enlarged. An illustration of this can be seen on Figure 60, which shows the rapid changes in the signal for 1 s of footage.

![Figure 60 – Fluctuation in the signal received from heat flux measurements during a timeframe of 1 s](image-url)
4.3.1 MDF tests

In this section, the results for the total heat flux measurements for the MDF tests are shown on Figure 61, Figure 62 and Figure 63. For test MCS1, no useable heat flux measurements by sensors 1 and 2 were made due to a human error.

In the first 60 s of the test, the heat fluxes measured are only influenced by the radiation and convection coming from the burner as the panels do not yet contribute to the fire at this stage. This can be observed as the total heat flux curves collapse for all tests in all three locations, however this is most noticeable for sensors 2 and 3. Consequently, the heat flux evolution in this stage of the test is highly similar to the evolution for test CSCS at the same location.

For the tests where the long panel is made of combustible material (MCS1, MCS2 and MM3), the total heat flux curve shows a similar evolution in time as the HRR curve at the locations of sensors 2 (Figure 62) and 3 (Figure 63). Here, a peak in the total heat flux curve can be seen in the first three minutes of the tests. The peaks in the total heat flux curves occur at the same time as the peaks in the HRR curves manifest. In case the long panel is inert (test CSM1), the peak in the total heat flux curve occurs at a later time for sensor 2 (300 s), whereas for sensor 3 a maximum in the curve occurs at 290 s but this value cannot be considered a peak in the curve. The peak value in the HRR curve for this test was also delayed, but occurs sooner (225 s) than the peak in the heat fluxes. After the peak in the total heat fluxes, a drop in the curves can be seen which is most pronounced for sensor 2. This was also concluded in (Zeinali et al., 2015; Zeinali et al., submitted March 2017a; Zeinali et al., submitted March 2017b) where it was stated that the reason for this is that sensor 2 is located furthest away from the corner. For sensor 1 (Figure 61), the total heat flux evolutions are similar for the three types of tests as this sensor is located directly above the burner. The average heat flux after 120 s for test MCS2, CSM1 and MM3 is 60.1 kW, 60.2 kW and 57.7 kW respectively. Consequently, the heat flux values found at this location show close resemblance to the values found for test CSCS, as the average heat flux is 52.6 kW at this location (Figure 67). Overall, the total heat flux evolutions found for tests MCS1 and MCS2 show the most resemblance to the evolution for test MM3.

Although the HRR values are in general significantly higher when both panels are made of MDF, the heat fluxes are in the same order of magnitude when only one panel is made of combustible material. The largest differences between test MM3 and the other tests can be seen in the first half of the experiment, as high as 30 kW/m². Towards the end of the test, the total heat flux values are similar for all four tests performed at all three locations. This is in line with the conclusion made in (Zeinali et al., submitted March 2017b), that towards the end of the test, the contribution of the burning panels is smaller than in the beginning of the test. This can be seen most clearly for sensor 2 and sensor 3. When only one panel is combustible, very good agreement between tests MCS1, MCS2 and CSM1
exists at the location of sensor 3, when not accounting for the lack of peak heat flux value in the beginning of test CSM1.

Figure 61 – Total heat flux measurements by sensor 1 for the MDF tests

Figure 62 – Total heat flux measurements by sensor 2 for the MDF tests

Figure 63 – Total heat flux measurements by sensor 3 for the MDF tests
4.3.2 Plywood tests

In this section, the results for the total heat flux measurements for the plywood tests are shown on Figure 64, Figure 65 and Figure 66. In the beginning of the test, the panels do not contribute to the fire yet, causing the total heat flux values at all three locations to collapse for all three tests. However, unlike with the MDF tests this period seems to be shorter than 60 s for sensors 1 and 3. Another difference in the plywood tests is that no peaks in the total heat flux evolution can be seen at the location of sensor 3 (Figure 66). At this location, the curves for tests PP1 and PCS1 collapse in the first 120 s. Afterwards, the total heat flux for test PP1 becomes higher than for test PCS1 and stays higher until the end of the test. This suggest that after two minutes, the contribution of the second panel burning has an impact on the total heat flux at the location of sensor 3. As this is the sensor positioned close to the corner and at 80 cm above the bottom of the panels, it is possible that from this point onward, the burning of the second panel causes the flame heights to increase. Another difference between the heat flux evolutions at sensor 3 for the plywood tests and MDF tests is that for plywood, the heat flux values measured are lower when the short panel is combustible than if the long panel is combustible. For the MDF tests, the values for the test in which the short panel is combustible are only lower in the first 3 minutes of the test after which the values are very similar to those of tests MCS1 and MCS2. This is expected to be because of the more extensive delamination and flame spread on the MDF panels compared to plywood.

Similar to the MDF tests, the heat fluxes measured at sensor 1 are in the same order of magnitude for all three tests, particularly at the end of the test. In the first 480 s of the test, the heat flux evolution is slower when only the short panel is composed of plywood. This is also the case at the location of sensor 2 as no peaks in the heat flux values are observed unlike for the other two tests. Comparing the values found in the first half of the test for test CSP1 to those of test CSCS, it can be concluded that the values are quite similar to the 30 kW inert test for all three sensors. Combining all these observations leads to conclude that, in the case of plywood panels, the heat flux values found in the first half of the test are determined mainly by the burning behavior of the long panel.

Another likeness between the plywood tests and the MDF tests is the fact that the peaks in the heat flux values for sensor 2 occur around the same time as the peaks in the HRR. Although the peaks in the HRR are not in the same order of magnitude for test PCS1 as for test PP1, this is the case for the peak values in the heat flux measurements. However, the drop in the heat flux curve afterwards is more extensive and rapid for test PCS1 than for PP1.
Figure 64 – Total heat flux measurements by sensor 1 for the plywood tests

Figure 65 – Total heat flux measurements by sensor 2 for the plywood tests

Figure 66 – Total heat flux measurements by sensor 3 for the plywood tests
4.3.3 Inert tests

Similar to the HRR, the total heat fluxes show a slight increase over 1200 s, particularly at the location of sensor 1. As discussed in section 4.1.3, this is assumed to be due to the slow pyrolysis of surface particles and dust present on the panels. Another additional factor causing this slight increase is the fact that the panels heat up gradually, increasing the total heat flux at the sensors due to the added radiation coming from the panels (Zeinali et al., submitted March 2017a). A second additional factor is the soot deposition on the panels, slightly changing the emissivity and absorptivity of the panels (Zeinali et al., submitted March 2017a). The latter is not expected to have much impact on the total heat flux values (Zeinali et al., submitted March 2017a). The increase heat flux values can be observed on the graphs presented in this section and on Table 6.

Table 6 – Comparison of the average total heat fluxes for the inert tests at the beginning (120 – 180 s), halfway through (570 – 630 s) and at the end of the test (1140 – 1200 s)

<table>
<thead>
<tr>
<th>Location</th>
<th>Test</th>
<th>Initial heat flux [kW/m²]</th>
<th>Midway heat flux [kW/m²]</th>
<th>Final heat flux [kW/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor 1</td>
<td>CSCS</td>
<td>47.3</td>
<td>54.4</td>
<td>55.2</td>
</tr>
<tr>
<td></td>
<td>CSCS10</td>
<td>21.1</td>
<td>24.8</td>
<td>28.2</td>
</tr>
<tr>
<td></td>
<td>CSCS50</td>
<td>56.8</td>
<td>63.1</td>
<td>61.2</td>
</tr>
<tr>
<td>Sensor 2</td>
<td>CSCS</td>
<td>17.7</td>
<td>22.2</td>
<td>20.8</td>
</tr>
<tr>
<td></td>
<td>CSCS10</td>
<td>3.3</td>
<td>4.0</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>CSCS50</td>
<td>25.7</td>
<td>29.0</td>
<td>29.6</td>
</tr>
<tr>
<td>Sensor 3</td>
<td>CSCS</td>
<td>24.7</td>
<td>24.5</td>
<td>25.4</td>
</tr>
<tr>
<td></td>
<td>CSCS10</td>
<td>3.3</td>
<td>4.0</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>CSCS50</td>
<td>32.5</td>
<td>35.1</td>
<td>35.2</td>
</tr>
</tbody>
</table>

As expected, the heat fluxes measured in test CSCS50 are the highest for all three sensors and the values for the heat fluxes found in test CSCS are located in between those of tests CSCS50 and CSCS10. However, it can be graphically observed that the difference between tests CSCS and CSCS10 is larger than between tests CSCS and CSCS50 for all sensors. As sensor 1 is located directly above the burner, flames are always present at this position causing the relative difference between the three tests to be the smallest at this position. As the other two sensors are located further away from the burner (sensor 2 in the lateral direction and sensor 3 in the vertical direction), differences between the three tests are more noticeable in these positions. This can be observed most easily for test CSCS10. At the location of sensors 2 and 3, the total heat flux values are very low compared to the values measured by sensor 1. This is due the fact that the flames coming from the burner are much smaller compared to the other two tests due to the lower HRR. Increasing the standard HRR from 30 kW to 50 kW seems to have less of an impact on the heat fluxes. The differences in total heat fluxes to those in test CSCS are similar for all three locations.
Notice how the heat flux peaks in the beginning of test CSCS50 for sensor 2, whilst at the same time the heat flux at sensor 3 is very low. For the same test, the heat fluxes measured at sensor 2 show large peaks and fluctuations.

Figure 67 – Total heat flux measurements by sensor 1 for the inert tests

Figure 68 – Total heat flux measurements by sensor 2 for the inert tests

Figure 69 – Total heat flux measurements by sensor 3 for the inert tests
4.4 Flame spread

This section discusses the flame spread monitored during the different tests. Two aspects of flame spread are addressed: instantaneous flame height and lateral flame spread.

The instantaneous flame height is obtained using the video camera footage and software analysis (Zeinali et al., submitted March 2017b; Merci & Beji, 2017b) based on the intensity of color and contrast between the pixels in the individual frames of the footage. The footage is sampled at a rate of 25 frames per second, using a frameskip of 6 to obtain instantaneous flame heights at every 0.28 s. This means that per tests, 1108 s of footage is analyzed using the video footage analysis technique. As a relatively high frameskip is used, no averaging of the data is performed so no mean flame heights are obtained. The apparatus height is limited to 1.5 m, meaning flames heights of more than 1.5 m cannot be captured by the camera. Another remark to be made is that the instantaneous flame heights are obtained by the footage coming from the camera viewing the long panel. As discussed in (Zeinali et al., submitted March 2017b), the level of uncertainty associated with the flame detection method is approximately 10% as the flame detection is sensitive to the view angle of the footage.

The lateral flame spread is discussed in the same manner as was done in (Zeinali et al., submitted March 2017b), by visually defining the lateral pyrolysis front as the outermost location at which the panel material has ignited. The pyrolysis front is tracked at the top of the combustible panel (Y = 1.5 m) and near the middle of the panels (Y = 0.8 m) at 900 s and 1200 s.

4.4.1 MDF tests

The instantaneous flame heights for test MCS1, MCS2 and CSM1 are shown on Figure 70, Figure 71 and Figure 72 respectively. The evolution of the instantaneous flame heights is similar to that of the HRR profiles shown on Figure 24 as a peak value is obtained in the beginning of the test. On the instantaneous flame height graphs, this is visualized as the disappearance of the instantaneous flame height values and moving average values. The moving average is obtained by using a central averaging technique over a period of 30 s. As the apparatus height is limited to 1.5 m, flame heights obtained by the software exceeding this maximum are removed as the accuracy of the value cannot be guaranteed. However, it is certain that at these times, the flame height has exceeded 1.5 m.

In tests MCS1 and MCS2, the instantaneous flame height drops below 1.5 m after more or less 180 s and remains below this level until the end of the test. In test CSM1, it can be seen that the instantaneous flame height does not drop below 1.5 m until 260 s. This is fairly consistent with the HRR evolution for CSM1, as the second peak in HRR occurred later as well (around 235 s). Comparing the average instantaneous flame height from 270 s until the end of the measurements (1108 s), shows an identical value for tests MCS1 and MCS2 (1.10 m). The average instantaneous
flame height of test CSM1 is 5% higher with a value of 1.16 m. Considering a 10% uncertainty level, the average instantaneous flame height values show good agreement for all three tests.
Whilst for the instantaneous flame height, good agreement could be noticed between tests MCS1 and MCS2, this is less the case for the lateral flame spread. Table 7 shows the position of the pyrolysis front at 900 s and at the end of the test for three different heights. Near the end of the test, the pyrolysis front in test MCS2 has advanced more in comparison to test MCS1. Another remark to be made is that it can be observed from the footage of that test that the lateral pyrolysis front stops moving at a certain point in time. First, the front stops moving at the top of the panel. A while later, it also stops moving at the bottom of the panels. From this point on, the advancement of a delamination front starting near the corner and moving in the lateral direction can be noticed that continues until the end of the test. Note that this delamination front never reaches up to the same position of the last observed lateral pyrolysis front.

For test MCS1, the pyrolysis front stops moving after 385 s. In test MCS2, the pyrolysis front only stops moving temporarily around 300 s, but then continues to advance at 469 s until the end of the test. Notice that at 300 s, the front location at the bottom and midway on the panel of test MCS2 was quite similar to what is observed at those heights at the end of test MCS1. At the end of test MCS2, the pyrolysis front has advanced well beyond the positions found for test MCS1 at the bottom of the panel and midway on the panel. However, at the top of the panel both tests show the same values at the end of the test. Overall it can be concluded that the pyrolysis front has advanced more at 40 and 80 cm heights for test MCS2, whilst at the top the lateral flame spreading is similar for both tests. This contrasts with the results when both panels are MDF (Zeinali et al., submitted March 2017b), where it was found that, the flame spread was most similar in the region of Y = 40 cm.

Comparing the lateral flame front positions for test CSM1 with those of tests MCS1 and MCS2 shows the flame front has advanced to a similar position at the top of the panel. At Y = 80 cm, good similarity can be seen between tests MCS1 and CSM1. At the bottom of the panel, the largest differences between positions of the flame front can be found with the value for test CSM1 being in between those of tests MCS1 and MCS2. Table 7 indicates that the flame front keeps on advancing for a longer period of time for test CSM1 than for test MCS1.

*the front location at this time is 0.25, 0.3 and 0.18 m at heights 0.4, 0.8 and 1.4 m

Table 7 – Lateral pyrolysis front locations in the MDF tests

<table>
<thead>
<tr>
<th>@ Height</th>
<th>MCS1</th>
<th>MCS2</th>
<th>CSM1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flame front at t = 900 s</td>
<td>Y = 0.4 m</td>
<td>X = 0.25 m</td>
<td>X = 0.33 m</td>
</tr>
<tr>
<td></td>
<td>Y = 0.8 m</td>
<td>X = 0.27 m</td>
<td>X = 0.33 m</td>
</tr>
<tr>
<td></td>
<td>Y = 1.4 m</td>
<td>X = 0.26 m</td>
<td>X = 0.25 m</td>
</tr>
<tr>
<td>Flame front at t = 1200 s</td>
<td>Y = 0.4 m</td>
<td>X = 0.25 m</td>
<td>X = 0.36 m</td>
</tr>
<tr>
<td></td>
<td>Y = 0.8 m</td>
<td>X = 0.27 m</td>
<td>X = 0.33 m</td>
</tr>
<tr>
<td></td>
<td>Y = 1.4 m</td>
<td>X = 0.26 m</td>
<td>X = 0.26 m</td>
</tr>
<tr>
<td>Time front stops</td>
<td>t = 385 s</td>
<td>t = 300 s*</td>
<td>t = 478 s</td>
</tr>
<tr>
<td>Time front starts moving again</td>
<td>-</td>
<td>t = 469 s</td>
<td>-</td>
</tr>
</tbody>
</table>
4.4.2 Plywood tests

The instantaneous flame height evolution for test PP1 shows various peaks. This is in contrast with the instantaneous flame height evolution for the MDF tests MCS1, MCS2 and CSM1, where only peaks occurred around the same time as the occurrence of the peaks in the HRR. A difference with the MDF tests performed in (Zeinali et al., submitted March 2017b) is that for test PP1, the instantaneous flame heights do not seem to be increasing around the time the flames penetrate the short panel. The average instantaneous flame height found between 1020 and 1070 s is 1.17 m, whilst the average over the total time span is 1.27 m. However, note that since the uncertainty level is 10% and the difference between both averages is less than 10%, a firm conclusion regarding this cannot be drawn.

In test CSP1, the fire also penetrates the short panel in the end of the test. But since this only starts after 1070 s and the footage was only analyzed for 1108 s, no conclusions can be drawn regarding a possible increase in instantaneous flame heights related to the increase in HRR based on Figure 75. However, an increase in the flame heights could be observed visually from the footage. With regards to the beginning of test CSP1, again no similarities seem to be found between the instantaneous flame height evolution and the HRR evolution. In fact, when a slight increase in the HRR could be observed around 120 s, a drop in the instantaneous flame heights can be seen.

Now comparing the instantaneous flame heights of the tests previously discussed to those of test PCS1, shows that the overall lowest flame height values can be observed when only the long panel consists of plywood. The average instantaneous flame height found for the total length of test PCS1 amounts to 1.06 m, whereas for the other tests PP1 and CSP1 the average values are 1.27 and 1.17 respectively. In test PCS1, the instantaneous flame heights do not seem to be showing any distinct peak values which could be related to an increase in the HRR. The higher instantaneous flame heights for test CSP1 might be related to the bending of the panel.

![Figure 73 – Instantaneous flame heights for test PP1](image-url)
Comparing the lateral flame spread for the tests where only one panel consists of plywood shows that the pyrolysis front position at the end of the tests is quite similar (shows a more advanced lateral pyrolysis front near the bottom of the short panel at the end of the test. It can also be seen that the propagation of the pyrolysis front takes last longer on the short panel than on the long panel. Note that in the last 170 s of the test, the pyrolysis front advances approximately 7 cm at the top of the panel. This might be related to the fact that the fire starts penetrating the short panel around that time.

Finally comparing the long panel of PCS1 to that of PP1, it can be found that quite a good agreement exists between the lateral pyrolysis front propagation for both tests. The only difference is that in test PP1, the lateral pyrolysis spread lasts somewhat longer than in test PCS1. The lateral pyrolysis front of the short panel of tests CSP1 and PP1 show less agreement, particularly at the bottom of the panel.

Table 8). However, when comparing the times at which the pyrolysis front stopped moving, it can be noticed that the front propagation lasted more than twice as long for test CSP1 than for test PCS1. Combining this with the similar end positions for the pyrolysis front, it is possible that the lateral flame spread is slower in the short panel test than when the long panel is composed of plywood.
For test PP1, Table 8 shows a more advanced lateral pyrolysis front near the bottom of the short panel at the end of the test. It can also be seen that the propagation of the pyrolysis front takes last longer on the short panel than on the long panel. Note that in the last 170 s of the test, the pyrolysis front advances approximately 7 cm at the top of the panel. This might be related to the fact that the fire starts penetrating the short panel around that time.

Finally comparing the long panel of PCS1 to that of PP1, it can be found that quite a good agreement exists between the lateral pyrolysis front propagation for both tests. The only difference is that in test PP1, the lateral pyrolysis spread lasts somewhat longer than in test PCS1. The lateral pyrolysis front of the short panel of tests CSP1 and PP1 show less agreement, particularly at the bottom of the panel.

**Table 8 – Lateral flame spread values for the plywood tests**

<table>
<thead>
<tr>
<th>@ Height</th>
<th>CSP1</th>
<th>PCS1</th>
<th>PP1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Short panel</td>
<td>Long panel</td>
<td>Long panel</td>
</tr>
<tr>
<td>Flame front at t = 900 s</td>
<td>Y = 0.4 m</td>
<td>X = 0.27 m</td>
<td>X = 0.28 m</td>
</tr>
<tr>
<td>Flame front at t = 1200 s*</td>
<td>Y = 0.8 m</td>
<td>X = 0.29 m</td>
<td>X = 0.29 m</td>
</tr>
<tr>
<td></td>
<td>Y = 1.4 m</td>
<td>X = 0.29 m</td>
<td>X = 0.26 m</td>
</tr>
<tr>
<td>Flame front at t = 1200 s*</td>
<td>Y = 0.4 m</td>
<td>X = 0.27 m</td>
<td>X = 0.28 m</td>
</tr>
<tr>
<td></td>
<td>Y = 0.8 m</td>
<td>X = 0.29 m</td>
<td>X = 0.29 m</td>
</tr>
<tr>
<td></td>
<td>Y = 1.4 m</td>
<td>X = 0.29 m</td>
<td>X = 0.26 m</td>
</tr>
<tr>
<td>Time front stops</td>
<td>t = 720 s</td>
<td>t = 320 s</td>
<td>t = 435 s</td>
</tr>
<tr>
<td>Time front starts moving again</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Test PP1 finished at t = 1070 s*

### 4.4.3 Inert tests

The average instantaneous flame height over 1200 s amounts to 0.51 m for test CSCS10 and 1.34 m for test CSCS50. This means that the average instantaneous flame height in the 10 kW test is 41% lower than the average mean flame height in the 30 kW test, reported to be 0.87 m (Zeinali et al., submitted March 2017a). For the 50 kW, such conclusions cannot be drawn with certainty as the instantaneous flame height is frequently higher than 1.50 m as can be seen on Figure 77 as the moving average frequently disappears throughout the test. Therefore, the average value of 1.34 m is most likely an underestimation of the actual average instantaneous flame height. The instantaneous flame height values for the 50 kW test also show higher fluctuations.

A final remark regarding the instantaneous flame heights for test CSCS10 is that it can be seen on Figure 76 that the values decrease gradually as the test progresses. This might be related to the gradual decrease in HRR which was observed in section 4.1.3.
Figure 76 – Instantaneous flame heights for test CSCS10

Figure 77 – Instantaneous flame heights for test CSCS50
Chapter 5  Conclusions

The fire growth behavior in a corner configuration of MDF and plywood panels was investigated in the form of SBI tests, as part of a larger experimental campaign. In these tests, also calcium silicate panels were used to examine the difference in fire growth behavior when only one of the panels in the corner is combustible. Furthermore, inert tests with calcium silicate panels at both a lower and higher heat release rate than the standard test (10 kW and 50 kW) were performed as well, in order to examine the impact of the HRR delivered by the burner on the parameters monitored. The total Heat Release Rates (HRR) and Smoke Production Rates (SPR) were discussed, as well as total heat fluxes at several characteristic locations. In order to compare the results with CFD model predictions, the instantaneous flame heights and lateral flame spread were reported and discussed. Moreover, the through-thickness and backside temperatures were presented and discussed. The latter is useful for establishing a backside boundary condition.

Analyzing the HRR for the different tests performed has shown that for both types of materials two peak values could be observed in the first half of the test. For MDF, the second peak in the HRR followed shortly after first one and was the highest of the two. In the case of the plywood tests, it was found that the second peak occurred much later and was equal in height to the first peak. This was shown to be because the char cracking and delamination processes occur at a more gradual pace for plywood compared to MDF. When only one panel is combustible, the peaks in the HRR are less pronounced for both materials. For the inert tests, the average HRR amounts to 11.1 kW for the 10 kW test and to 54.5 kW for the 50 kW test.

The panel temperatures measured at the surface showed a jump followed by a drop in the temperatures after drying, caused by the change in rate of heat transfer due to char formation and delamination. Afterwards, the temperature profiles showed a slower increase in temperatures as before. For plywood, this jump followed by a drop, is less noticeable as char cracking and delamination is less rapid and extensive as for MDF. A faster temperature development near the bottom of the corner of the short panel could be observed when either both or no panels are combustible. This was also seen in terms of faster lateral flame spread on the short panel for plywood. In case only 1 panel is combustible, this phenomenon was not observed. In general, the highest temperatures were observed at 40 cm above the bottom of the panels.

For both MDF and plywood, the least amount of difference between the different types of tests can be seen at the location of sensor 1, as flames are constantly present at this location. At the location of sensor 2, only peaks in the heat fluxes are observed when the long panel is combustible. The height of the peaks is the same if only one or two panels are combustible. For the plywood tests, it was found that in the first half of the test, the heat fluxes at sensors 1 and 2 are mainly influenced by the burning behavior of the long panel. In case of the MDF tests, peaks in the heat flux can be seen at the position
of sensor 3 when the long panel is combustible. In the plywood tests, no peaks in the heat flux could be observed for sensor 3. However, for both types of materials, the influence of the second panel burning became noticeable after 120 s as the heat flux became higher when both panels are combustible. Near the end of the test, the contribution of the panels to the heat flux was seen to become less. For the inert tests, it was shown that decreasing the standard heat release rate by 20 kW has a higher impact on the heat fluxes observed at every location than increasing it by 20 kW.

Analyzing the instantaneous flame heights, showed that for MDF peaks in the flame height could be observed in the beginning of the test, around the same time of the occurrence of the peaks in the HRR. This could not be observed in the plywood tests. A second difference regarding the flame heights of the two materials is that for plywood, no significant increase in flame heights could be observed as the flames started to penetrate the panels. However, for both types of materials, higher instantaneous flame heights were monitored when only the short panel is combustible compared to only the long panel being combustible. In the case of the inert tests, an average flame height of 0.51 m and of 1.34 m was found for the 10 kW and 50 kW tests respectively. Note, that the latter value is most likely to be an underestimation caused by the limitations of the apparatus height.

Monitoring the lateral flame spread showed that for MDF, the propagation of the pyrolysis front is halted early in the test when only one panel is combustible. Afterwards, only the propagation of a ‘delamination front’ was seen. In the case of plywood panels, this was observed for all types of tests performed. Moreover, similar positions of the pyrolysis front were seen at the end of the test when only one panel is combustible. However, the lateral pyrolysis spread continued to propagate long in the case of only the short panel being combustible. For plywood, it was seen that if both panels are combustible, the lateral pyrolysis front has advanced more on the short panel and for a long period of time.
References


EN 13823 (2002). *Reaction to fire tests for building products – Building products excluding floorings exposed to the thermal attack by a single burning item*. Brussels: Comité Européen de Normalisation.


