Ignition and Flame Spread in Wood-Based Composites

Shettihalli Anand Reddy, Vikas

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

Ignition and Flame Spread in Wood-Based Composites

VIKAS SHETTIHALLI ANANDREDDY
DIVISION OF FIRE SAFETY ENGINEERING | FACULTY OF ENGINEERING | LUND UNIVERSITY

Ignition and Flame Spread in Wood-Based Composites

Ignition and Flame Spread in Wood-Based Composites

Vikas Shettihalli Anandreddy

LICENTIATE DISSERTATION

by due permission of the Faculty of Engineering, Lund University, Sweden. To be publicly defended on January 9th at 10:00 in room V:D, V-huset, John Ericssons väg 1, Lund

Faculty opponent

Dr. Bjarne Husted, Associate Professor, Department of Civil and Mechanical Engineering, Technical University of Denmark (DTU)

Organization: LUND UNIVERSITY, Faculty of Engineering, Division of Fire Safety Engineering

Document name: LICENTIATE THESIS

Date of issue: 2025-01-09

Author: Vikas Shettihalli Anandreddy

Sponsoring organization: Trä och Möbelföretagen, Svenskt trä and RISE

Title: Ignition and Flame Spread in Wood-Based Composites

Abstract:

This thesis investigates the ignition and flame spread behaviour of engineered wood-based materials, focusing on Medium-Density Fibreboard (MDF), Particleboard, Oriented Strand Board (OSB), and Plywood. Thermal properties, such as thermal conductivity and specific heat capacity, were analysed using Transient Plane Source (TPS) measurements.

A new technique has been introduced for measuring thermal inertia as a surface property, enabling its determination through a single measurement. This method addresses the limitations of traditional approaches, which involve separate measurements of thermal conductivity, density, and specific heat capacity, often leading to compounded uncertainties. By consolidating the measurement process, the new method reduces uncertainty levels, and this improvement is particularly beneficial for applications involving ignition and flame spread.

Fire behaviour was assessed through small- and medium-scale tests, including Cone Calorimeter, Single Burning Item (SBI), and Intermediate-scale façade fire tests. Results showed variations in ignition times, heat release rates (HRR), and flame spread across different materials and heat flux levels. Plywood, for example, exhibited earlier ignition and faster flame spread compared to other materials.

Additionally, the study compared several classical empirical ignition models against experimental data. While the models corresponded well to the experimental data at higher heat flux levels (35 and 50 kW/m²), discrepancies were noted at lower heat flux level (20 kW/m²), indicating that factors beyond thermal inertia have a stronger influence on ignition under certain conditions.

Overall, this research contributes a more practical method for measuring thermal inertia and detailed insights into the fire behaviour of wood-based materials.

Key words: Ignition, flame spread, thermal properties, thermal Inertia, wood-based materials

Classification system and/or index terms (if any)

Supplementary bibliographical information

Language: English

Number of pages: 59

ISSN and key title: 1402-3504

ISBN: 978-91-8104-310-5 (print), 978-91-8104-311-2 (pdf)

Signature

Date 2024-12-04

Ignition and Flame Spread in Wood-Based Composites

Vikas Shettihalli Anandreddy

Lund University

Coverphoto by Vikas Shettihalli Anandreddy

Faculty of Engineering Department of Building & Environmental Technology
Division of Fire Safety Engineering

ISBN 978-91-8104-310-5 (print)
ISBN 978-91-8104-311-2 (pdf)
ISSN 1402-3504
ISRN LUTVDG/TVBB--1074—SE

Printed in Sweden by Media-Tryck, Lund University
Lund 2024

NORDIC SWAN ECOLABEL
Printed matter 3041 0903

Media-Tryck is a Nordic Swan Ecolabel certified provider of printed material. Read more about our environmental work at www.mediatryck.lu.se

MADE IN SWEDEN

Acknowledgement

This research would not have been possible without the unwavering support I have received from my sponsors, colleagues, friends, and family.

First and foremost, I would like to sincerely thank my sponsors, Trä och Möbelföretagen, Svenskt trä, and RISE for providing the financial support that allowed me to carry out this research and complete my licentiate thesis.

I am deeply grateful to my supervisors and colleagues at RISE in the Division of Fire Safety and at LTH in the Department of Fire Safety Engineering. A special thanks to Johan Anderson, Robert McNamee, and Per Blomqvist for their invaluable guidance, encouragement, and constant support throughout my research journey. I would also like to extend my gratitude to Professor Patrick van Hees and Nils Johansson for their insightful comments and advice, which significantly shaped my work.

I am particularly indebted to Johan Sjöström for his thoughtful feedback, for challenging my work when it was needed, and for guiding me in the right direction. My heartfelt thanks go to Hasan Sokoti for his help in conducting experiments and to Fredrik Kahl, not just for his technical support but also for being a true friend, offering both encouragement and emotional support during challenging times.

Finally, I owe my deepest gratitude to my wife Greeshma, the cornerstone of my life, whose love, unwavering patience, and belief in me have been my greatest source of strength. To my parents and family, who have always been my guiding light, and to my friends, who provided laughter and relief during the tougher moments, I am forever grateful. This journey has been made possible because of each one of you. Thank you for standing by me.

Vikas Shettihalli Anandreddy

Summary

This thesis investigates the ignition and flame spread properties of engineered wood-based materials, including Medium-Density Fibreboard (MDF), Particleboard, Oriented Strand Board (OSB), and Plywood. To understand how these materials behave under fire exposure, essential thermal properties—such as thermal conductivity and specific heat capacity—were measured using the Transient Plane Source (TPS) technique, a method that captures material-specific responses to heat. A key contribution of this work is the development of a new methodology for determining thermal inertia directly as a surface property. The simplified methodology streamlined the process of measuring thermal inertia, allowing it to be determined in a single measurement rather than through multiple experiments or tests. This approach reduces complexity and enhances the applicability of thermal inertia measurements for wood.

The fire behaviour of each material was tested on small to medium scales through a range of standardized and custom tests, including the Cone Calorimeter, Single Burning Item (SBI), and Intermediate-scale façade fire tests. These tests assessed critical fire performance metrics, such as ignition time, heat release rate (HRR), and flame spread, across different heat flux levels. Results showed notable differences among the materials, with Plywood exhibiting a tendency to ignite earlier and support faster flame spread compared to the other composites, especially at higher heat flux levels. The study also evaluated several empirical models for predicting ignition time, comparing model-based predictions with experimental data. At higher heat fluxes, the models showed good alignment with experimental results; however, lower heat flux conditions revealed discrepancies, suggesting that factors beyond thermal inertia, such as charring and material heterogeneity, may influence ignition.

Comparative analysis between the standard SBI test and the custom Intermediate-scale tests demonstrated that test configuration largely impacts fire behaviour. For example, introducing a wing flange on the Intermediate-scale façade increased both the HRR and the speed of flame spread, indicating that structural elements can intensify fire development. These findings underscore the importance of accounting for material configuration and orientation when assessing fire risk, as these factors can amplify or mitigate fire spread in practical applications.

In summary, this thesis provides a more efficient approach for measuring thermal inertia in wood composites and offers detailed insights into how various materials and configurations influence fire progression.

To love of my life Greeshma

List of figures

Contents

Appendices (only in printed version)

Paper 1 - Thermal Properties of Wood-Based Materials: Determination of Thermal Inertia.

Paper 2 - Wood-Based Material Fire Behaviour: Analysis of Vertical Flame Spread in Different Test Setups.

1 Introduction

This chapter outlines the background and motivation for the thesis, along with the research objectives. It also includes a summary of relevant publications and discusses the limitations of the study.

1.1 Background

Wood and wood-based materials, such as Medium-Density Fibreboard (MDF), Particleboard, Oriented Strand Board (OSB), and Plywood, are widely used in construction due to their versatility, favourable mechanical properties, and cost-effectiveness. These materials serve key roles in structural elements, wall panels, flooring, and furniture, adding strength and aesthetic appeal to a range of building types. With a growing emphasis on sustainable building practices, engineered wood products have become popular as renewable alternatives to traditional materials like concrete and steel (Gustavsson & Sathre 2006). However, their combustibility presents fire safety concerns, particularly regarding ignition and flame spread.

Fire safety in buildings constructed with wood-based materials is crucial, as these materials are inherently flammable and can accelerate fire growth once ignited. Wood acts as fuel, increasing heat release rates and potentially compromising structural integrity in a fire, thus posing serious risks to building occupants (White & Dietenberger 2010). Understanding the fire behaviour of wood-based materials, especially in terms of ignition characteristics and flame spread, is essential for assessing these risks and enhancing fire-safe building practices. To this end, research into factors such as thermal properties, material composition, and environmental conditions is necessary for developing building codes and fire protection systems tailored to the specific risks associated with wood in construction (Buchanan & Abu 2017).

The thermal properties of these materials, such as thermal conductivity, specific heat capacity, and density, are key factors in determining their response to heat exposure. These properties influence how quickly heat is absorbed and distributed in the material, directly affecting ignition times and flame spread rates. A useful metric that incorporates these properties is thermal inertia (Cleary 1992, Quintiere 1984), which represents a material's resistance to surface temperature changes. Materials with high thermal inertia absorb heat more effectively, leading to a slower increase in surface temperature, which delays ignition and mitigates flame spread, whereas those with lower thermal inertia, their surface heat up faster, leading to quicker ignition.

Estimating thermal inertia by measuring individual thermal properties has traditionally been a complex and time-consuming process, often resulting in uncertainty, especially for heterogeneous materials like wood composites (Li 2013, Czajkowski 2016, Lewis 1967). This research aims to address these challenges by developing a simplified methodology that improves the practical application of thermal inertia measurements. By focusing on surface temperature response, this method streamlines the process and provides a more representative understanding of fire behaviour at the material's surface, where combustion processes primarily occur.

In addition to thermal properties, factors such as geometry, orientation, and heat flux from a fire source also largely influence ignition and flame spread in wood-based materials. Sample orientation plays a key role in flame spread behaviour, with vertically positioned samples exhibiting faster flame propagation due to buoyancy effects, while horizontal samples tend to experience slower flame spread (Atreya 1986). The heat flux from a fire source is also crucial; higher fluxes deliver more energy to the material, resulting in faster ignition and more intense flame spread. Studies such as Kasymov (2020) have shown that lower heat fluxes delay ignition due to heat losses and slower pyrolysis, whereas higher fluxes allow for rapid energy absorption and quicker ignition.

To investigate these factors, a series of small- and medium-scale fire tests were conducted on four different wood-based materials from the same batch. This research examines key parameters, including ignition time, heat release rate, and fire growth rate, to improve understanding of fire performance in wood-based materials. By refining thermal property measurements, especially thermal inertia, and conducting controlled fire behaviour experiments, this study aims to provide valuable insights that will contribute to enhancing fire safety in wood-based construction applications.

1.2 Research objectives

This thesis explores the ignition and flame spread behaviour of engineered wood materials. By analysing the thermal properties that influence these processes, the research utilizes experimental methods to gain deeper insights into the fire performance of wood-based materials. The main objectives of the study are outlined below and are primarily addressed through two research papers, which are introduced in the following section:

1. *To develop a simplified methodology for measuring thermal inertia as a surface property, enhancing the practical applicability of this estimation for wood-based materials.*
2. *To explore the fire behaviour of engineered wood materials under small- and medium-scale tests.*

1.3 Publications

This thesis is based on following papers:

- Paper 1: Shettihalli Anandreddy, V., Sjöström, J., McNamee, R., Anderson, J., "Thermal Properties of Wood-Based Materials: Determination of Thermal Inertia" *(Paper is under review in a scientific journal)*
- Paper 2: Shettihalli Anandreddy, V., McNamee, R., Anderson, J., "Wood-Based Material Fire Behaviour: Analysis of Vertical Flame Spread in Different Test Setups" *The 4th International Symposium on Fire Safety of Facades - FSF 2024, RISE report 2024:45, ISBN 978-91-89971-04-2.*

The following abstract was also presented at a conference:

- Abstract: Shettihalli Anandreddy, V., Anderson, J., McNamee, R., "Comparing Empirical Ignition Models for Wood-Based Materials with Cone Calorimeter Experiment". Abstract accepted to the Nordic and Fire Safety Days and was presented at the same, 18-19 June 2024 in Lund, Sweden.

Additional publications during the research:

- Brandon, D., Sjöström, J., Just, A., Li, T., van Mierlo, R., Shettihalli Anandreddy, V. & Robijn-Meijers, P. (2023). Limiting flame spread rates in large compartments with visible timber ceilings. RISE Research Institutes of Sweden, 2023:131.

The author of this thesis led the development of both papers and was actively involved in every aspect of the research process, as detailed in Table 1.

Table 1. The author's contribution to the thesis papers.

	Author's contributions	
Research process	Paper 1	Paper 2
Formulating the research aim and planning the research design	Collaborated with the other authors in defining the research objectives and designing the concept.	Collaborated with the other authors in defining the research objectives and designing the concept.
Experiments and data collection	Primarily responsible for conducting the experiments and collecting data.	Primarily responsible for conducting the experiments and collecting data.
Analysis	Main responsible for data analysis	Main responsible for data analysis
Writing the paper	Primary author of the final paper, with contributions from other authors in the development process.	Primary author of the final paper, with contributions from other authors in the development process.
Presenting at conference	-	Delivered a poster presentation at the 4th International Symposium on Fire Safety of Facades - FSF 2024 in Lund, Sweden.

1.4 Limitations of the work

The limitations of the study can be summarized as follows, based on the content provided in the thesis:

- Thermal inertia measurement: The developed methodology for measuring thermal inertia is applied only to the specific materials used in this study. No validation will be conducted for materials beyond the scope of this research.
- Ignition Model Validation: The study does not aim to provide a comprehensive validation of the ignition model. Instead, it demonstrates the application of thermal inertia in predicting ignition time. Since ignition time is affected by multiple factors, an in-depth examination of each factor for precise model validation lies outside the scope of this research.
- Flame Spread Analysis: The flame spread analysis is limited to comparing burners with identical heat flux but different test configurations, restricting a broader understanding of how varying setups or burner characteristics might impact flame spread in other contexts.

2 Theory

The chapter provides a brief overview of wood combustion, focusing on the ignition and flame spread stages. It discusses the theory behind these stages and examines factors influencing ignition and flame spread, particularly thermal properties and their effects. The concept of thermal inertia is also introduced as an essential factor in understanding fire behaviour.

2.1 Burning of wood

The combustion of wood is a multi-stage process involving distinct phases such as smouldering, charring, ignition, and flame spread, each shaped by the unique fire properties of wood. Under heat exposure, wood undergoes pyrolysis—a process of thermal degradation that generates flammable gases. In the early stages at lower temperatures, smouldering and charring dominate. Smouldering is characterized by slow, flameless oxidation of the charred surface rather than gas release. During charring, a carbon-rich layer forms, which insulates the unburned wood beneath, reducing heat transfer into the material and influencing the progression of fire (Drysdale 2011).

As temperatures increase, flaming ignition may occur, marking the transition from smouldering to open-flame combustion. Ignition depends on intrinsic wood properties, such as density, moisture level, and specific heat, alongside external factors like oxygen concentration and surrounding temperature (Babrauskas 2003). Released pyrolysis gases combine with oxygen, sustaining visible flames and initiating the flame spread across the wood's surface. Flame spread behaviour is shaped by surface texture, orientation, and fuel layout.

In this thesis, the focus will be on studying the ignition and flame spread characteristics of wood to provide an understanding of these stages in the burning process.

2.2 Ignition

Ignition refers to the point at which a solid material, upon sufficient heating, undergoes pyrolysis, releasing flammable vapours that mix with oxygen, leading to sustained combustion (Babrauskas 2003). This process marks the transition from a solid state to active burning, depending on specific conditions such as heat flux, material decomposition, and environmental factors like oxygen availability. There are two primary types of ignitions: piloted ignition, where an external source like a spark or flame initiates combustion, and autoignition, where the material ignites on its own without any external source, due to heat accumulation (Drysdale, 2011).

Several factors affect the ignition of materials, including their thermal properties as discussed (Section 2.4). Additionally, geometric factors, such as the orientation of the sample (Shields 1993) and the placement of the ignition source, play a key role. Furthermore, the heat flux from the ignition source (Kasymov 2020)) influences the ignition process.

This study focuses on piloted ignition, utilizing a series of tests conducted with a cone calorimeter (ISO 5660-1 2015) to examine the ignition of materials under different heat fluxes. Additionally, further analysis was conducted to investigate how ignition time is influenced by thermal properties.

2.2.1 Ignition models

Several ignition models have been developed to predict pilot ignition times for wood-based materials. One of the earliest models is the Lawson and Simms (1952) model, which empirically relates radiation intensity, time to ignition, and thermal properties of wood species based on experimental data. The model relies on two hypotheses: (1) wood behaves as an inert material, and (2) surface cooling follows Newton's law, meaning the rate of heat loss from the wood surface is proportional to the temperature difference between the surface and the surrounding environment. The model concludes that pilot ignition occurs for heat fluxes exceeding a critical value, expressed in the following equation:

$$(\dot{q}''_e - \dot{q}''_{cr}){t_{ig}}^{2/3} = 0.025 \times 10^6(k\rho c + 68 \times 10^{-6}) \qquad \text{eqn. 1}$$

Where, $\dot{q}''_e$ is the Incident heat flux, $\dot{q}''_{cr}$ is the critical heat flux, $k\rho c$ is the Thermal inertia, and t_{ig} is the ignition time.

The model effectively predicts ignition time in controlled conditions but is limited by its assumptions, such as the exclusion of pyrolysis, variations in wood species, and assumes constant thermal properties.

Janssens (1991) model is a simplified thermal model for piloted ignition of wood, incorporating several assumptions to focus on the heat transfer process. It assumes constant thermal properties, treating wood as a semi-infinite solid with no pyrolysis or chemical effects before ignition. Heat flow is one-dimensional, and the surface loses heat through both radiation and convection. This model predicts ignition when the wood surface reaches a material-dependent critical temperature. The mathematical expression is given below:

$$\dot{q}_e'' = \dot{q}_{cr}'' \left[1 + 0.73 \left(\frac{k\rho c}{h_{ig}^2 t_{ig}}\right)^{0.547}\right] \qquad \text{eqn. 2}$$

Where, h_{ig} is the convection coefficient from the surface at ignition.

In this model, the critical heat flux ($\dot{q}_{cr}''$) is found by plotting $(1/t_{ig})^{0.547}$ against incident heat flux, with the intercept of the line providing ($\dot{q}_e''$). The apparent thermal inertia ($k\rho c$) is calculated from the slope of the same line. For wood materials, this apparent value represents a temperature that lies midway between the ambient temperature and the ignition temperature (T_{ig}), giving an average thermal response over the ignition process.

Spearpoint and Quintiere (2001), Tewarson (2002), and Quintiere (2006) developed similar ignition models based on time to ignition derived from cone calorimeter experiments. This model, as shown in eqn. (3), assume that ignition occurs when the surface reaches a critical temperature (T_{ig}), treating the material as inert up to ignition and infinitely thick.

$$t_{ig} = \frac{2}{3}\frac{k\rho c\left(T_{ig}-T_0\right)^2}{\dot{q}''^2} \qquad \text{eqn. 3}$$

Where, T_0 ambient temperature and $\dot{q}''$is net heat flux.

Like Janssens' model (Janssens 1991), the critical heat flux ($\dot{q}_{cr}''$) is determined by plotting $1/\sqrt{t_{ig}}$ against the incident heat flux. The thermal inertia ($k\rho c$ is found from the slope, and the average ignition temperature can be calculated from the critical heat flux. Janssens' model uses a power-law relationship with an exponent of 0.547 to plot ignition time against heat flux, providing a more accurate fit by accounting for temperature-dependent thermal properties. In contrast, Quintiere's model uses a simpler exponent of 0.5, offering a more straightforward approach that simplifies analysis but may reduce precision. These models are accurate for high heat flux (>20 kW/m^2), but at lower heat fluxes, different ignition mechanisms (such as char oxidation, heat loss to the boundary) may precede flaming (Spearpoint and Quintiere 2001).

The Wickström (2015) model is an analytical approach to calculate the time for semi-infinite solids, like wood, to reach a specified ignition temperature when exposed to constant incident radiation and gas temperatures. The model assumes constant thermal properties, emissivity, and convection heat transfer coefficients, while solving the heat conduction equation. It simplifies the non-linear boundary condition (due to radiative heat losses) using a semi-empirical formula, providing an efficient approximation for predicting ignition time without needing complex numerical simulations and expressed as:

$$t_{ig} = \frac{\pi(k\rho c)}{4}\left[\frac{T_{ig}-T_0}{\varepsilon(\dot{q}_e''-0.8\,\dot{q}_{cr}'')}\right]^2 \qquad \text{eqn. 4}$$

Where, ε is emissivity (An emissivity value of 0.7 was chosen based on literature, as engineered wood products may have a more reflective surface, which can result in a lower emissivity compared to natural wood. This choice accounts for the smoother, possibly more uniform finish that engineered wood products often exhibit.).

The value of 0.8 in the equation is an empirically derived constant, optimized by comparing the formula's predictions with accurate numerical solutions obtained using finite element methods.

Babrauskas' (2002) ignition model establishes a relationship between ignition time, wood density, and incident heat flux. Through theoretical and experimental analysis, Babrauskas gathered data on wood specimens with varying densities (170–850 kg/m³). His model suggests that as density increases, so does the material's thermal conductivity, affecting the time to ignition. He developed a correlation based on the incident heat flux and material density, expressing ignition time as a function of these variables. This model is further refined by adjusting moisture content and geometric orientation effects and expressed as:

$$t_{ig} = \frac{130\rho^{0.73}}{(\dot{q}_e''-11.0)^{1\cdot 82}} \qquad \text{eqn. 5}$$

Where, ρ is density.

Despite its utility, the model has notable limitations. With a root-mean-square error of 64%, it provides only semi-quantitative predictions of ignition times. Additionally, at lower heat fluxes (below 15 kW/m²), wood deviates from the thermally thick assumptions, leading to systematic errors (Babrauskas 2002). Thus, while helpful, the model's accuracy diminishes under certain conditions, particularly at lower heat flux values.

2.3 Flame spread

Flame spread refers to the process by which flames propagate across a material's surface during combustion. It is a critical aspect of fire behaviour, as the rate and extent of flame spread can influence the intensity and progression of a fire. Flame spread is affected by several factors, including thermal inertia, surface charring, and heat flux. A key parameter in understanding fire behaviour is the HRR (Martinka 2023), which provides insight into fire characteristics such as total heat release, effective heat of combustion, and the fire growth rate index (FIGRA).

FIGRA is defined as the maximum ratio of HRR to time, represented by the following equation:

$$FIGRA = max_{\mathrm{i}=t_s}^{t_{end}} \left(\frac{HRR}{t_i}\right) \qquad \text{eqn. 6}$$

Where, t_s is start time.

FIGRA serves as an indicator of flame spread. A material with a higher FIGRA value releases a more amount of heat over a short time, thus accelerating flame spread. Conversely, a material with a lower FIGRA value indicates slower fire development and a reduced rate of flame spread. This metric is crucial in assessing fire safety and material performance during combustion.

In this study the fire growth rate was determined using two test methods under different configurations, one is Single burning item (SBI) (EN 13823:2020) and the other Intermediate-scale test.

Quintiere's (1988) model further refines the understanding of upward flame spread by connecting flame spread velocity (V_p) to material properties and flame heat flux, described by the following equation:

$$V_p = \left(\frac{4\left(\dot{q}_f''\right)^2}{\pi k\rho c\left(T_{ig}-T_s\right)^2}\right)\left(x_f - x_p\right) \qquad \text{eqn. 7}$$

Where, $\dot{q}_f''$ is flame heat flux, $k\rho c$ is thermal inertia, T_{ig} is ignition temperature, T_s is surface temperature, x_f is flame height, and x_p is pyrolysis front.

The eqn. (7) shows that flame spread velocity is directly proportional to the flame heat flux and inversely related to the material's thermal inertia. High heat flux accelerates flame spread, while materials with higher thermal inertia require more energy to reach ignition, thereby slowing down the spread rate. This theoretical framework underlines how external heat and inherent material properties collectively drive flame spread behaviour.

2.4 Parameters influencing ignition and flame spread

Several studies have been carried out on assessing parameters that influence ignition and flame spread of wood-based materials, like density, materials, heat flux, porosity, moisture content, etc Zhou (2024), Bartlett (2019), Hao (2020), Marková (2022). Key parameters discussed here are the thermal properties of the materials.

2.4.1 Thermal conductivity, specific heat capacity, and density

Thermal conductivity refers to a material's ability to conduct heat. Higher thermal conductivity enables a material to conduct heat more effectively throughout its volume. Such an effective distribution of heat usually results in a slower rise in surface temperature and can delay ignition of the material. This follows since, in materials where thermal conductivity is lower, there will be more rapid heating at the surface due to less heat being conducted away. It may then lead to quicker ignition, as the surface reaches the critical ignition temperature more rapidly.

Specific heat capacity is the energy required to raise the temperature of a unit mass of any material by one-degree Kelvin. High specific heat materials require more energy to increase their temperature. This characteristic implies that these materials, compared to others, will absorb more heat before a substantial rise in their temperature is noted, and hence take a longer time to achieve their ignition temperature. Generally, this means that materials with larger specific heat capacities will experience ignition at more delayed times compared to those with lower values of this property.

The relationship between thermal conductivity and ignition is dependent on aspects such as density. Denser materials usually have fewer air gaps and a higher proportion of solid constituents, which eases the flow of heat. Experiments have proven that the thermal conductivity of wood-based materials rises with increasing densities. For example, Shida and Okuma (1981) observed that the higher the apparent specific gravity of particleboard, the higher the thermal conductivity. Similarly, findings by Suleiman et al. (1999) also showed that the higher the density in wood materials, the higher the thermal conductivity, as the reduction in space for air allows for a clearer route for the conduction of heat.

It is important to note that among the materials used in this study, MDF, particleboard, and OSB exhibit very similar thermal conductivity and density, while plywood has a noticeably lower thermal conductivity and density compared to the other materials. On the other hand, all the materials tested have very similar specific heat capacities, with variations within ±10% (Paper 1). Given the similarities in specific heat capacity, the differences in thermal conductivity and density become particularly important when evaluating their impact on ignition and flame spread. Understanding how these properties influence the fire behaviour of materials is therefore essential for accurately assessing their fire performance.

Moisture content affects both thermal conductivity and specific heat capacity of wood-based materials. Higher moisture levels normally raise thermal conductivity since water is a better conductor of heat compared to air. Additionally, water, having a higher specific heat capacity than dry wood, increases the overall specific heat capacity of the material. This effect was noted by TenWolde et al. (1988), who discussed how moisture variations impact the thermal properties of wood and wood-based materials, which directly influence ignition and flame spread.

Furthermore, it is important to recognize that wood is an anisotropic material, meaning its thermal properties, such as thermal conductivity, differ depending on the direction of heat transfer relative to the grain pattern. Thermal conductivity along the grain is higher than across the grain in both radial and tangential directions, as demonstrated by Adl-Zarrabi and Boström (2004). Hu (2023) further showed that, for spruce, the longitudinal thermal conductivity is approximately three times greater than the radial thermal conductivity. This directional dependence is important when considering the performance of the material under conditions where the direction of heat flow is a key factor. For example, Czajkowski et al. (2016) demonstrated that thermal conductivity in wood-based panels was higher in the plane of the panel than perpendicular to it, highlighting the need to account for directional properties in thermal modelling.

The factors influencing thermal conductivity and specific heat capacity also pose challenges during measurements. One important issue is the anisotropic nature of wood, where the thermal conductivity varies depending on the direction of heat flow relative to the grain, leading to variability in measurements (Suleiman et al., 1999). Additionally, moisture content plays a crucial role; even minor changes can cause fluctuations in thermal conductivity and specific heat capacity, making it difficult to obtain consistent results (TenWolde et al., 1988). Temperature dependency is another factor, as both thermal conductivity and specific heat capacity of wood can change non-linearly with temperature, complicating the process of obtaining a single representative value (Siau, 1984; Kollmann & Côté, 1968). The heterogeneous composition of wood composites, with varying grain orientations and material densities, further complicates measurements, as these variations can result in non-uniform thermal properties across different samples (Steinhagen, 1977). Furthermore, the limitations of existing experimental methods and equipment, such as the difficulty in maintaining uniform temperature distribution and ensuring proper contact between sensors and samples, introduce additional uncertainties in data collection (Gustafsson, 1991).

The density of wood is a crucial factor that impacts heating and charring times, thereby influencing ignition and flame spread processes in wood-based materials. As previously discussed, it has been well-established that variations in density of wood lead to differences in the material's thermal and combustion properties.

When considering ignition, density plays a key role by affecting the adsorption and retention of heat within the material. Higher-density woods contain more mass per unit volume, which means they store more energy. Consequently, the time required to reach ignition temperature is longer for denser materials, as they store more energy before becoming exposed to the heat source. This phenomenon was also demonstrated in the research conducted by White and Dietenberger (2010), which showed that denser wood species generally have longer ignition times due to their higher thermal mass and a slower rate of surface temperature increase.

Both White and Dietenberger (2010) and Babrauskas (2003) observed that density of wood plays a key role in fire behaviour. White and Dietenberger noted that denser hardwoods generally have slower flame spread rates than less dense softwoods under similar conditions. Similarly, Babrauskas found that high-density woods like oak take longer to ignite compared to low-density woods, such as pine, when exposed to the same heat sources. These findings highlight that denser woods tend to resist ignition and flame spread more effectively due to their ability to absorb and store heat.

After ignition has occurred, the area-weighted density of wood still plays a role in the spread of flames over its surface. In general, flame spread rates are slower in materials of higher densities. Basically, this is because the thermal mass is usually enhanced in denser materials, hence an increased ability to absorb more heat. In turn, this reduces the heat that can preheat adjacent unburned material and, therefore, slows the advance of the flame front.

Density also plays a key role in influencing the heat release rate (HRR) of wood during combustion. Formally speaking, it may be that denser materials tend to release more energy over the duration of their combustion due to the greater amount of fuel per unit volume. However, in many cases, the energy is released at a lower rate, which leads to a more controlled and slower combustion process. On the other side, Janssens (1991) provides empirical evidence of the fact that wood species having a higher density released a lower amount of heat in comparison to the species having a lower one. Herein, the rate of the spread of the flame is delayed in case of higher density wood.

Another critical area where density influences wood combustion is in char formation. Char is a carbonaceous residue that forms during burning of wood. This char layer plays a crucial role as a barrier, insulating much of the underlying fuel from additional heat. Denser woods tend to produce thicker and more cohesive char layers, which makes it more difficult for flames to penetrate. Hong and Park (2023) studied flame spread in Douglas Fir, revealing that the char formed acts as a thermal insulating layer, effectively impeding the rate of flame spread, particularly in thermally thick regimes. Their research demonstrated that this effect is even more pronounced in thicker wood specimens, where the char layer obstructs heat from reaching the interior, thereby reducing the pyrolysis rate and limiting flame spread.

2.4.2 Thermal Inertia

Thermal inertia, defined by the combination of thermal conductivity (k), specific heat capacity (c), and density (ρ), describes how a material's surface temperature changes when exposed to heat. It reflects a material's ability to absorb and distribute heat: materials with higher thermal inertia ($k\rho c$) experience a slower surface temperature increase, which helps delay ignition and flame spread, enhancing fire resistance. In contrast, materials with lower thermal inertia heat up rapidly, leading to quicker ignition and flame spread. These behaviours are illustrated in Figure 1, showing temperature curves for materials with both higher and lower thermal inertia.

However, ignition and flamespread are influenced by various parameters as described in previous section, measuring those parameters individually requires analysing each property under varying conditions, which can lead to a large number of tests and complex analysis. To avoid the extensive testing and to streamline the process, an optimal solution must be found for measuring thermal inertia.

Additionally, ignition and flame spread are surface phenomena in fire propagation, thermal inertia plays a crucial role in analysing these parameters (Quintiere 1987).

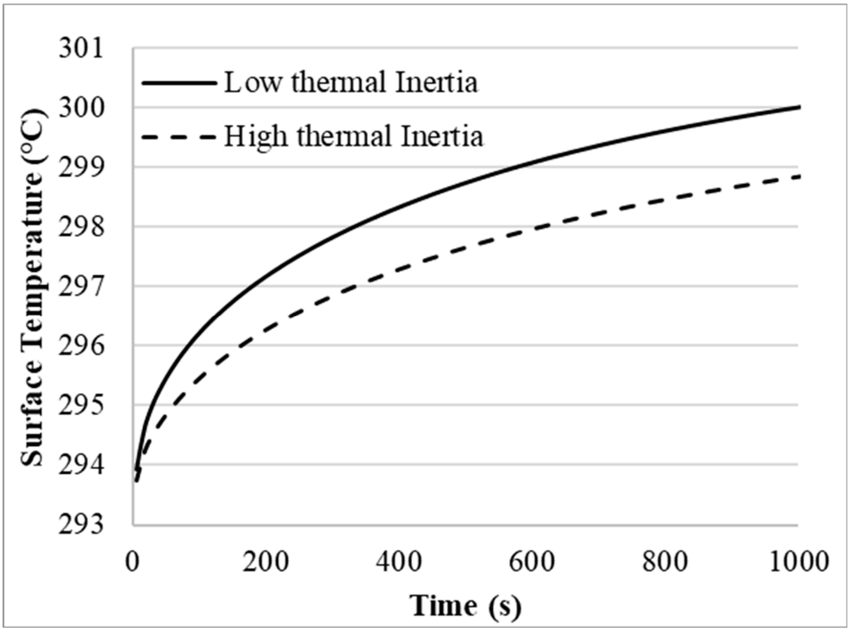


Figure 1. Effect of thermal inertia on surface temperature, where a constant heat of 50 mW was applied: low thermal inertia (plywood) vs. High thermal inertia (OSB).

3 Materials & Experiments

This chapter outlines the materials and experimental methods used in the study. The experimental methods are divided into two groups, the first group focuses on determining the thermal properties of materials, including thermal conductivity, specific heat capacity, and thermal inertia. The second group involves reaction-to-fire tests, such as the Cone Calorimeter, Single Burning Item (SBI), and Intermediate-scale tests, to evaluate the ignition and flame spread behaviour of these wood-based composites.

3.1 Materials

A brief overview of the materials used in the study is presented, focusing on four wood-based materials: Medium-Density Fibreboard (MDF), Particleboard, Oriented Strand Board (OSB), and Plywood, as illustrated in Figure 2. These composite materials are made from fibres, particles, flakes, or veneers bonded with adhesives. They consist of 94% or more wood by mass, with common binders being phenol-formaldehyde, urea-formaldehyde, melamine-formaldehyde, and isocyanate (Stark 2010).

MDF is derived by defibrating wood into fine fibres that are combined with adhesives and then compressed under high pressure and temperature. MDF is produced through a dry process and has consistent density with a smooth surface, which is useful in numerous applications.

Particleboard consists of wood flakes and wood wastes converted into minute particles. These are then mixed with adhesives, formed into sheets, and compressed in two stages: at room temperature and finally at high temperature.

OSB is manufactured by layering different sizes of wood strands oriented otherwise and combining them with adhesives before pressing the mixture under high temperature to bond. In each layer, strands are organized to a degree that maximizes mechanical strength and minimizes anisotropy; hence, larger strands are placed in the outer layers and smaller strands within the centre.

Plywood is an assembly of layers pressed together that have been placed so that the grain of one layer will be at right angles to the adjacent one. The stacking of layers, or cross-graining, adds strength and dimensional stability, reducing swelling, shrinking, or warping. In most instances, plywood has an odd number of layers with the grain of the outside veneer running lengthwise of the panel, and the inner crossband set perpendicularly.

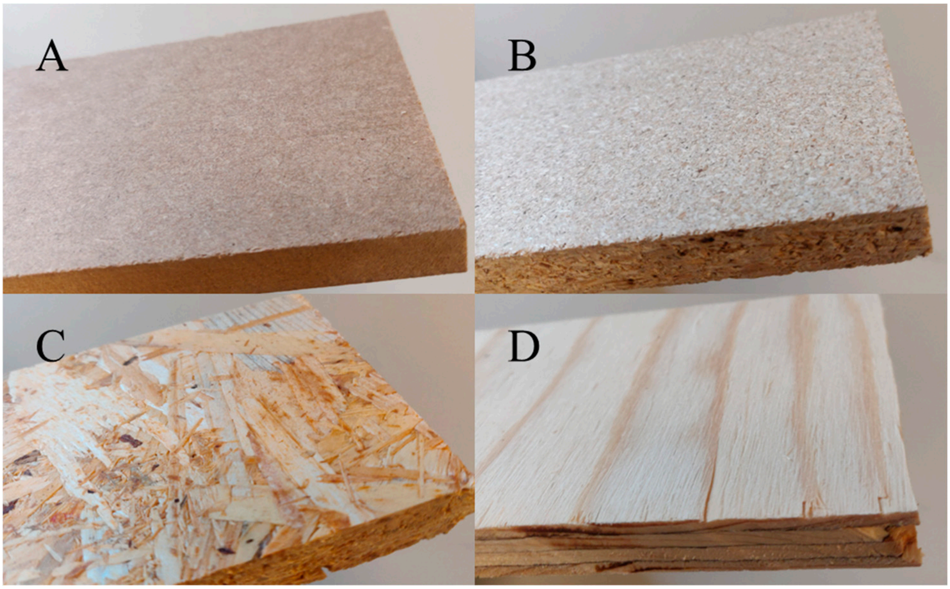


Figure 2. Visual comparison of four common wood-based composite panels: A-MDF, B-Particleboard, C-OSB, and D-Plywood.

3.2 Experiments to determine material properties

3.2.1 Transient plane source (TPS)

The thermal conductivity of the materials was measured using the Transient Plane Source (TPS) technique at room temperature, following the method described by Gustavsson (1991). The experimental setup included a hot disk sensor made from a 10 µm bifilar nickel spiral sandwiched between two layers of Kapton insulation, with an overall thickness of 70-80 µm. This sensor functions as both the heating source and the temperature sensor.

During the test, the sensor was placed on the centre of 100 x 100 mm samples, and another sample was placed on top to ensure optimal contact without compression as shown in Figure 3. A constant power of 60 mW was supplied to the sensor for about 80 seconds. As the temperature increased, the resistance of the nickel changed, which was recorded and analysed using the integrated software of the TPS equipment (Hot Disk TPS 2500S, software version 7.5.15) to determine the thermal conductivity of the materials. The TPS equipment is effective for homogeneous and isotropic materials, as it enables the simultaneous measurement of thermal conductivity, thermal diffusivity, and volumetric heat capacity. However, when applied to heterogeneous and anisotropic materials, the accuracy of the TPS equipment depends on the provided volumetric heat capacity. For precise thermal property measurements in anisotropic materials, the volumetric heat capacity must be determined separately through an additional measurement before testing (Trofimov, 2020). Furthermore, the method reports an uncertainty of 3% in thermal conductivity measurements as per Gustavsson (1991) and 5% according to Tarasovs (2021).

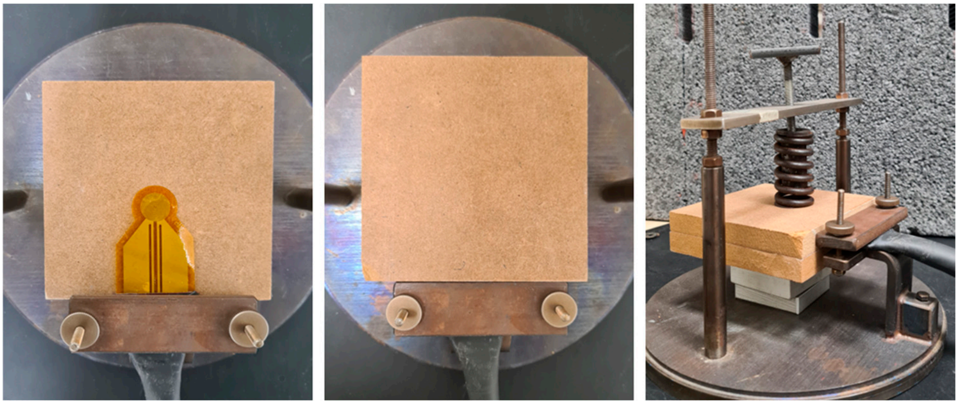


Figure 3. TPS experimental setup.

3.2.2 Gold-box method

Specific heat capacity was determined at room temperature using a sample holder with a TPS sensor according to Gustavsson (1996). The setup involved attaching a brass cylinder, measuring 19 mm in diameter and 5 mm in height, to the TPS sensor as shown in the Figure 4. To ensure accurate readings, the holder was thoroughly insulated, and the sample was subjected to a constant power supply for 80 seconds. A baseline measurement was taken by running the test without a sample, using the same duration but with reduced power to account for heat losses. The heating powers used were 70 mW for the empty holder, 90 mW for MDF and plywood, and 95 mW for OSB and particleboard. To accurately set up the test, several precautions must be followed, and by adhering to the steps specified in the Hot Disk manual (Hot Disk 2001), the specific heat capacity can be determined with an accuracy of ±2% through a series of repetitions. According to Berger (2013), the measurement uncertainty for this method is reported to be 6%.

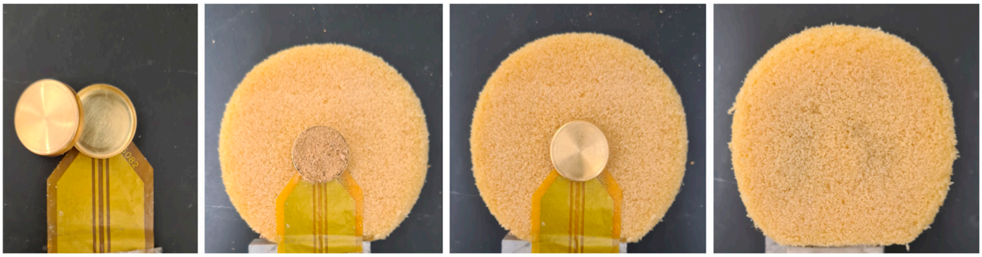


Figure 4. Experimental setup for specific heat capacity measurement.

3.2.3 1D experiment

This experimental setup was designed by the author and researchers at RISE to measure thermal inertia as a surface property and the experimental setup consist of:

Circular samples, denoted as (1) in Figure 5, were prepared with a uniform thickness and cut to match the radius of the TPS sensor (9.7 mm) to ensure the validity of the one-dimensional heat transfer assumption. The TPS sensor (2) was positioned symmetrically between two of these samples to maintain effective insulation along the symmetry line. The entire setup was insulated using extruded polystyrene (XPS) (3), as shown in Figure 5, to adhere closely to the one-dimensional heat transfer requirement. This insulation setup minimized lateral heat loss, ensuring accurate results under the experimental conditions.

The TPS sensor consisted of a bifilar nickel spiral with a radius of 9.72 mm and a thickness of approximately 10 μm. The spiral was insulated with Kapton, bringing the total thickness of the sensor to around 70-80 μm, which temperature measurements. The experiments were conducted in a controlled laboratory environment at 22°C and 50% relative humidity. The TPS sensor delivered a constant power of 50 mW over a period of 1280 seconds, during which the temperature data was recorded.

After obtaining the temperature-time curve from the experiment, a one-dimensional (1D) heat transfer equation was applied to fit the curve. A challenge in this approach was the inability to confirm if heat transfer remained strictly 1D throughout the entire test duration, as heat loss to the boundaries can occur over prolonged periods. To address this limitation, a 1D heat transfer simulation was conducted to identify the time range during which the 1D assumption held true. This validated segment of the temperature-time curve was then used to calculate thermal inertia.

A detailed discussion on the methodology for measuring thermal inertia is provided in Paper (1).

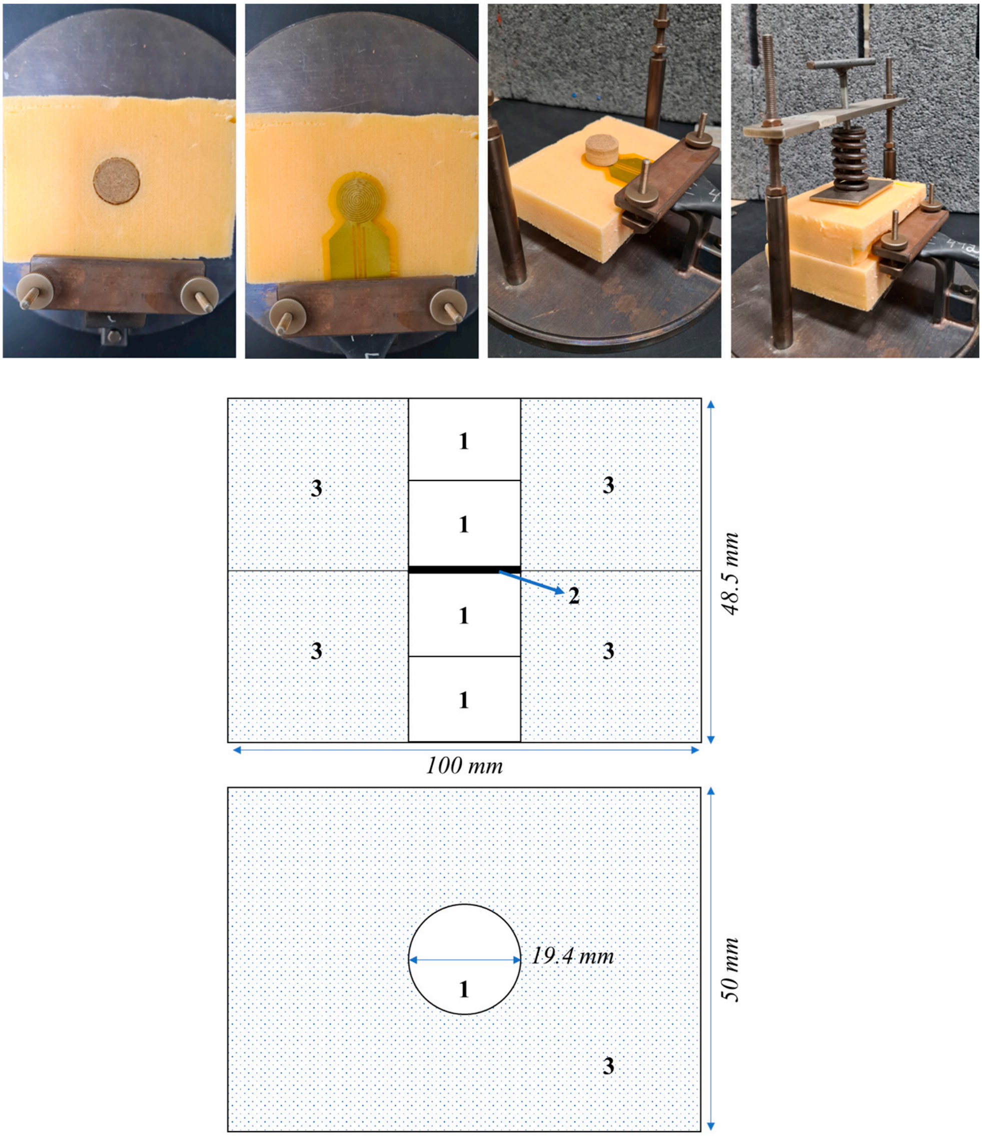


Figure 5. 1D heat transfer experimental setup and the schematic of the same.

The proposed methodology offers several advantages:

- Practicality: Traditional methods require multiple experiments and assumptions about certain parameters to gather the necessary data, which can be time-consuming and resource intensive. This streamlined approach requires only one experiment, making it more practical for both research and industrial applications. This increased efficiency not only saves time but also reduces the cost and complexity associated with fire behaviour analysis.

- Surface Property Relevance: Ignition and flame spread predominantly occur at the surface of materials, making surface temperature response crucial in determining fire behaviour. By accurately measuring thermal inertia, which reflects how surface temperature reacts to heat exposure, we can better capture the key factors influencing fire dynamics. This approach enhances the reliability of fire scenario predictions by focusing on the most relevant aspects of material behaviour during fire events.
- Reduction of Measurement Uncertainty: Measuring thermal inertia as a single property, rather than individually determining thermal conductivity, specific heat capacity, and density, reduces potential errors and inconsistencies. This method minimizes cumulative uncertainties that often arise from conducting multiple separate measurements.

Limitations of the method:

- Potential error in fitting the temperature-time curve to the one-dimensional (1D) equations: This could arise from the approach used to determine thermal conductivity, where a range of conductivity values was tested in the simulation to match the experimental temperature-time curve. Using thermocouples near the boundaries and on the opposite side of the sample could improve accuracy by providing clearer indications of when the 1D assumption breaks down.
- Additionally, since the tests were conducted solely on the materials used in this study, further validation with standardized materials would strengthen the reliability and applicability of the methodology.

3.3 Reaction to fire test

3.3.1 Cone Calorimeter

The Cone Calorimeter is a small-scale reaction-to-fire testing instrument, standardized under ISO 5660-1 (2015). This test is essential for measuring various fire-related parameters, including heat release, ignition time, and smoke production. Named for its heater, which is shaped like a truncated cone, the calorimeter features an electrical heating element capable of delivering 5,000 W at the operating voltage and producing a heat flux ranging from 0 to 75 kW/m². The setup includes several key components: a radiation shield to protect the specimen from irradiance before testing, an electric spark plug for ignition, a weighing device to measure the mass loss of samples during the test, and an exhaust system to collect combustion gases to calculate HRR and containing a laser system to determine smoke production. The schematic diagram of the Cone Calorimeter setup is provided in the Figure 6.

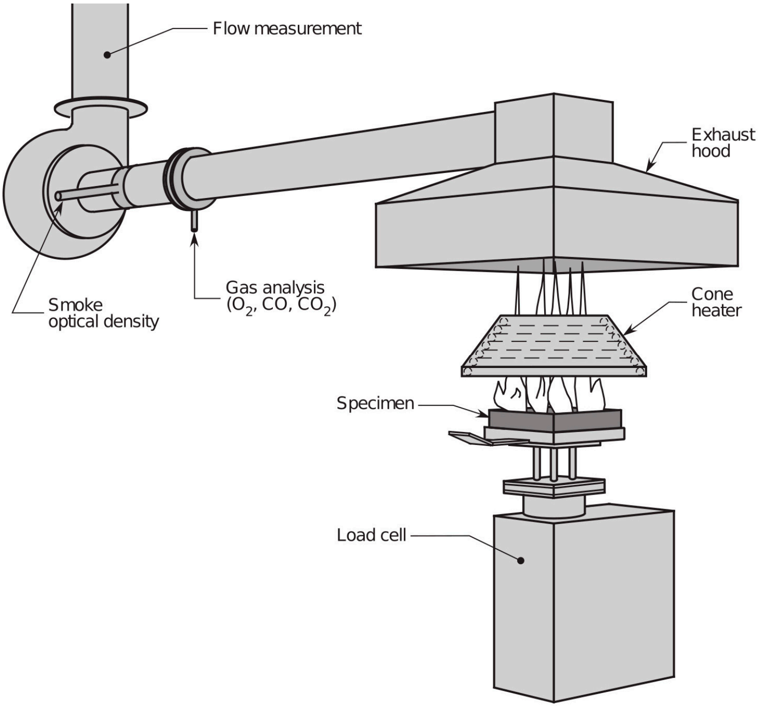


Figure 6. Cone calorimeter experimental setup

Sample Preparation

Prior to testing, samples were conditioned for over four weeks in a climate-controlled environment set at approximately 23°C with 50% relative humidity. Samples were prepared according to ISO standards by cutting them to dimensions of 100 mm x 100 mm from their original boards. The sample thickness was about 11-12 mm, thus using the entire sample as is.

Each sample was then wrapped in a single layer of aluminium foil, with the shiny side facing the sample. The foil was pre-cut to cover the bottom and sides of the sample, extending 3 mm beyond the upper surface. The excess foil was folded to ensure no foil was visible after placing the sample in the holder and securing it with a retainer frame.

Testing Procedure

Before beginning the test, the equipment was calibrated for each change in irradiance level to ensure accurate heat flux. Once the calibration was completed, the prepared sample was placed on the weighing device. The radiation shield was kept in place to protect the sample from the heater until the test began. When ready, the shield was removed, and the test was initiated by inserting the spark plug igniter. The igniter was removed once sustained flaming occurred, and the ignition time was recorded.

Tests were conducted at three different heat flux levels: 20, 35, and 50 kW/m². Each test was repeated three times at each heat flux level for each sample, as per the standard requirements. Data was recorded at every 2-second interval throughout the test.

Data Collection and Analysis

Throughout the test, several parameters were measured and recorded. These included the heat release rate, time to ignition, and smoke production, etc. Physical changes to the sample, such as swelling, or cracking, were also observed and documented. The data collected was analysed to determine the mean heat release rate readings for the three tests conducted at each heat flux level. Any deviations from the mean of the three tests (greater than 10%) prompted additional testing to ensure the accuracy and reliability of the results.

The cone calorimeter test was specifically conducted to investigate the ignition behaviour of engineered wood materials under controlled heat flux conditions. The primary interest was measuring the ignition time at different flux levels and correlating these findings with the thermal inertia of each material. This data was used to compare experimentally measured ignition times with those predicted by various ignition models, providing a basis for assessing the fire response of these materials on a small scale. The insights from the cone calorimeter test contribute directly to the broader goal of exploring the fire behaviour of engineered wood.

3.3.2 Single Burning Item

The Single Burning Item (SBI) test, defined by European standard EN 13823:2020, assesses the reaction to fire performance of building products, excluding flooring, when exposed to thermal attack from a single burning source. This test is used for classifying materials within the Euroclass system (EN 13501-1:2018).

The test apparatus comprises several components, including a trolley, frame, burners, a hood to collect combustion gases, and a collector with baffles and a horizontal outlet for the exhaust duct. The entire setup is situated in a test room with specific dimensions and construction materials to ensure consistent and accurate testing conditions, as illustrated in the Figure 7.

The SBI test setup features a movable trolley with a fixed frame designed to hold the test specimens. These specimens are mounted on two perpendicular wings: the short wing, measuring 0.5 meters in width and 1.5 meters in height, and the long wing, measuring 1 meter in width and 1.5 meters in height. The specimens are backed by calcium silicate boards, which serve as backing boards but are not fixed to the samples.

The SBI setup also includes two triangular-shaped burners: the primary burner and the secondary burner. The secondary burner, attached to the trolley frame, is ignited at the test's start to optimize the heat release rate. After 300 seconds, the primary burner, located in the corner near the samples, is ignited. Both burners produce approximately 30 kW of heat, creating a controlled thermal exposure on the specimens.

The SBI test was conducted to assess parameters such as the HRR and the Fire Growth Rate (FIGRA), among others. These metrics are used to classify the fire performance of materials under the Euroclass system. It also providing insights into the behaviour of materials under different testing conditions and heat sources. By using a different burner configuration, the SBI test helps in understanding how the materials respond, and it allows for comparisons with other tests to verify the consistency of the findings. Prior to testing, samples were conditioned for over four weeks in a climate-controlled environment set at approximately 23°C with 50% relative humidity. Each material undergoes three tests to ensure the reliability and accuracy of the results.

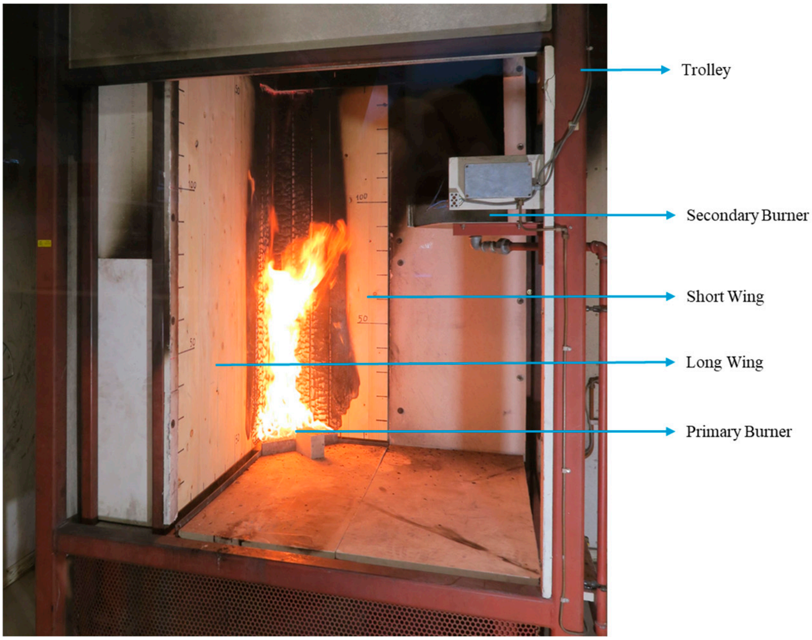


Figure 7. Single Burning Item test setup.

3.3.3 Intermediate scale test

A custom test rig was designed and built for flat façade testing, as shown in Figure 8, inspired by the ISO 13785-1:2002 reaction-to-fire test for façades, which was also used by Hakkarainen (2002) in similar studies. The ISO 13785-1 setup typically employs a corner configuration to evaluate three-dimensional flame spread and heat transfer effects. However, a flat façade configuration was chosen in this study to investigate differences in fire spread behaviour under varying façade configurations and ignition sources.

The rig was constructed using 40 mm square steel rods, with an overall height of 2.4 meters and a width of 1.2 meters. Additional components included gypsum boards for the floor and rollers to support the specimens.

The test specimens were conditioned for over four weeks in a climate-controlled environment set at approximately 23°C with 50% relative humidity and then cut to a height of 2.2 meters and a width of 1.2 meters. They were placed freely on the test rig, supported by rollers on both sides, and positioned within a U-shaped profile resting on two load cells at either end of the rig, as shown in Figure 8.

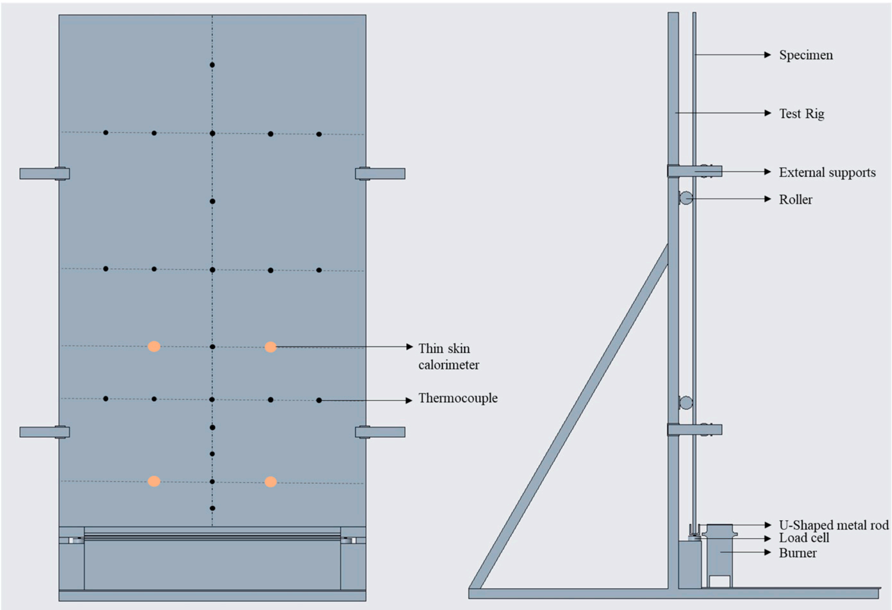


Figure 8. Intermediate-scale test setup (Front and Side view) showing all the instrumentations.

A line burner was used as the fire source, placed 5 cm away from the specimen. The burner measured 1 meter long, 0.2 meters high, and 0.1 meters wide, providing a constant heat output of 30 kW. When comparing the SBI test and the intermediate scale test, even though the overall heat output is similar, the burner configurations and placements differ between the two tests. In the SBI test, a triangular burner is positioned in the corner of the setup, which creates a concentrated flame and directs more heat onto the adjacent surfaces. Conversely, in the Intermediate-scale test, a rectangular burner is placed along the base of the façade, providing a more distributed heat source across the specimen.

To verify the heat flux delivered to the surface in the Intermediate-scale setup, a test was conducted using a series of plate thermocouples arranged in three rows and columns on an inert material, along with a heat flux meter, as shown in Figure 9.

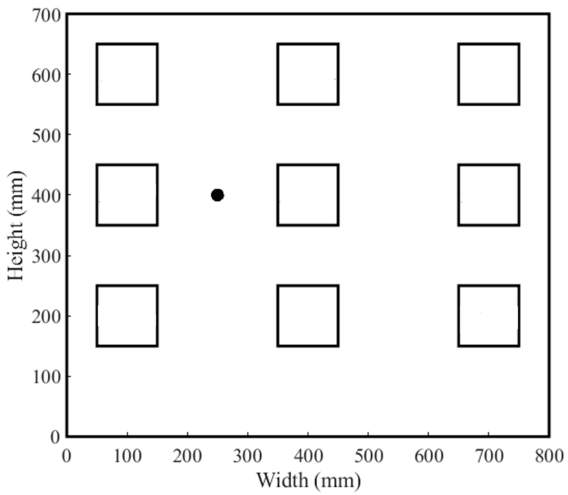


Figure 9. Experimental measurement of temperature using plate thermocouples (square) and heat flux via total heat flux meter (black circle) under 30 kW heat flow from burner.

Temperature measurements were taken at various heights along the board and horizontally. The temperature measurements provide insights into the extent of flame travel along both the vertical and horizontal surfaces of the material. The detailed instrumentation is shown in Figure 10, with black dots representing 0.2 mm K-type thermocouples, orange circles indicating thin skin calorimeters, and a black square on top indicating a plate thermocouple. Holes were drilled through the samples to insert the thermocouples, which were placed 5 mm away from the samples with the tips facing downwards.

The entire setup was placed under a hood to collect smoke, and heat release measurements were taken during the test. Heat release data were recorded every 2 seconds, while temperature data were recorded every second. Each test lasted 15 minutes and was repeated twice for each sample.

A distinctive experiment was conducted with plywood, featuring the addition of a 100 mm wing flange positioned at the center of the board. The test utilized the same burner setup as in the Intermediate-scale test, and temperature data were collected in a similar manner. The configuration of this setup is shown in the Figure 11.

The key parameters of interest in this experiment were the HRR over time curves, which were used to calculate FIGRA values, and the temperature data collected from thermocouples along the vertical axis. These measurements directly relate to the research objective of exploring the fire behaviour of engineered wood materials.

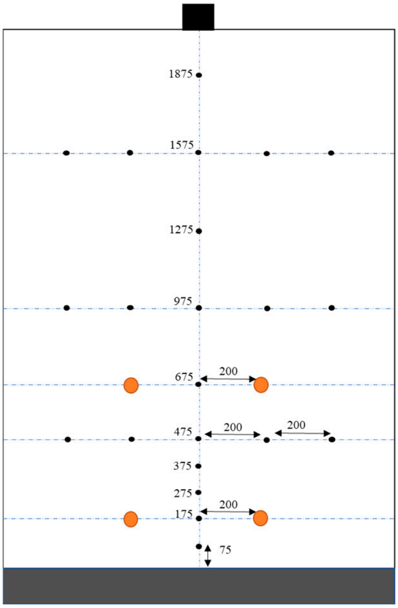


Figure 10. Detailed instrumentation layout for the Intermediate-scale test, showing thermocouples (black dots), thin skin calorimeters (orange circles), and a plate thermocouple (black square), with corresponding dimensions.

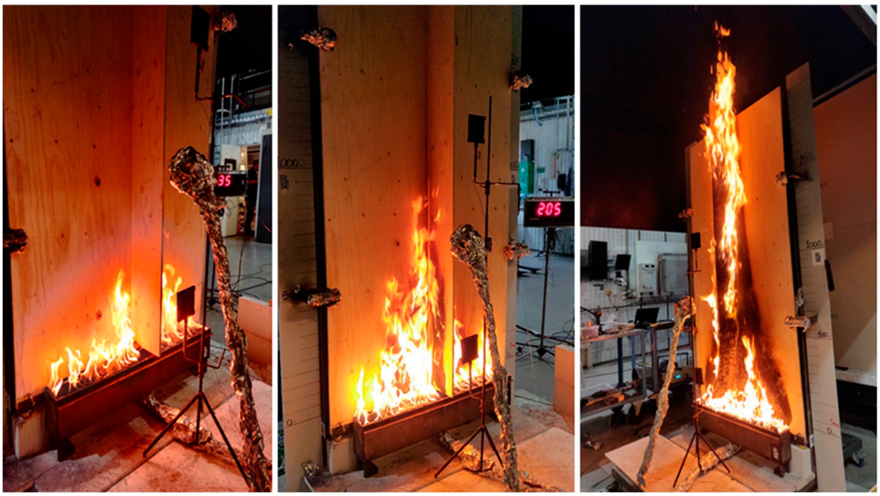


Figure 11. Intermediate-scale test setup for plywood façade with added central wing flange.

4 Results and Discussion

In the following section, the ignition times from the cone calorimeter tests and the predicted values from the ignition model will be presented and discussed. Additionally, the HRR curves from the SBI and Intermediate-scale façade tests, as well as the temperature profiles, will be reviewed. The thermal inertia derived from the newly developed methodology, along with the measurements of individual thermal properties, will also be included in the analysis.

4.1 Ignition time

The ignition times measured from the cone calorimeter experiments are presented here. Figure 12 shows the relationship between ignition time and heat flux for each material, with the y-axis representing the average ignition time from three tests and the x-axis displaying the corresponding heat flux values. The error bars indicate the range of ignition times observed across the three tests for each material. The data reveals that ignition time decreases as heat flux increases. Additionally, it is notable that plywood and OSB exhibit a wider range of ignition times at lower heat flux levels compared to other materials, while particleboard shows highly consistent ignition times across all heat flux levels, with minimal variation.

The relationships between density and average ignition time, as well as thermal inertia and average ignition time, are illustrated in Figure 13 and Figure 14, respectively. The plot of density versus average ignition time (Figure 13) generally supports the theory that materials with lower density ignite more quickly, while those with higher density ignite more slowly. For instance, at 35 and 50 kW/m^2, plywood, which has lower density, ignites earlier than the other materials. However, different behaviour is observed at 20 kW/m^2. Despite OSB having a higher density, it shows a reversal in ignition times at lower and higher heat flux levels: at lower heat flux, OSB has a longer ignition time compared to MDF and Particleboard, while at higher heat flux, it ignites more quickly than these materials.

To investigate whether other thermal properties influence this behaviour, thermal inertia is plotted against average ignition time in Figure 14, showing similar patterns across all materials. This consistency is expected, as these materials have similar specific heat capacities, and their thermal conductivity correlates closely with their density.

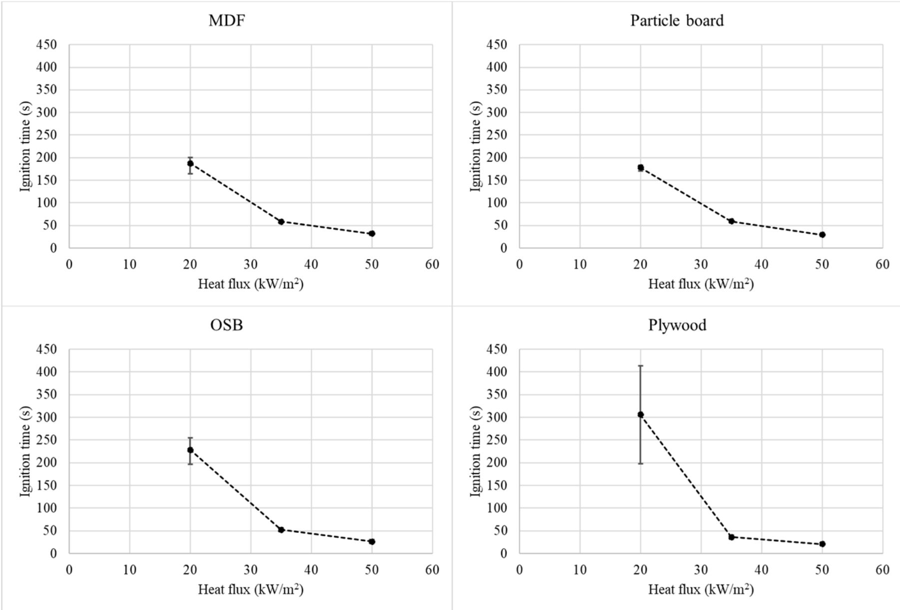


Figure 12. Comparison of average ignition times across varying heat flux levels for different materials.

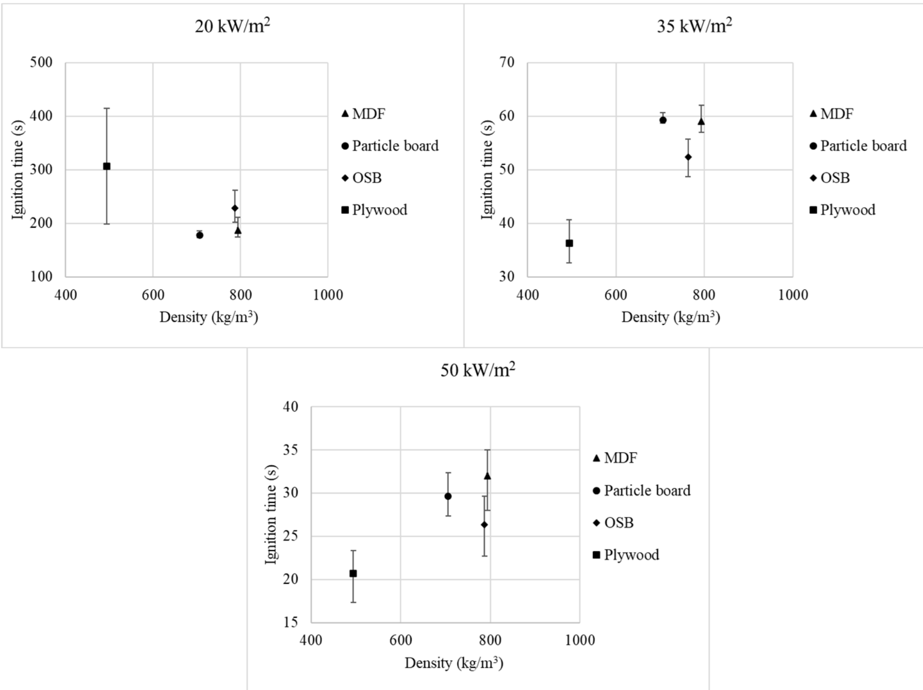


Figure 13. Average ignition time as a function of material density across different heat flux levels.

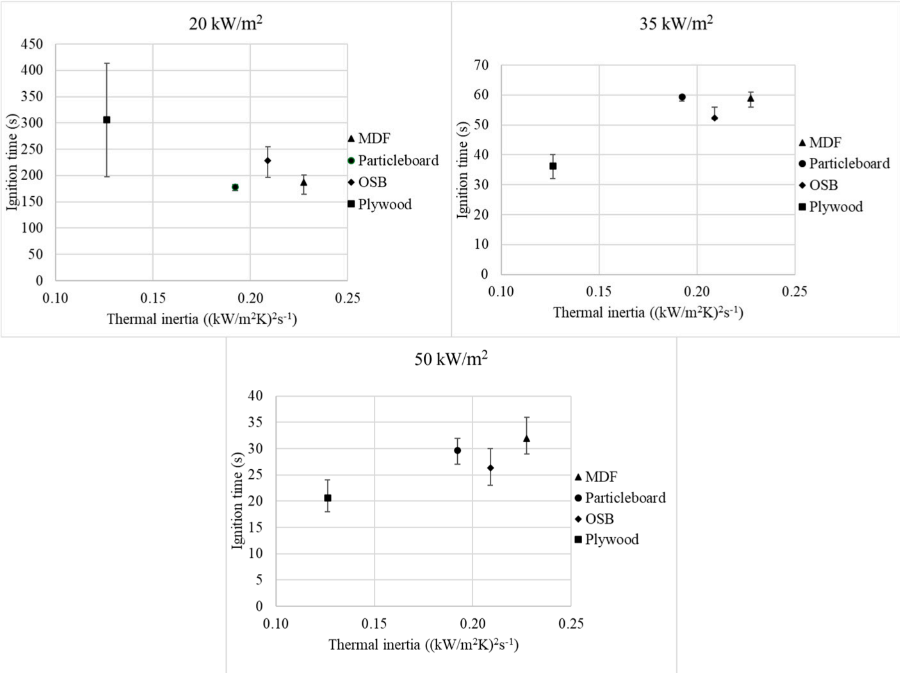


Figure 14. Average ignition time as a function of thermal inertia across different heat flux levels.

This behaviour at 20 kW/m² may be attributed to the increased char formation in plywood at lower temperatures, which could have delayed ignition as char acts as an insulation and slowed down heat transfer. This hypothesis is supported by the notably higher smoke production observed for plywood at 20 kW/m² compared to the other materials shown in Table 2.

Thermogravimetric analysis (TGA) conducted in a nitrogen environment prevents complete degradation of the materials, as the absence of oxygen means that the char formed during pyrolysis cannot be further oxidized (Fateh 2013). Among all the materials tested, plywood exhibited the lowest mass loss, which may indicate a higher degree of char formation compared to the other materials as shown in Figure 15.

Table 2. Average total smoke production from start to ignition in cone calorimeter tests for all materials at different heat flux levels (values represent average of three tests)

	Average total smoke production before ignition (m²/m²)			
Heat flux (kW/m²)	**MDF**	**Particleboard**	**OSB**	**Plywood**
20	48.87	32.30	52.10	106.90
35	14.47	13.60	9.17	7.67
50	5.93	6.93	4.63	5.90

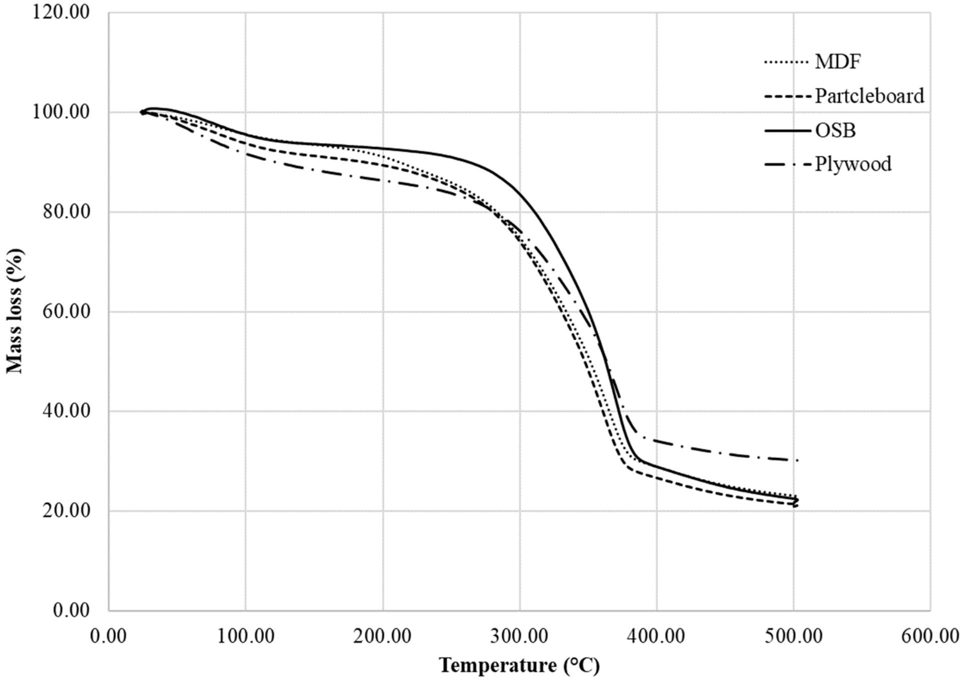


Figure 15. Percentage mass loss vs. Temperature for all materials from TGA analysis.

4.1.1 Comparison of ignition times from cone calorimeter test and empirical models

The average ignition times from cone calorimeter tests are compared with predicted times from various models at different heat fluxes, as shown in Figure 16. Each plot represents ignition time on the y-axis and different materials on the x-axis. The models perform well at 35 kW/m² and gives fair predictions at 50 kW/m², but its accuracy at 20 kW/m² is poor. As noted by Spearpoint and Quintiere (2001), at lower heat fluxes, the ignition mechanism differs from higher fluxes due to char oxidation, supported by smoke production and TGA results. Additionally, at lower heat flux levels, heat transfer is more largely influenced by boundary conditions and heat losses, as compared to higher heat fluxes, where the energy input is sufficient to minimize these effects (Kang 2019).

The ignition temperatures used in this study were drawn from Babrauskas (2003), where the materials had similar moisture content and density. For 25 kW/m², a temperature of 250°C was selected due to the low heat flux, which aligns with literature suggesting this as the minimum temperature for ignition at low flux levels. For 35 and 50 kW/m², the ignition temperatures are 400°C, 420°C, 364°C, and 368°C for MDF, particleboard, OSB, and plywood, respectively. Although the literature does not specify the heating rate, these values were selected based on the same materials with similar density and moisture content. In both the Quintiere and Wickström models, ignition time is directly proportional to the square of the ignition temperature. This relationship implies that even a slight change in the ignition temperature can largely impact the predicted ignition time, making accurate determination of this parameter crucial for reliable predictions.

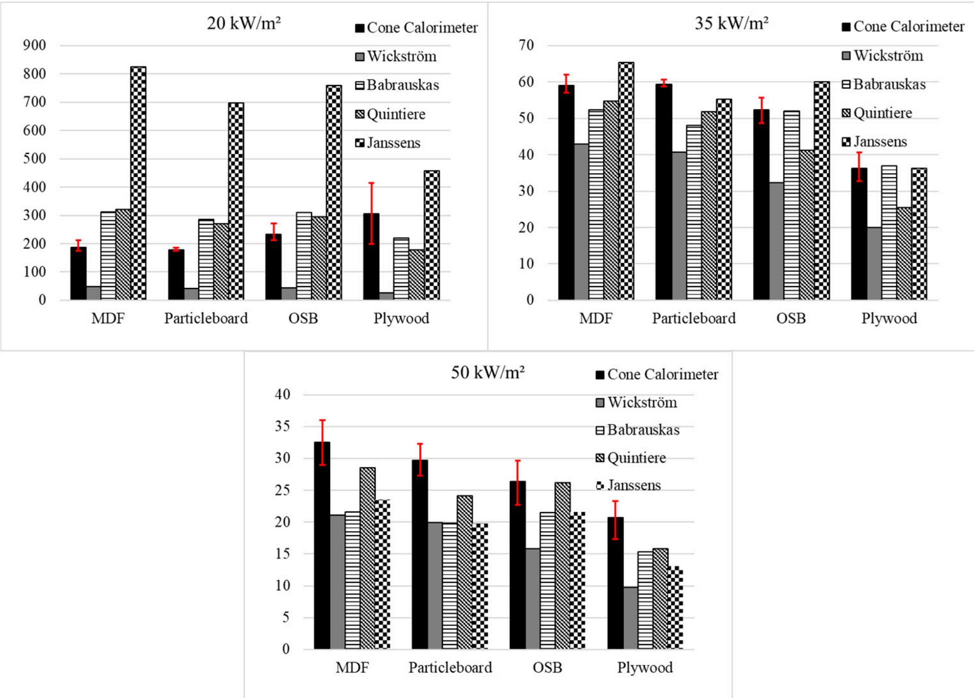


Figure 16. Comparison of average ignition time from cone calorimeter test to predicted ignition time from different models.

Additional sources of error in the Quintiere model could stem from the use of thermal inertia values obtained at room temperature, as the model derives these values using ignition times from cone calorimeter tests. Furthermore, the critical heat flux was assumed to be 15 kW/m² (approximation from literature, Babrauskas 2003), and errors in determining this flux via the Janssens or Quintiere process may contribute to inaccuracies. In the Janssens model, errors could also arise from using heat transfer coefficients (34 W/m^2K) from the literature. For the Babrauskas model (2002), the constants used in the equation were not specifically derived for the tested material, and variations in moisture content could affect density. Moreover, the assumed critical heat flux of around 11 kW/m² could also introduce uncertainties.

Despite these potential sources of error, the models performed reasonably well at higher heat fluxes of 35 and 50 kW/m², providing fairly accurate predictions.

The predicted ignition times from the Lawson and Simms model were compared with average ignition times from cone calorimeter tests, as shown in Figure 17. The model consistently over-predicts ignition times across all heat flux levels for MDF, particleboard, and OSB. However, its predictions at 50 kW/m² are relatively more accurate compared to lower heat fluxes. For plywood, the model provides highly accurate predictions, likely due to the model's limitation, which is most effective for certain wood species, aligning closely with the properties of plywood.

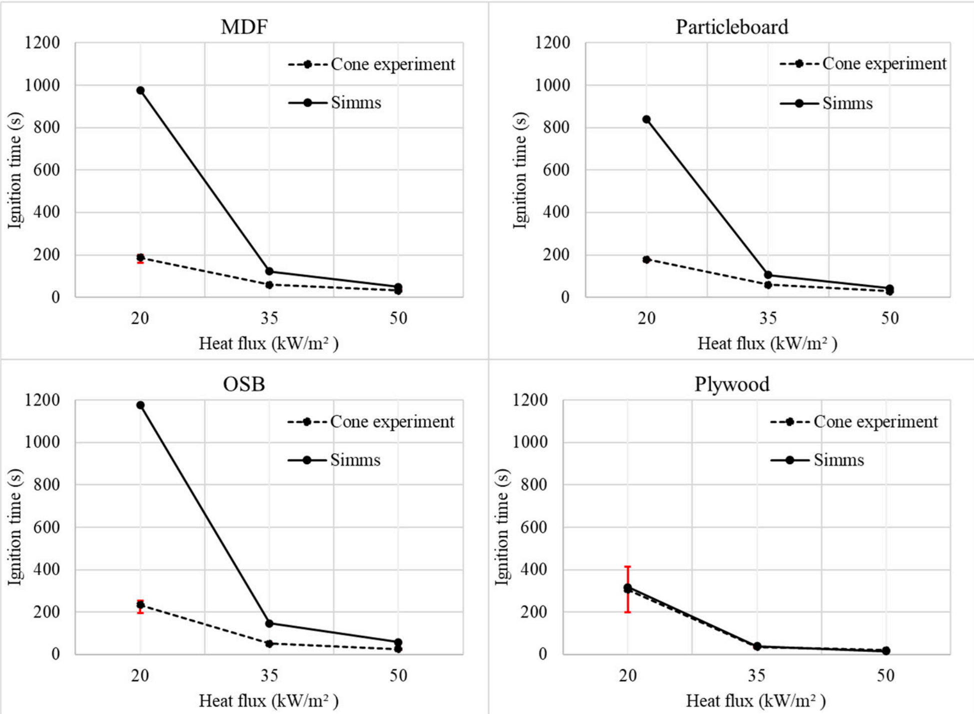


Figure 17. Comparison of average ignition time from cone calorimeter test to predicted ignition time from Lawson and Simms model.

An attempt was made to estimate the critical heat flux for the materials using the Janssens and Quintiere methods, where (1/tig)0.547 and 1/√tig are plotted against incident heat flux, with the intercept providing ($\dot{q}_e''$). The results from the Janssens correlation, shown in Figure 18, indicate critical heat flux values of 2.5 kW/m² for particleboard, 8.7 kW/m² for plywood, and 1 and 8 kW/m² for MDF and OSB, respectively. These values appear lower than those typically reported in the literature (Fateh 2014). Similar results were found using the Quintiere method, with critical heat flux values of 2, 2.5, 9, and 8 kW/m² for MDF, particleboard, OSB, and plywood, respectively.

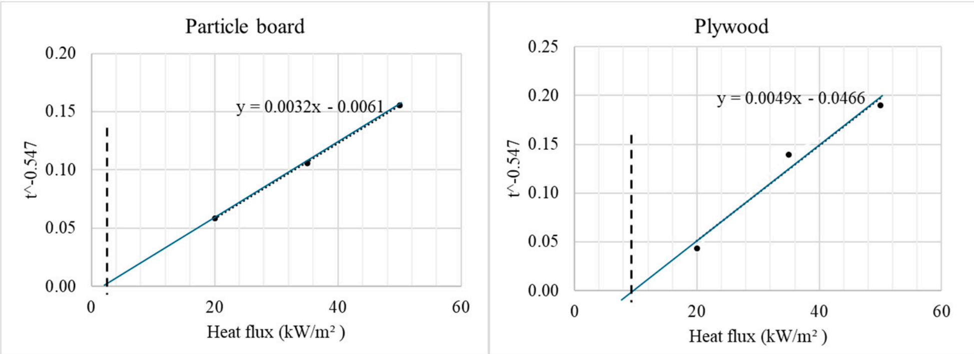


Figure 18. Determination of the critical heat flux (x-axis intercept of the linear fit, as indicated by the dashed black line) for ignition for particleboard and plywood using Janssens correlation.

Esko and Indrek (1989) proposed a correlation specifically for particleboard and plywood, suggesting the use of $(1/t_{ig})^1$ plotted against incident heat flux to find the intercept, as shown in Figure 19. The critical heat flux values obtained ranged from 15 to 17.4 kW/m², with OSB having the highest and MDF the lowest values. They attributed using different correlation to the production process of engineered materials, where density varies between the core and surface, and for plywood, the glue layer acts as a heat sink due to its higher density.

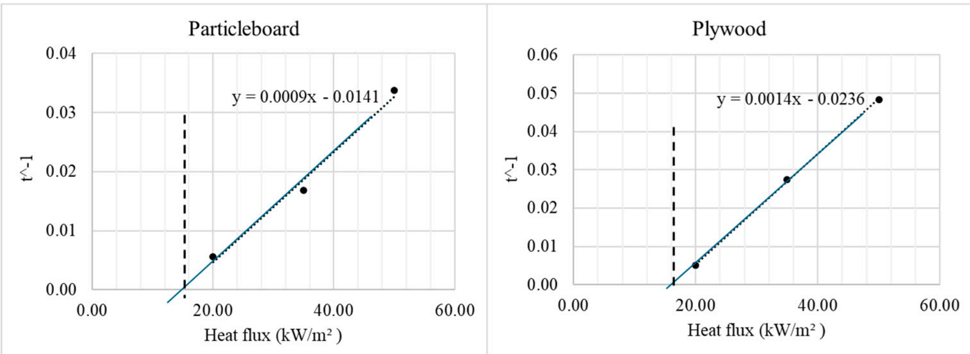


Figure 19. Determination of the critical heat flux (x-axis intercept of the linear fit, as indicated by the dashed black line) for ignition for particleboard and plywood using Esko and Indrek correlation.

4.2 Flame spread and Heat release rate

The flame spread behaviour of the materials can be assessed by analysing FIGRA values from both the SBI and Intermediate-scale façade tests, in addition to key data such as peak HRR, time to peak HRR, and THR_{600}. As shown in Table 3, Plywood exhibits the lowest peak HRR, but it reaches this peak much faster than other materials, a trend that holds in both tests. The other materials, such as MDF, Particleboard, and OSB, display similar peak HRR values but differ slightly in the time taken to reach those peaks.

Table 3. Average peak values of HRR, time for peak HRR, FIGRA for SBI and Intermediate-scale test along with THR_{600} from SBI test.

	SBI				Intermediate-scale test		
Material	**Peak HRR (kW)**	**Time for peak HRR (s)**	**FIGRA (W/s)**	**THR_{600} (MJ)**	**Peak HRR (kW)**	**Time for peak HRR (s)**	**FIGRA (W/s)**
MDF	78	129	671	25	40	185	260
Particleboard	73	165	528	23	45	200	260
OSB	74	207	482	33	41	215	252
Plywood	45	93	578	19	35	131	304

When comparing THR_{600} values, Plywood again shows a lower total heat release, whereas OSB registers the highest THR_{600}. This difference indicates that Plywood burns quickly but contributes less total heat over time, while OSB sustains its burning for longer, contributing more heat overall. The heat release curves presented in Figure 20 and Figure 21 (left image) further emphasize these differences, showing that Plywood rapidly reaches its peak HRR while other materials reach their peaks more gradually. In the SBI test, OSB maintains a higher heat release for a prolonged period, which accounts for its higher THR_{600}.

This comparison between FIGRA and THR_{600} values allows to draw general conclusions about flame spread. Plywood, with a comparatively higher FIGRA and lower THR_{600}, indicates that flames spread more quickly but release less total heat over time. This behaviour makes Plywood more hazardous during the early stages of a fire due to its rapid flame spread, although it does not contribute as much sustained heat to the fire. In contrast, OSB, with a lower FIGRA but higher THR_{600}, indicates slower flame spread but greater overall heat release, posing a higher risk of prolonged fire intensity. This prolonged burning could sustain a fire for a longer time, contributing to greater heat buildup and potential hazards in long-duration fire scenarios.

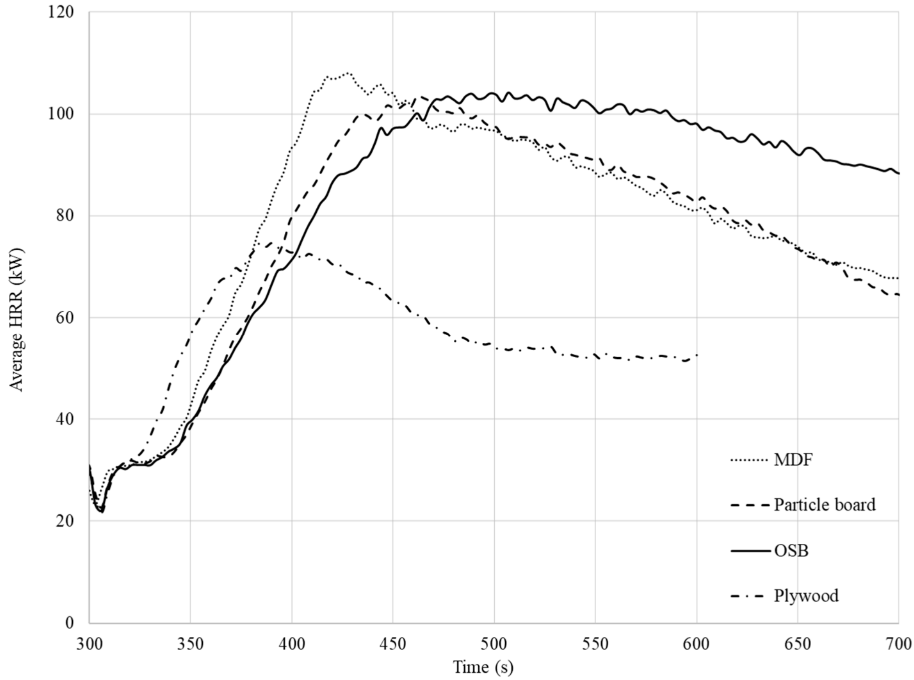
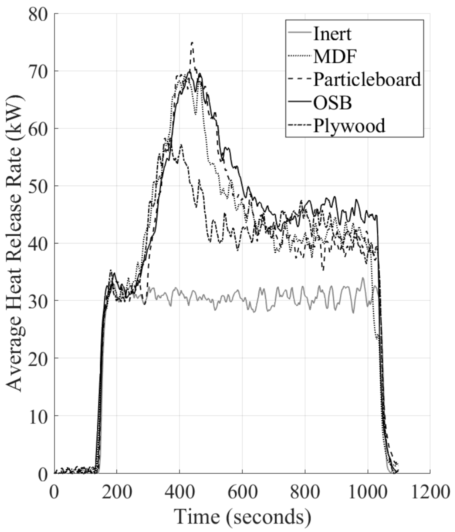


Figure 20. Average Heat Release Rate vs. Time for SBI Test, displaying data following primary burner ignition.



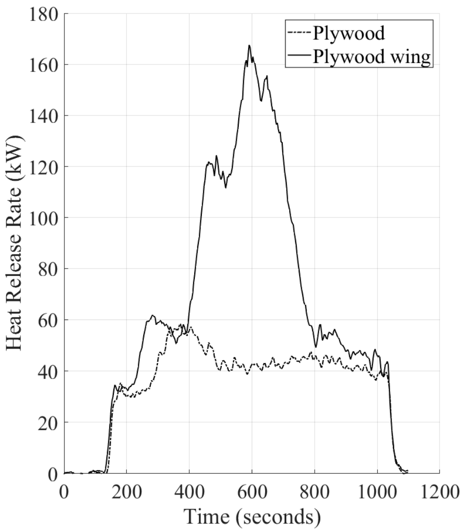


Figure 21. Heat release rate (average of two tests) comparison in intermediate scale tests. Left: Flat façade. Right: Plywood façade with and without central wing flange.

The SBI and Intermediate-scale façade tests were both performed using burners with a heat output of 30 kW. However, the HRR plots show that the average HRR from the SBI test is 1.2 to 2 times higher than that of the Intermediate-scale test. This discrepancy can be explained by the test configurations and burner designs. The SBI test, conducted as a corner test, uses a triangular burner, which has a smaller surface area and produces more intense and concentrated flames. In contrast, the Intermediate-scale façade test is a flat façade test and utilizes a rectangular burner that runs along the entire length of the façade. This burner setup results in a more distributed flame with lower intensity, which leads to a lower heat flux to the surface of the material.

The HRR curve shown in Figure 21 (right image) presents data from tests carried out on both a flat façade and a façade with an added wing flange at the centre. The curves reveal a sizable increase in heat release for the façade with the wing flange, as the material is positioned directly above the burner. This setup results in approximately a fivefold increase in the peak heat release rate compared to the flat façade configuration. This emphasizes the role of burner placement and façade geometry in influencing fire behaviour.

Additionally, a small experiment was carried out to analyse the heat flux to the surface of an inert material. It was found that the heat flux in the Intermediate-scale test ranged between 12–15 kW/m² at 400 mm above the burner as shown in Figure 22 whereas in the SBI test, the heat flux to the surface was comparatively higher, around 30–35 kW/m² (Zhang, 2010). The more concentrated heat flux in the corner configuration of the SBI test is a key factor contributing to the higher HRR values compared to the flat façade setup in the Intermediate-scale test. This difference highlights how the burner configuration and placement can largely influence the heat exposure pattern, which is important for understanding fire behaviour under different test setups.

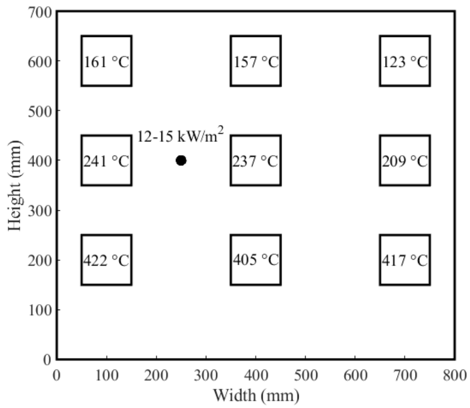


Figure 22. Maximum temperature measured using plate thermocouples and heat flux via total heat flux meter under 30 kW heat flow from burner.

4.3 Temperature along the vertical axis

The temperature distribution along the height of the boards during the flat Intermediate-scale tests at various times is shown in Figure 23. Data points were collected from thermocouples positioned at different heights, offering detailed insight into the temperature profiles. As the fire progressed upwards, the temperature increased steadily from the base to the top of the board. Notably, plywood ignited earlier than the other materials tested, while MDF, particleboard, and OSB displayed similar temperature patterns, suggesting comparable fire spread behaviours. The temperature data indicate that the flame height remained below 1 meter for all materials, with temperatures exceeding 200°C at only a few points above this height.

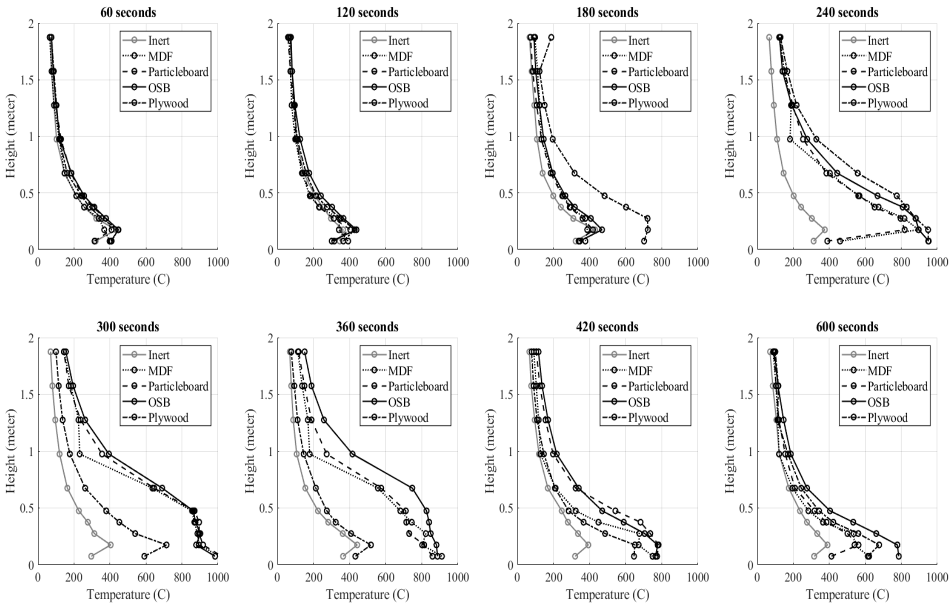


Figure 23. Flat façade: Temperature distribution along board height at various time intervals post-ignition.

The temperature profiles for plywood facades with and without a central wing at various times during the fire test is shown in Figure 24. The façade with the wing ignited much earlier (60 seconds) compared to the flat façade (120-180 seconds). Additionally, the temperature readings revealed substantial differences, with most thermocouples in the test with the wing recording temperatures above 800°C at 300 seconds, while the flat façade showed limited flame spread, remaining under 1 meter. By 420 seconds, the flames had reached and surpassed the top of the façade in the winged test. These findings highlight the role of the wing in accelerating flame spread and increasing the fire's overall intensity.

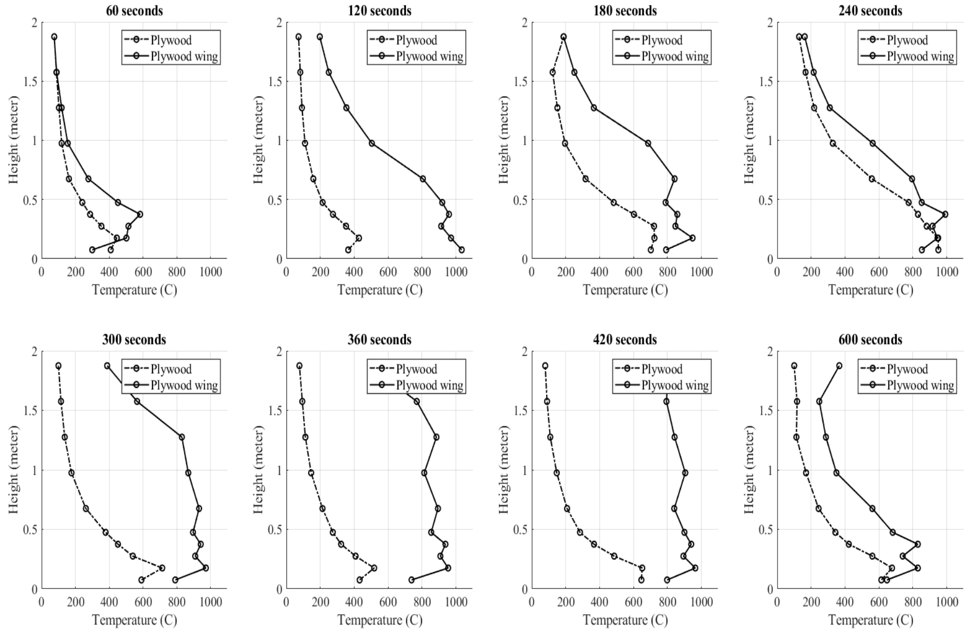


Figure 24. Temperature distribution along the height of plywood façades with and without wing at various time intervals post-ignition.

4.4 Thermal Inertia

Thermal inertia was measured both by individually assessing the thermal properties and through a newly developed 1D methodology (Section 3.1.3) The results, presented in Table 4, show that the thermal inertia values from both methods were comparable, with the largest deviation observed for plywood, likely due to its heterogeneity. The uncertainty from the newly developed methodology is approximately half that of the uncertainty from the individual measurement of thermal properties. More detailed explanation about the methodology is provided in Paper (1).

Table 4. The thermal inertia (W/m^{2}K)^{2}s) values from measurements of individual thermal properties and values calculated from the temperature-time curve of the experiments are provided along with their residual standard deviation (%) and percentage difference between the two methods.

Material	Individual measure of thermal properties	Calculated from temperature-time curve of 1D experiment	Percentage difference
MDF	194802 (2.7)	215808 (2.3)	±9.7 %
Particleboard	177518 (2.1)	183600 (2.4)	±3.3 %
OSB	218601 (4.6)	208908 (4.9)	±4.6 %
Plywood	97041 (3.0)	126267 (5.0)	±23.1 %

4.5 Reflection on experiments

The experiments conducted to determine thermal inertia were specifically to the materials used in this study. The methodology proved efficient in estimating the surface properties of the materials. Thermal inertia was determined using temperature-time data obtained from the experiments and calculated through fitting the curve to a 1D heat transfer equation. It is important to note that while the experiments represented 1D heat transfer for a certain duration, beyond that point, heat loss to the boundaries occurred, causing the 1D assumption to fail. One of the key limitations of the method lies in identifying the appropriate portion of the temperature-time curve to use for fitting the data. In this study, 1D heat transfer simulations were performed to determine when the assumption breaks down, and only data before that point was used to estimate thermal inertia. Moving forward, the experimental setup could be further refined to eliminate the need for simulations, allowing thermal inertia to be derived directly from the experiments. Additionally, further validation across a wider range of materials with varying thermal inertias is recommended.

The cone calorimeter was employed to estimate ignition times for different wood materials under varying heat fluxes. While the experiments provided valuable insights into ignition times, the process of validating ignition models could have been enhanced by collecting additional data. For example, performing tests at more heat flux levels to estimate the critical heat flux, and measuring the temperature at the point of ignition, would have provided more precise validation of the models.

The Intermediate-scale test and the SBI test offered a useful comparison of material behaviour under similar heat flow conditions but with different test configurations. However, additional temperature measurements along the board in the SBI test would have provided deeper insights into the comparison between these two tests. Moreover, conducting the Intermediate-scale test at different heat flux levels, along with more repetitions, would have aided in assessing the materials' fire behaviour across various scenarios. In the Intermediate-scale test, an attempt was made to measure the mass loss of the sample. However, due to the expansion of the material during the test, accurate data could not be obtained.

5 Paper Summaries

The complete papers on which this work is based are included as appendices to this thesis. This chapter provides brief summaries of the two papers and highlights their key findings. Additional details can be found in the papers included in the annex.

5.1 Paper 1

Thermal Properties of Wood-Based Materials: Determination of Thermal Inertia

This paper introduces a novel approach to determining the thermal inertia of wood-based materials. Thermal inertia plays a critical role in fire safety by influencing the rate at which a material's surface temperature rises when exposed to heat. The method described combines a hot disk sensor and one-dimensional (1D) heat transfer simulations to estimate thermal inertia more efficiently than traditional techniques.

Key Findings:

- Novelty of the 1D Experiment: The 1D method was simpler and more efficient than measuring thermal properties individually (thermal conductivity, heat capacity, and density). While both methods yielded comparable standard deviations (2.2-4.6%), the 1D method showed that thermal inertia could be measured with reduced experimental complexity and lower overall uncertainty.
- Reduced Uncertainty: The 1D experimental method reduces the uncertainty in thermal inertia measurements to ±4.9-6%, approximately half that of traditional methods (±9.6-10.6%).
- Material Properties and Behaviour: The study compared four common wood-based materials: plywood, particleboard, OSB, and MDF. Among these, plywood exhibited the highest variability in thermal inertia due to its inherent heterogeneity, whereas MDF and particleboard had more consistent thermal properties.

Implications:

This study directly supports the objective of developing a simplified methodology to estimate thermal inertia for wood-based materials. The novel 1D experimental method reduces measurement uncertainty and simplifies the process, addressing the need for a more efficient and practical approach. This method is particularly beneficial for materials like MDF and particleboard, where homogeneity is higher, while materials like plywood require more caution due to variability.

5.2 Paper 2

Wood-Based Material Fire Behaviour: Analysis of Vertical Flame Spread in Different Test Setups

This paper investigates the vertical flame spread characteristics of wood-based materials using different experimental setups. These include the Single Burning Item (SBI) test, which is standardized in Europe, and Intermediate-scale tests that simulate flat façade conditions and configurations with additional structural features, such as wings.

Key Findings:

- Variation in peak heat release rate: The Intermediate-scale test, which used a flat façade configuration, resulted in a peak heat release rate that was approximately 30% lower than that observed in the SBI test despite same heat flow from the burner. This finding indicates that the configuration of the test setup has a large impact on the observed fire behaviour.
- Impact of structural features: When a wing was added to the plywood in the Intermediate-scale test, the peak heat release rate increased significantly—three times higher than in the SBI test and five times higher than in the flat façade test. This suggests that additional structural elements can greatly influence the severity of fire spread.
- Temperature distribution and flame spread: Temperature measurements along the height of the boards indicate that plywood ignites earlier and shows quicker flame spread compared to the other materials. In contrast, MDF, OSB, and particleboard exhibit similar flame spread behaviour, with OSB showing a more sustained flame spread over time compared to other materials.

Implications:

The study supports the research objective by examining fire performance across different testing scales and configurations. The results emphasize the importance of using varied test setups when assessing the fire behaviour of wood-based materials. The differences observed in flame spread between the SBI and Intermediate-scale tests suggest that standard tests alone may not fully capture a material's fire behaviour. Therefore, incorporating additional testing methods that simulate other real-world conditions (Sadaoui 2024), where possible, could provide a more comprehensive evaluation of fire risks.

6 Conclusion

This thesis has explored the ignition and flame spread behaviour of engineered wood materials, focusing on Medium-Density Fibreboard (MDF), Particleboard, Oriented Strand Board (OSB), and Plywood. By addressing the two key objectives outlined, the research makes meaningful contributions to the understanding of fire behaviour in wood-based composites.

Development of a simplified methodology for estimating thermal inertia:

The first objective was to develop a methodology that reduces uncertainties and improves the practical applicability of thermal inertia estimation for wood-based materials (Paper 1). This objective was achieved through the introduction of a novel method combining a hot disk sensor with one-dimensional heat transfer simulations. This method reduced the overall uncertainty in thermal inertia measurement to a range of ±4.9% to ±6%, approximately half the uncertainty of traditional approaches. The methodology demonstrated reliability in capturing thermal inertia as a bulk property, simplifying the measurement process by eliminating the need for separate measurements of thermal conductivity, specific heat capacity, and density. The improved accuracy and reduced complexity make this method highly practical for both research and fire safety assessments.

Exploration of fire behaviour in small- and medium-scale tests:

The second objective aimed to explore the fire behaviour of engineered wood materials under small- and medium-scale tests. This was fulfilled through extensive testing, including cone calorimeter tests, Single Burning Item (SBI) tests, and Intermediate-scale facade tests. The experiments provided valuable data on key fire safety metrics such as ignition times, heat release rate (HRR), and flame spread (Paper 2). The research demonstrated that the fire behaviour of materials varied depending on heat flux levels, material density, and structural configurations. Notably, Plywood exhibited earlier ignition, but slower flame spread, while OSB showed sustained burning with higher heat release over time. These findings offer a comprehensive understanding of how engineered wood materials behave under different fire conditions and scales, fulfilling the objective of exploring their fire behaviour in depth.

In summary, this research provides a robust method for estimating thermal inertia and explores fire behaviour in wood-based materials, enhancing understanding of ignition and flame spread to inform improved fire safety standards.

7 Future work

Based on the limitations of this study, the following areas should be considered for future work

- Further Validation of Thermal Inertia Methodology: The experimental setup for measuring thermal inertia, while effective for the materials tested, needs further validation across a broader range of materials. Refining the methodology to eliminate reliance on simulations and obtaining results directly from experiments will improve both accuracy and practicality.
- Comprehensive Ignition Model Validation: Additional data from the cone calorimeter, particularly ignition temperature measurements and critical heat flux determination, will help provide a more precise validation of the ignition models. This will ensure a better understanding of ignition behaviour under various heat flux conditions.
- Expanded Intermediate-scale Testing: Conducting more Intermediate-scale façade tests with a variety of heat flux levels will allow for a deeper analysis of flame spread behaviour. Testing different façade configurations and comparing these results with the SBI tests will help to establish a more thorough understanding of the influence of test setups on fire behaviour.
- Correlation Between Test Scales: Investigating potential correlations between small-, medium-, and Intermediate-scale tests will help unify the understanding of fire behaviour across different testing scales. This could lead to more cohesive models and better predictions of real-world fire scenarios.

By focusing on these areas, future work will address current limitations and contribute to a more comprehensive understanding of fire behaviour in engineered wood materials.

8 References

Adl-Zarrabi, B., Boström, L., “Determination of Thermal Properties of Wood and Wood-Based Products Using Transient Plane Source”, In: 8th World Conference on Timber Engineering, 2004.

Atreya, A., Carpentier, C., Harkleroad, M., “Effect of Sample Orientation on Piloted Ignition and Flame Spread”, Fire Safety Science 1: 97-109, 1986. http://dx.doi.org/10.3801/IAFSS.FSS.1-97

Babrauskas, V., “Ignition Handbook: Principles and Applications to Fire Safety Engineering, Fire Investigation, Risk Management and Forensic Science”, Issaquah: Fire Science Publishers, 2003.

Babrauskas, V., “Ignition of Wood: A Review of the State of the Art”, Journal of Fire Protection Engineering. 12 (3), 163–189, 2002.

Bartlett, A. I., Hadden, R. M., Bisby, L. A., “A Review of Factors Affecting the Burning Behaviour of Wood for Application to Tall Timber Construction”, Fire Technol 55, 1–49, 2019. https://doi.org/10.1007/s10694-018-0787-y

Buchanan, A. H., & Abu, k. A., “Structural Design for Fire Safety: Second Edition”, 2016. https://doi.org/10.1002/9781118700402

Cleary, T., “Flammability Characterization with the Lift Apparatus and the Cone Calorimeter”, Fire Retardant Chemicals Association, Orlando, FL, 1992.

Czajkowski, L., Olek, W., Weres, J., Guzenda, R., “Thermal Properties of Wood-Based Panels: Specific Heat Determination”, Wood Sci Technol, 50:537–545, 2016.

Czajkowski, L., Olek, W., Weres, J., Guzenda, R., “Thermal Properties of Wood-Based Panels: Thermal Conductivity Identification with Inverse Modelling”, Eur. J. Wood Prod., 74:577–584, 2016.

Drysdale, D., “An Introduction to Fire Dynamics”, 3rd Edition, John Wiley & Sons, Ltd., New York, 2011. https://doi.org/10.1002/9781119975465

Elkholy, A., Sadek, H., Kempers, R., “An Improved Transient Plane Source Technique and Methodology for Measuring the Thermal Properties of Anisotropic Materials”, Int. J. Therm. Sci., 135, 362–374, 2019.

EN 13501-1:2018, “Fire Classification of Construction Products and Building Elements - Part 1: Classification Using Data from Reaction to Fire Tests”.

EN 13823:2020, “Reaction to Fire Tests for Building Products – Building Products Excluding Floorings Exposed to the Thermal Attack by a Single Burning Item”.

Fateh, T., Rogazme, T., Luche, J., Jabouille, F., "Kinetic and Mechanism of the Thermal Degradation of a Plywood by Using Thermogravimetry and Fourier-Transformed Infrared Spectroscopy Analysis in Nitrogen and Air Atmosphere", Fire Saf J, 58:25–37, 2013.

Fateh, T., Rogazme, T., Luche, J., Richard, F., Jabouille, F., "Characterization of the Thermal Decomposition of Two Kinds of Plywood with a Cone Calorimeter – FTIR Apparatus", Journal of Analytical and Applied Pyrolysis, 107, 87–100, 2014.

Gustafsson, M., Saxena, N. S., Karawacki, E., Gustafsson, S. E., "Specific Heat Measurements with the Hot Disk Thermal Constants Analyser", Thermal Conductivity, 23, 56-65, 1996.

Gustafsson, S. E., "Transient Plane Source Techniques for Thermal Conductivity and Thermal Diffusivity Measurements of Solid Materials", Review of Scientific Instruments, 62(3), 797-804, 1991.

Gustavsson, L., Sathre, R., "Variability in Energy and Carbon Dioxide Balances of Wood and Concrete Building Materials", Building and Environment, 41(7), 940-95. 2006.

Hakkarainen,T., Oksanen, T., "Fire Safety of Wooden Facades", Fire Mater., 26, 7–27, 2002.

Harangozó, J., Tureková, I., Marková, I., Hašková, A., Králik, R., "Study of the Influence of Heat Flow on the Time to Ignition of Spruce and Beech Wood", Appl. Sci., 14, 4237, 2024. https://doi.org/10.3390/app14104237

Hao, H., Chow, L. C., Lau, D., "Effect of Heat Flux on Combustion of Different Wood Species", Fuel, 278, 118325, 2020.

Hong, S., Park, S., "Influence of Char Formation on Flame Spread in Wood Materials: A Study on Douglas-Fir", Fire Safety Journal, 138, 102914, 2023.

Hu, YP., Li, WB., Wu, S. *et al.* "Experimental Study of the Anisotropic Thermal Conductivity of Spruce Wood", *Int J Thermophys* **44**, 131, 2023. https://doi.org/10.1007/s10765-023-03238-7

ISO 13785-1:2002, "Reaction-to-Fire Tests for Façades – Part 1: Intermediate-scale test".

ISO 5660-1:2015, "Reaction-to-Fire Tests – Heat Release, Smoke Production and Mass Loss Rate – Part 1: Heat Release Rate (Cone Calorimeter Method) and Smoke Production Rate (Dynamic Measurement)".

Janssens, M., "A Thermal Model for Piloted Ignition of Wood Including Variable Thermophysical Properties", Fire Safety Science Proceedings of the 3rd International Symposium, pp. 167-176, 1991.

Janssens, M. L., "Rate of Heat Release of Wood Products", Fire Safety Journal, Vol. 17, pp. 217-238, 1991.

Kang, S., Kwon, M., Choi, J. Y., Choi, S., "Thermal Boundaries in Cone Calorimetry Testing", Coatings, 9(10), 629, 2019. https://doi.org/10.3390/coatings9100629

Kasymov, D., Agafontsev, M., Perminov, V., Martynov, P., Reyno, V., Loboda, E., "Experimental Investigation of the Effect of Heat Flux on the Fire Behavior of Engineered Wood Samples", Fire, 3, 61, 2020. https://doi.org/10.3390/fire3040061

Kollmann, F. F. P., Côté, W. A., "Principles of Wood Science and Technology: Solid Wood", Springer, 1968.

Lawson, D., Simms, D., “The Ignition of Wood by Radiation”, British Journal of Applied Physics, 3, 288-292, 1952.

Lewis, W. C., “Thermal Conductivity of Wood-Base Fibre and Particle Panel Materials”, U.S. Forest Service Research Paper, Forest Products Laboratory, U.S.D.A. (No. FPL 77), 1967.

Li, Y. K., Fleischmann, M. C., Spearpoint, J. M., “Determining Thermal Physical Properties of Pyrolyzing New Zealand Medium-Density Fibreboard (MDF)”, Chemical Engineering Science, 95, 211-220, 2013.

Marková, I., Ivaniˇcová, M., Osvaldová, L. M., Harangózo, J., Tureková, I., “Ignition of Wood-Based Boards by Radiant Heat”, Forests, 13, 1738, 2022. https://doi.org/10.3390/f13101738

Martinka, J., Rantuch, P., Martinka, F., Wachter, I., Štefko, T., “Improvement of Heat Release Rate Measurement from Woods Based on Their Combustion Products Temperature Rise”, Processes, 11, 1206, 2023. https://doi.org/10.3390/pr11041206

Mikkola, E., Wichman, S. I., “On the Thermal Ignition of Combustible Materials”, Fire and Materials, Volume 14, Issue 3, pp. 87-96, 1989.

Quintiere, J. G., “The Application of Flame Spread Theory to Predict Material Performance”, Journal of Research of the National Bureau of Standards, 93, pp. 61-70, 1988. https://doi.org/10.6028/jres.093.007

Quintiere, J. G., “Fundamentals of Fire Phenomena”, John Wiley and Sons: USA, 2006. ISBN: 13978-0-470-09113-5.

Quintiere, J., Harkleroad, M., “New Concepts for Measuring Flame Spread Properties”, National Institute of Standards and Technology, Gaithersburg, MD, 1984.

Sadaoui, A., Dagenais, C., Blanchet, P., “A Comparative Study of Fire Code Classifications of Building Materials”, Fire, 7, 252, 2024. https://doi.org/10.3390/fire7070252

Shields, T., Silcock, G., Murray, J., “The Effects of Geometry and Ignition Mode on Ignition Times Obtained Using a Cone Calorimeter and ISO Ignitability Apparatus”, Fire Mater., 17(1), pp. 25-32, 1993.

Shida, S., Okuma, M., “The Effect of Apparent Specific Gravity on Thermal Conductivity of Particleboard”, Mokuzai Gakkaishi, 27(11), 775-781, 1981.

Siau, J. F., “Transport Processes in Wood”, Springer-Verlag, 1984.

Spearpoint, M. J., Quintiere, J. G., “Predicting the Piloted Ignition of Wood in the Cone Calorimeter Using an Integral Model - Effect of Species, Grain Orientation and Heat Flux”, Fire Safety Journal, 36(4), 391-410, 2001.

Stark, N. M., Cai, Z., Carll, C., “Wood-Based Composite Materials. In: Ross R. J. (ed.) Wood Handbook: Wood as an Engineering Material”, Forest Products Laboratory, United States Department of Agriculture Forest Service, Madison, Wisconsin, 2010.

Steinhagen, H. P., “Thermal Conductivity of Wood Composites”, Forest Products Journal, 27(10), 41-45, 1977.

Suleiman, B. M., Larfeldt, J., Leckner, B., Gustavsson, M., “Thermal Conductivity and Diffusivity of Wood”, Wood Science and Technology, 33(6), 465-473, 1999.

Tarasovs, S., Bulderberga, O., Zeleniakiene, D., et al., “Sensitivity of the Transient Plane Source Method to Small Variations of Thermal Conductivity”, Int. J. Thermophys, 42, 173, 2021. https://doi.org/10.1007/s10765-021-02923-9

TenWolde, A., McNatt, J. D., Krahn, L. A., “Thermal Properties of Wood and Wood Panel Products for Use in Buildings”, USDA Forest Service, Forest Products Laboratory, 1988.

Tewarson, A., “Generation of Heat and Chemical Compounds in Fire”, The SFPE Handbook of Fire Protection Engineering (3rd edn). Section 3, Chapter 4. The National Fire Protection Association Press: Quincy, MA, 3–161, 2002.

Trofimov, A. A., Atchley, J., Shrestha, S. S., et al., “Evaluation of Measuring Thermal Conductivity of Isotropic and Anisotropic Thermally Insulating Materials by Transient Plane Source (Hot Disk) Technique”, J Porous Mater, 27, 1791–1800, 2020.

Wickström, U., “New Formula for Calculating Time to Ignition of Semi-Infinite Solids”, Fire Mater. 40, pp. 464-471, 2015. https://doi.org/10.1002/fam.2303

White, R. H., Dietenberger, M. A., “Fire Safety of Wood Construction”, USDA Forest Service, General Technical Report FPL–GTR–190, 2001.

White, R. H., Dietenberger, M. A., “Wood Products: Thermal Degradation and Fire”, USDA Forest Products Laboratory, Madison, Wisconsin, USA, 2001. https://doi.org/10.1016/B0-08-043152-6/01763-0

Zhang, J., Delichatsios, M., Colobert, M., et al., “Assessment of Fire Dynamics Simulator for Heat Flux and Flame Height Predictions from Fires in SBI Tests”, Fire Technol, 46, 291-306, 2010.

Zhou, Y., Qiu, Q., Zhou, P., Wang, Z., Zhang, X., Mao, X., Bu, R., “Influence of Species and Density on the Horizontal Flame Spread Behaviour of Densified Wood”, Buildings, 14, 620, 2024. https://doi.org/10.3390/buildings14030620

Printed by Media-Tryck, Lund 2024 NORDIC SWAN ECOLABEL 3041 0903

Lund University

LTH
FACULTY OF ENGINEERING

Division of Fire Safety Engineering
Department of Building & Environmental Technology
Faculty of Engineering

ISBN: 978-91-8104-310-5
ISSN: 1402-3504
ISRN: LUTVDG/TVBB--1074—SE

9 789181 043105