

Influence of Horizontal Projections on Thermal Exposure to Façades in Fire Scenarios

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Title

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Abstract

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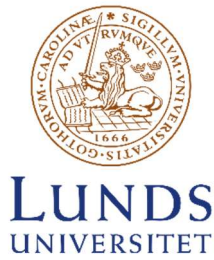
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This study contributes to a better understanding of how building geometry—specifically horizontal projections—influences fire spread risk in alternative facade designs.

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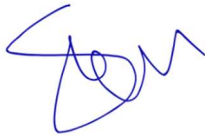
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Disclaimer

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ملخص (Arabic)

أكد التواتر المتزايد لحرائق الواجحات، التي غالبًا ما تتفاقم بسبب أنظمة الكسوة القابلة للاحتراق، على الحاجة إلى استراتيجيات الحماية السلبية من الحرائق. من بين هذه الاستراتيجيات، برزت الإسقاطات الأفقية - مثل الشرفات والمظلات والعاكسات - كعناصر محتملة للسلامة من الحرائق. تبحث هذه الأطروحة في تأثير الإسقاطات الأفقية على التعرض الحراري وانتشار اللهب الجانبي عبر واجحات المباني، خاصة في السيناريوهات التي تتضمن حرائق داخلية تخرق فتحات النوافذ. تم تطوير نموذج عددي باستخدام برنامج (FDS)، استنادًا إلى الاختبار الموحد (SP FIRE 105). ثم أُجريت سلسلة من عمليات المحاكاة المقارنة، لتحليل تأثير أعماق الإسقاط الأفقي (من 0 سم إلى 100 سم) على مسار اللهب ودرجات حرارة السطح وتوزيع التدفق الحراري الساقط. تؤكد النتائج أن الإسقاطات الأفقية تقلل بشكل كبير من انتشار اللهب الرأسي والتعرض الحراري للواجهة فوق الإسقاط. ومع ذلك، فإنها تعزز أيضًا التدفق الحراري الجانبي وتزيد من درجات الحرارة السطحية تحت الإسقاطات وبجوارها. تسببت الإسقاطات العميقة في إعادة توجيه اللهب بشكل أكبر، مما يزيد من التعرض الحراري الجانبي ويزيد من خطر انتشار الحريق الأفقي إلى الأجزاء المجاورة. تُسهم هذه الدراسة في فهم أفضل لكيفية تأثير هندسة المباني - خاصة الإسقاطات الأفقية - على مخاطر انتشار الحرائق في سيناريوهات تصميم الواجحات البديلة.

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1. Introduction

1.1. Background

The facade of a building represents far more than just its exterior shell – it acts as a barrier that separates the built and natural environments, functioning as both a protective interface and an architectural statement that reflects the building's image [1]. Beyond the architectural identity, the facade must also meet other functional requirements, such as providing weather protection, energy efficiency, thermal and acoustic insulation, and maintaining structural integrity, as well as ensuring fire safety [2].

Several devastating fire incidents have demonstrated how critical it is to design facades with proper fire safety measures, regardless of the materials used. One of the most tragic examples is the Grenfell Tower fire in London (2017), where the use of highly flammable cladding facilitated the rapid spread of flames, resulting in a significant loss of life. Similar concerns were raised in the Jiaozhou Road fire in Shanghai, China (2010) and the València residential complex fire in Spain (2024), where facade materials and design significantly influenced fire development and propagation. These cases reinforce the necessity of integrating fire safety measures into facade design to prevent such disasters.



Figure 1 - (a) London Grenfell Tower fire (2017), (b) Jiaozhou Road fire in Shanghai, China (2010), (c) València residential complex fire in Spain (2024).

To mitigate the risks associated with facade fires, various passive fire protection strategies have been developed to limit fire spread and improve building safety. One such measure is the use of horizontal projections (e.g., balconies, flame deflectors, canopies) [3], made from non-combustible materials like steel sheets or concrete. These elements serve as physical barriers that disrupt upward flame propagation by deflecting flames away from the facade surface, thereby significantly reducing the incident heat flux to the facade areas above the projection [4] [5] .

1.2. Problem Statement

Although horizontal projections effectively mitigate vertical fire spread, their influence on lateral fire spread remains unclear. These structural elements can disrupt the natural upward movement of fire plumes, potentially creating a zone where hot gases are trapped beneath the projection. This condition may lead to increased lateral heat flux along the facade, promoting the lateral spread of flames and posing a risk of fire propagation to adjacent compartments [6]. Moreover, increasing the depth of horizontal projections could intensify heat accumulation beneath them due to the buildup of unburnt gases [7], possibly

accelerating lateral fire spread or even leading to burn-through of facade elements. Therefore, a systematic investigation is needed to understand how horizontal projections affect the heat distribution and lateral fire dynamics on building facades.

1.3. Research Aims and Objectives

This thesis aims to comprehensively investigate and characterize the influence of horizontal projections on lateral fire spread along building facades using CFD simulations. The study will analyse how these projections affect fire dynamics, heat transfer, and potential risks in facade systems.

The specific objectives of the study are:

- To determine the influence of horizontal projection geometry on lateral thermal exposure and flame shape:
 - Evaluate how varying projection depths affect flame extension and height.
 - Assess the impact of projection depth on lateral heat flux and surface temperature distribution.
- To develop design recommendations for implementing horizontal projections in facades based on the research findings.

Research Questions:

1. How do different horizontal projection depths affect the heat flux and surface temperatures on building façades, both above and below the projection?
2. To what extent can varying the projection depth help reduce vertical thermal exposure, and what implications might this have for the risk of lateral fire spread?

1.4. Scope, Limitations and Delimitations

- The study is based on the SP Fire 105 test rig configuration, which includes a single flat facade wall and a single window opening. More complex configurations, such as facade corners or multiple window openings, are not considered.
- The analysis of horizontal projections is limited to typical design and configuration scenarios. The study will only focus on single and non-combustible horizontal projections.
- Wind effects are not considered in the simulations investigating horizontal projections, in order to isolate their specific impact on fire dynamics.
- This research is constrained by the available time and resources, which may limit the scope and methodology: conducting physical experiments was deemed beyond the feasible scope of this study. Instead, the research will focus entirely on numerical simulations using FDS, using high-quality experimental data from existing literature for validation purposes.
- The numerical simulations are also constrained by computational resources, which may limit result resolution and restrict the extent of sensitivity analyses that can be conducted within the available timeframe.
- Additionally, limitations inherent to the numerical model used (FDS, version 6.9.1) must be acknowledged. These include, but are not limited to, the use of a rectilinear

mesh, simplified radiation modelling, and one-dimensional heat conduction assumptions. Such constraints can affect the model's ability to capture certain complex fire dynamics with high fidelity.

1.5. Structure of the Thesis

The content of the thesis will be presented as follows:

- **Chapter 2: Literature Review**

This chapter provides an overview of the current understanding of fire spread across building façades. It discusses the risks associated with fires breaching openings and propagating externally. The role of horizontal projections in either mitigating vertical fire spread or potentially exacerbating lateral heat transfer is explored. Key findings from experimental and numerical studies are summarized, and gaps in the existing research are identified.

- **Chapter 3: Theoretical Framework**

This chapter outlines the fundamental principles of fire dynamics relevant to the study. It begins with an analysis of fire behaviour within enclosures and the conditions that lead to flames emerging from openings. It then examines the characteristics of fire plumes, including flame height and their interaction with horizontal projections, based on existing experimental and numerical research. Finally, it reviews the mechanisms of flame spread along façade walls and the heat transfer processes involved.

- **Chapter 4: Methodology**

This chapter details the methodological approach used to investigate the influence of horizontal projections on thermal exposure along building façades. The methodology includes model validation against the SP Fire 105 façade test and a comparative analysis of varying projection geometries under two design fires scenarios.

- **Chapter 5: Results**

This chapter presents the results of the validation of the numerical model of SP Fire 105 test, along with the results of the comparative study on how horizontal projections affect facade fire behaviour.

- **Chapter 6: Discussion**

This chapter interprets the findings from Chapter 5 and discusses their practical implications. It evaluates the role of horizontal projection geometry in influencing vertical and lateral fire spread and compares the results with previous research. Recommendations are provided based on the findings.

- **Chapter 7: Conclusion**

This chapter summarizes the key findings of the study and discusses the limitations of the current research, while also suggesting directions for future research.

2. Literature Review

2.1. Facade Fire Spread Mechanisms

The spread of fire along building facades is one of the most critical concerns in fire safety engineering, particularly with the rapid growth of high-rise and complex architectural structures. Façade fires pose a severe threat due to their potential for rapid vertical spread, which can compromise evacuation routes, hinder firefighting operations due to intense heat, smoke, and falling façade components, and significantly increase the risk of fire re-entering the building through windows or external openings, potentially igniting other compartments beyond the origin of the fire. The growing use of combustible materials in facade systems, along with inadequate fire safety design measures, has increased this risk, resulting in a rise in the number of facade fires in recent years.

Reports of facade fire incidents have grown in recent years, though it remains unclear whether this reflects an actual increase in occurrence, a higher number of buildings at risk, or improved reporting and documentation. Over the past two decades, a significant increase in high-rise facade fires has been observed, driven in part by changes in construction materials and building practices. **Figure 2** illustrates the data on large facade fires from 1990 to the present day. However, it is important to note that the data presented is based on documented events found in articles and technical publications and may therefore underrepresent earlier cases or those that were not reported.

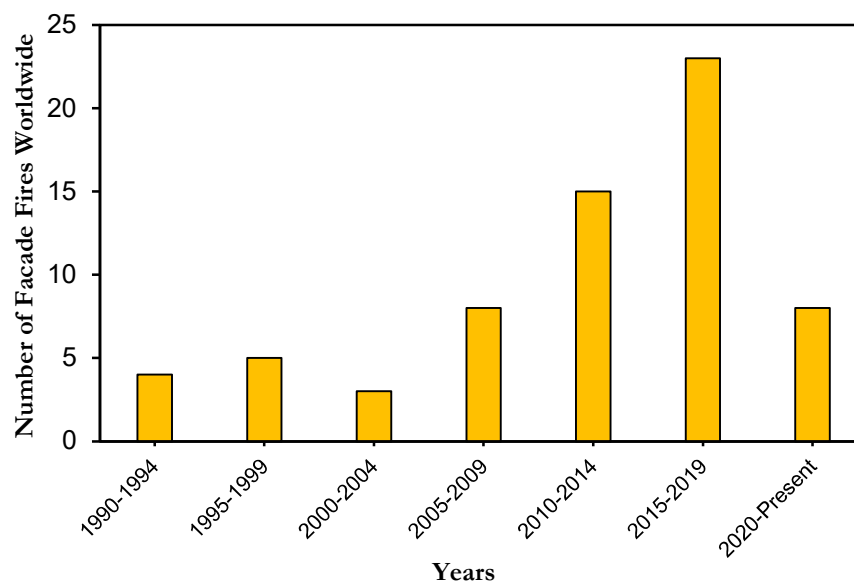


Figure 2 - Data of large facade fires from 1990 to present day. Adapted from [8] and updated with data from [9].

The mechanism of facade fire spread involves complex interactions between flame dynamics, thermal radiation, architectural design, façade technical design (e.g., cavity width, cladding materials, and connections), and environmental conditions such as wind. Once flames reach the exterior, rapid propagation can occur if combustible components are present. These may include cladding or insulation, with the spread often intensified by cavities that enable heat and flames to move both vertically and laterally. In such scenarios, fire can re-enter the

building at higher levels, potentially igniting secondary fires within the structure, as illustrated in **Figure 3**.

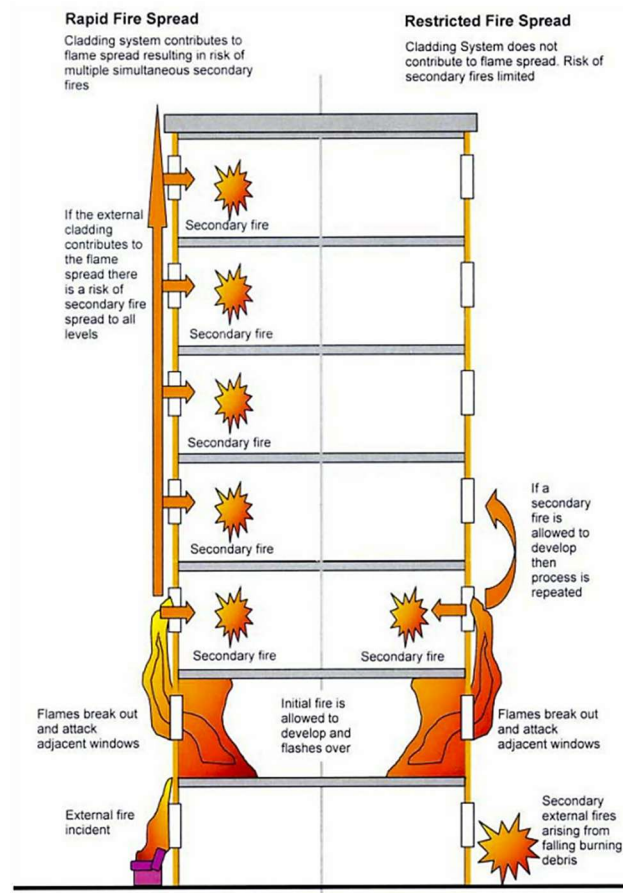


Figure 3 - Mechanism of fire spread on external cladding [10].

To mitigate these risks, fire safety regulations in many countries, such as Denmark, define key performance requirements for external walls and roofs. These include limiting fire spread on and within façades, preventing fire from traveling between fire compartments via the external envelope during evacuation, minimizing flaming droplets and particles, and ensuring façade elements do not fall off during a fire in a way that would endanger people. These functional goals guide fire-safe façade design through appropriate materials, cavity barriers, and detailing.

Façade fires are typically initiated through three main ignition scenarios, as illustrated in **Figure 4 [11]** :

- (1) radiation from neighbouring buildings.
- (2) fires originating from an external source near the façade.
- (3) internal fires breaching an opening and spreading externally.

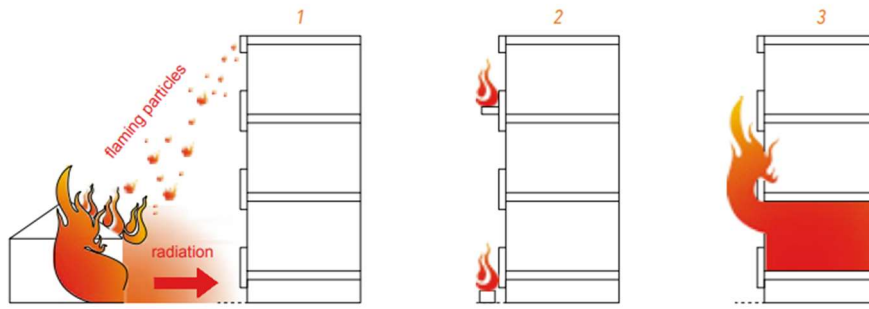


Figure 4 - Typical scenarios of fire spread across facades [11].

(1) Radiation from neighbouring buildings

When a nearby building is engulfed in flames, the heat it radiates can ignite the facade of the adjacent building if the heat flux exceeds the critical ignition threshold of the external cladding, particularly in the presence of flying embers or direct flame exposure. The severity of this mechanism depends on several factors, including the size of the fire, the separation distance between buildings (which influences the intensity of the radiated heat), and the combustibility of the facade materials exposed to this radiation [12].

(2) Fires originating from an external source near the facade.

External fires from vehicles, waste containers, or combustible items stored on balconies can significantly threaten a building's facade. These external heat sources can expose the combustible elements of the facade to high temperatures, increasing the likelihood of ignition. The likelihood of ignition depends not only on the intensity and duration of the external heat exposure but also on the thermal and ignition properties of the facade materials.

(3) Internal fire breaching an opening and spreading externally.

In this scenario, a fire originates inside the building and breaches an opening such as a window. Once outside, flames can impinge directly on the facade, initiating external fire spread.

Among the three mechanisms described, this is the most frequent and hazardous. A study conducted by VTT, which examined fire incidents in multi-story residential buildings in Sweden and Finland between 2004 and 2012, indicates that approximately 88-92% of fire ignitions originate internally, while only 2-3% are from external sources [13].

Several major fire incidents have demonstrated the catastrophic consequences of this scenario. The Grenfell Tower fire in London (2017) is one of the most well-known cases, where a fire originating from a kitchen spread through the building external cladding which was made of highly flammable ACM (aluminium composite material) [14], and resulted in rapid, uncontrolled fire spread, leading to 72 deaths [15].

Given its frequency and severity, this report will focus on the third mechanism—internal fire breaching an opening and propagating externally.

Importantly, the extent to which flame spread occurs depends heavily on the combustibility of the materials used. In many regulatory contexts, the default fire safety strategy is to avoid flame spread by using non-combustible or limited-combustibility materials. For example, in Denmark, buildings with floor heights up to 22 meters must typically use materials classified as Euroclass B-s1,d0 or better (reaction to fire classes are presented in **Table 1**), according to prescriptive provisions in the Danish Building Regulations [16]. This requirement minimizes fire risk by restricting the use of materials that could contribute significantly to flame spread.

Nevertheless, alternative design approaches allow for controlled use of combustible materials, provided that the entire facade system can be shown to meet specific fire safety objectives. This is typically done through large-scale system testing or performance-based fire engineering analysis. For example, under certain Danish provisions, up to 20% of the facade surface may consist of Euroclass D materials such as untreated wood [16]. Similarly, Swedish Building Regulations (BBR) [17] permit the use of combustible facade components in lower-risk buildings (e.g., class Br2 or Br3), while stricter rules apply for taller or higher-risk structures (class Br1). In such cases, compliance may be achieved by passing full-scale tests like SP Fire 105, which assess flame spread, temperature rise, and risk of falling debris [18].

Given this regulatory context, while the use of combustible materials on facades is restricted, it remains legally and practically feasible through alternative design approaches. Therefore, research such as this — which investigates the interaction between building geometry and flame spread—is especially relevant to alternative designs.

Table 1 - European reaction to fire classes for construction products excluding floorings and linear pipe thermal insulation products according to EN 13501-1 [19] :

Euroclass	Smoke class	Burning droplets class	Test required			FIGRA (W/s)	Combustibility
			Non-comb	SBI	Small flame		
A1	—	—	x	—	—	—	non-combustible
A2	s1, s2 or s3	d0, d1 or d2	x	x	—	≤120	limited combustibility
B	s1, s2 or s3	d0, d1 or d2	—	x	x	≤120	combustible, very limited contribution to fire
C	s1, s2 or s3	d0, d1 or d2	—	x	x	≤250	combustible, limited contribution to fire
D	s1, s2 or s3	d0, d1 or d2	—	x	x	≤750	combustible, moderate contribution to fire
E	—	- or d2	—	—	x	—	combustible, high contribution to fire
F	—	—	—	—	—	—	combustible, easily flammable

Non-comb = non-combustibility test (EN ISO 1182)

SBI = Single burning item test (EN 13823)

Small flame = Ignitability test (EN ISO 11925-2)

FIGRA = Fire growth rate index

2.2. Effect of Horizontal Projection on Fire Spread

Horizontal projections, such as balconies, plume deflectors, and overhangs, are commonly integrated into building facades for aesthetic, functional, and fire safety purposes. However, their influence on fire spread remains a complex and debated topic. These structural elements extending outward from the facade, create a perpendicular barrier to the exterior vertical wall.

Horizontal projections can either limit vertical flame propagation by deflecting flames away from the facade ([4], [5], [20], [21], [22], [23], [24]) or, under certain conditions, contribute to lateral fire spread by trapping heat beneath the projection and intensifying the lateral heat flux to the facade surface ([6], [25]).

2.2.1. Mitigation of Vertical Flame Spread

One of the earliest studies on horizontal projections was conducted by Yokoi [4], who examined their role in flame propagation through full-scale experiments focusing on window integrity in the floor above the fire compartment. His findings revealed that a 0.74 m deep projection effectively shielded the upper floor from fire exposure, influencing revisions to Japan's building code, which mandated horizontal projections as a fire protection measure. Oleszkiewicz [5] expanded on this research through full-scale fire experiments in a three-story burn facility that was 10.3m high by 6m wide and 4.5m deep concrete structure, demonstrating that horizontal projections significantly reduce heat flux to the upper facade. A 0.3 m projection provided noticeable protection, while a 0.6 m projection reduced heat exposure by approximately 60%, and a 1 m deep projection decreased exposure by 85% compared to no projection (Figure 5).

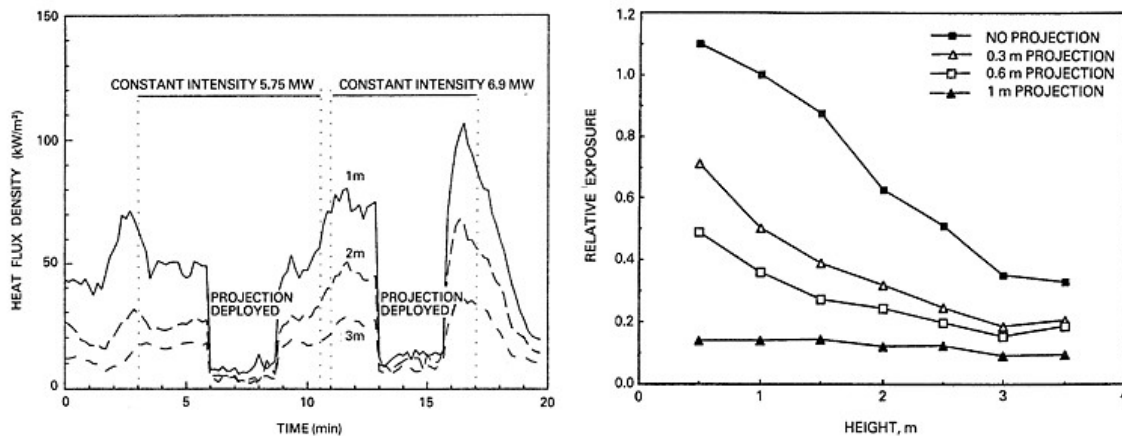


Figure 5 - Effect of horizontal projection on relative exposure and heat flux density [5].

Suzuki et al. [20] further explored the impact of balcony depth on ejected flames in high-rise buildings using a 1/7 scale model of a seven-story apartment building. Their experiments varied balcony depth and heat release rates, revealing that deeper balconies significantly reduced vertical flame length and deflected flames outward, mitigating flame spread and lowering radiative heat flux to the upper facade.

Building on this, Mammoser & Battaglia [21] used Fire Dynamics Simulator (FDS) to explore how varying balcony depths and geometries affect fire dynamics. Their numerical study

replicated Suzuki et al.'s experimental setup and confirmed that balconies can effectively reduce vertical fire spread. In the 1/7th scale model, optimal temperature reductions were seen with balcony depths exceeding 15 cm.

Morgado et al. [22] conducted a study combining numerical FDS simulations, analytical calculations (EN 1991-1.2), and experimental tests to assess balcony impact on fire spread between floors. They analysed three scenarios: (1) no balcony, (2) a balcony with the same width as the window, and (3) a balcony extending 1 m beyond each side of the window. Their findings showed that larger balconies reduced temperatures above them compared to shorter or no balcony configurations. While balconies effectively redirected flames away from the upper façade, the simulations showed an increase in lateral flame projection, particularly in the case of the extended balcony.

Lu et al. [23] conducted 1/8 scaled fire experiments examining how horizontal projection size influenced flame height and facade heat flux. Their study identified three distinct flame behaviour stages: (1) free flame stage (below the projection), (2) horizontal spread stage (flame extends beneath the projection), and (3) overflow stage (flame rises past the projection). Their findings showed that longer projections significantly reduced flame height and heat flux, with increased vertical projection height further decreasing facade heat exposure.

Kolaitis et al. [24] analysed the influence of vertical positioning of horizontal projections on heat flux distribution using a 1/4-scale compartment model. Their results demonstrated that increasing either the height or depth of projections reduced incident heat flux levels on facade surfaces above the projection by 25% to 57%, as projections distorted vented flames and forced them away from the facade.

Nilsson et al. [26], [27] conducted a comparative numerical study using FDS to evaluate the impact of horizontal projections. Their findings indicate that balconies with a minimum depth of 60 cm resulted in better fire protection compared to the standard 1.2 m spandrel requirement in Swedish building regulations. The 60 cm, 80 cm and 100 cm deep projections reduced adiabatic surface temperature exposure by 15-50% at 1.2 m above the opening.

The effectiveness of horizontal projections was found to vary based on opening configuration, with wide and short opening showing greater benefit from horizontal protection. Additionally, the research revealed that balcony width plays a crucial role, particularly when positioned directly above openings. Wider balconies resulted in lower adiabatic surface temperatures, especially for door configurations. Ventilation conditions were also identified as a critical factor, with restricted ventilation significantly increasing facade temperatures and altering flame behaviour.

2.2.2. Contribution to Lateral Flame Spread

While previous studies suggest horizontal projections act as effective fire barriers by limiting vertical fire spread into upper floors, recent research highlights their potential to exacerbate lateral fire spread under certain conditions.

McKeen and Liao [6] conducted a numerical investigation into the influence of horizontal projections, such as balconies, on lateral flame propagation in multi-unit residential buildings. Using FDS, they modelled facade fire experiments performed by the National Research

Council of Canada (NRCC), analysing fire sizes ranging from 5.5 MW to 10.3 MW and measuring heat flux distribution on facades with and without horizontal projections.

Their findings indicate that while balconies can reduce vertical flame attachment, they simultaneously amplify lateral heat flux. When fire plumes interact with these projections, the flames spread radially, intensifying heat transfer along the facade. In the absence of fire-rated balcony dividers, this effect can accelerate fire spread between adjacent units. While projections may function as fire barriers, they also concentrate heat beneath balconies, potentially facilitating horizontal flame spread. Furthermore, the researchers found that wider window openings dispersed fire plumes more effectively, reducing localized heat flux concentrations.

Peacock [25] explored how architectural features influence fire spread, introducing the concept of "feature-enhanced horizontal spread", where flames become trapped beneath horizontal facade elements, intensifying lateral propagation. She examined cases such as the Olympus Tower and Monte Carlo Casino & Hotel fires, where multiple horizontal projections contributed to rapid fire spread along the structure's decorative elements.

2.3. Research Gaps and Future Directions

The influence of horizontal projections on vertical flame spread has been widely studied, but their role in lateral fire propagation—particularly under conditions involving combustible façade systems—is less well understood.

In this regard, the dual effect of horizontal projections—limiting vertical flame spread while potentially promoting lateral fire propagation and thermal stress—remains an underexplored area in facade fire safety. While the benefits of projections in disrupting upward flame movement are well recognized, their contribution to lateral heat transfer, especially in the presence of combustible cladding systems, requires deeper investigation. To ensure both vertical containment and controlled lateral fire spread, future studies should focus on optimizing projection geometry, validating simulation results through experimental testing, and assessing projection performance under a variety of realistic material and environmental configurations.

3. Theoretical Framework

This section examines the existing literature on facade fire dynamics, exploring the following key aspects:

- **Compartment fire dynamics** – Examining combustion dynamics within the enclosure.
- **Flame ejection from the opening** – Analysing the conditions that lead to flame venting through openings.
- **Fire growth and spread outside the opening** – Examining the characteristics of ejected flames in free facades and beneath horizontal projections, and the mechanisms of flame spread to exterior cladding.

3.1. Compartment Fire Dynamics

Analysing fire behaviour inside a compartment is crucial for understanding flame spread on exterior cladding due to an ejected fire plume. The interaction between fire dynamics within the compartment and the geometry of openings determines the characteristics of the exiting flames.

A fire begins with the ignition of a fuel package within an enclosure, which can occur through either piloted ignition (flame or spark) or spontaneous ignition which occurs due to self-heating. The size and location of the ignition source play a critical role in the fire growth [28]. The complete stages of fire development are illustrated in Figure 6.

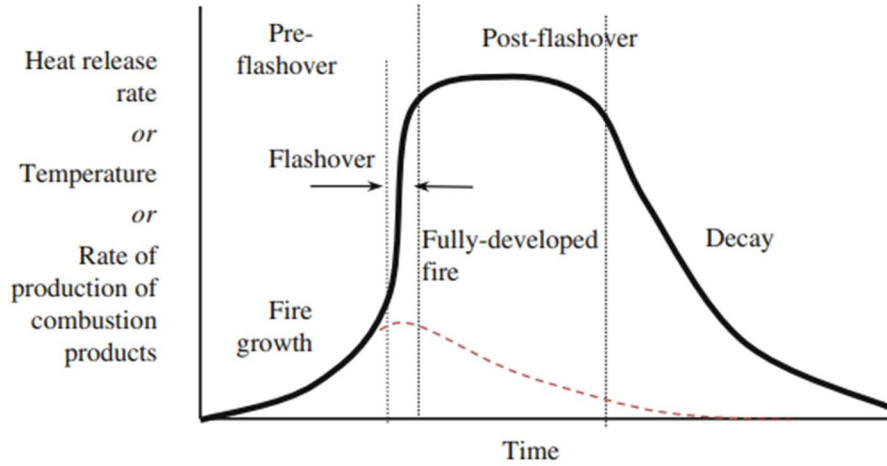


Figure 6 - Fire development inside a compartment [29].

During the growth phase, the fire is initially fuel-controlled, meaning there is sufficient oxygen for combustion, and its progression depends primarily on the flammability and configuration of the fuel. This phase is characterized by a clear stratification of gases, with a hot upper layer and a cool lower layer [28]. The HRR in fuel-controlled conditions is determined by Equation (1) [30] :

$$\dot{Q} = \dot{m}_f \Delta H_c \quad (1)$$

where $\dot{Q}$ is the heat release rate (kW), $\dot{m}_f$ is the mass burning rate of the fuel (kg/s) and ΔH_c is the heat of combustion (kJ/kg).

If the fire continues to grow, it may either transition into a fully developed fire through flashover or begin to decay due to limited oxygen availability or insufficient combustible materials to sustain it. This can occur when the fire is not intense enough to radiate the necessary heat to reach and ignite additional fuel packages (dashed line in **Figure 6**).

Flashover marks the rapid transition from a fuel-controlled to a ventilation-controlled fire, typically occurring when compartment temperatures reach 500-600 °C. A key indicator of flashover is radiation from the upper layer to the floor, reaching approximately 15-20 kW/m², causing the ignition of available fuels within the enclosure [28].

Once fully developed, the fire reaches its peak intensity, with compartment temperatures ranging from 700 to 1,200 °C. In this phase, fire growth becomes ventilation-controlled, limited by the inflow of fresh air rather than the availability of fuel [29]. The enclosure becomes under-ventilated as oxygen supply becomes insufficient to support complete combustion [28]. Consequently, unburnt gases accumulate and exit through the upper portion of the opening, where they mix with external air and ignite, producing external flaming.

Under ventilation-controlled conditions, combustion is governed by the available oxygen, and the maximum heat release rate (HRR) can be estimated based on the mass flow rate of incoming air. Assuming complete combustion, the heat released per kilogram of air consumed is approximately 3,000 kJ/kg [31].

Using the air mass flow rate ($\dot{m}_a$), the theoretical maximum HRR inside the enclosure is given by **Equation (2)** [31]:

$$\dot{Q}_{inside} = 3000 \times \dot{m}_a \quad (2)$$

The inflow rate of fresh air ($\dot{m}_a$) and the hot gas mass outflow rate ($\dot{m}_g$), shown in **Figure 7**, can be expressed as [28] :

$$\begin{cases} \dot{m}_a = C_d \int_0^{h_1} W \rho_a \vartheta_a(z) dz \\ \dot{m}_g = C_d \int_0^{h_o-h_1} W \rho_g \vartheta_g(z) dz \end{cases} \quad (3)$$

where C_d is the flow coefficient at the opening, h_1 is the height of the neutral plane from the bottom of opening (m), h_o is the height of the opening (m), ϑ_a and ϑ_g are air inflow velocity and hot gas outflow velocity through opening respectively, ρ_a and ρ_g are the density of ambient air and the density of the hot gases inside the enclosure and W is the width of opening (m).

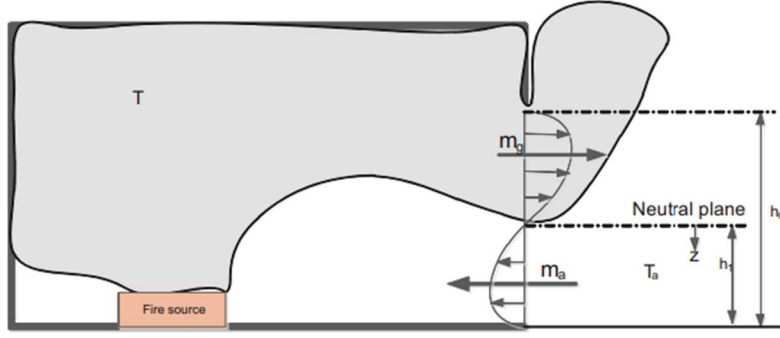


Figure 7 - Vent flow (well-mixed case) [29].

By integrating and simplifying, the equation for air inflow and hot gas outflow rates can be written as:

$$\begin{cases} \dot{m}_a = \frac{2}{3} C_d W \rho_a \sqrt{\frac{2(\rho_a - \rho_g)g}{\rho_a}} h_1^{3/2} \\ \dot{m}_g = \frac{2}{3} C_d W \rho_g \sqrt{\frac{2(\rho_a - \rho_g)g}{\rho_g}} (h_o - h_1)^{3/2} \end{cases} \quad (4)$$

Based on the conservation of mass, the mass flow rate of air entering the compartment ($\dot{m}_a$) is approximately equal to the mass flow rate of combustion gases leaving the compartment ($\dot{m}_g$) [28]:

$$\dot{m}_g \approx \dot{m}_a \quad (5)$$

The height of the neutral plane (h_1) depends on the temperature inside the enclosure. Assuming that the temperature inside the compartment is uniform (well-mixed assumption), meaning the gas temperature (T_g) and density (ρ_g) are the same throughout the enclosure. The position of the neutral plane is derived from inserting **Equation (4)** into **(5)** :

$$h_1 = \frac{h_o}{1 + (\rho_a/\rho_g)^{1/3}} \quad (6)$$

The mass flow rate of air entering through an opening can be further refined as:

$$\dot{m}_a = \frac{2}{3} C_d A \sqrt{h_o} \sqrt{2g\rho_a} \sqrt{\frac{(\rho_a - \rho_g)/\rho_a}{[1 + (\rho_a/\rho_g)^{1/3}]^3}} \quad (7)$$

Karlsson and Quintiere [28] showed that the density factor:

$$\sqrt{\frac{(\rho_a - \rho_g)/\rho_a}{[1 + (\rho_a/\rho_g)^{1/3}]^3}}$$

can be approximated to 0.214 for fully developed fires. By substituting values ($C_d = 0.7$, $g = 9.81 \text{ m/s}^2$, $\rho_a = 1.2 \text{ kg/m}^3$), **Equation (7)** simplifies to:

$$\dot{m}_a = 0.5A\sqrt{H} \quad (8)$$

where A is the area of the opening (m^2) and H is the height of the opening (m). The term $A\sqrt{H}$ is defined as the ventilation factor in the literature [28], [32].

3.2. Ejected Fire Plume

Ohmiya et al. [33] identified two distinct types of flame ejections (**Figure 8**). The first, known as ceiling jet flames, occurs early in the fire (fuel-controlled) when flames extend outward near the top of the opening. The second type, flame ejection from unburnt gases, happens during the under-ventilated stage when oxygen levels are critically low. In this scenario, the flames are more stable, with their base starting at the neutral plane, positioned approximately $0.4H$ from the bottom. The HRR inside during this stage can be approximated by $1500A\sqrt{H}$ kW.

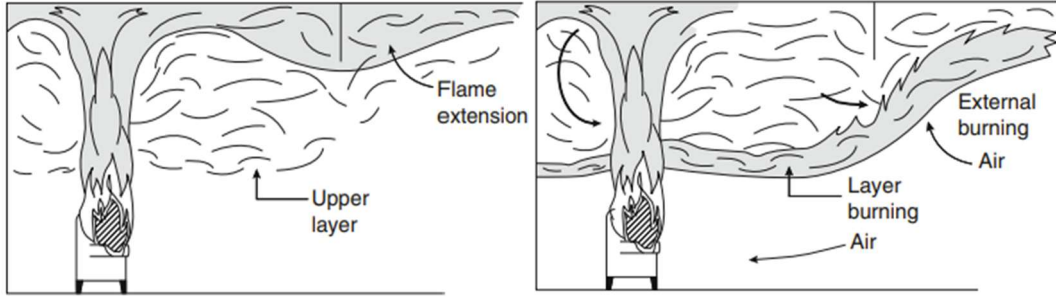


Figure 8 - Flame extension due to ceiling jet (left) and external burning in under-ventilated fire (right) [34].

According to experimental studies, under-ventilated conditions lead to flame ejection when the theoretical heat release rate (based on the burning rate of available fuel) exceeds a critical value of $1500A\sqrt{H}$ kW [31]. In such scenarios, complete combustion cannot be sustained within the compartment, resulting in unburned fuel gases escaping through the openings. These unburned gases then ignite upon mixing with air outside, forming an ejected fire plume on the exterior cladding.

The excess HRR ($\dot{Q}_{ex}$) due to the combustion of unburnt gases outside the enclosure is defined by **Equation (9)** as the difference between the total HRR from the fuel combustion and the maximum HRR inside the compartment ($\dot{Q}_{inside}$) :

$$\dot{Q}_{ex} = \dot{m}\Delta H_c - 1500A\sqrt{H} \quad (9)$$

where $\dot{m}$ is the mass burning rate (kg/s), ΔH_c is the heat of combustion (kJ/kg) of the fuel, A is the area of the opening (m^2) and H is the height of the opening (m).

3.3. Characteristics of Ejected Flames

The properties of the ejected flames (shape and dimensions) are important parameters that define the thermal exposure on the facade surface. In this section, we will be discussing the

characteristic length scale of the ejected plume as well as the flame height and extension radius when horizontal projection is present.

3.3.1. Characteristic Length Scale

Yokoi's [4] early work on ejected flames introduced a length scale to represent the radius of the circular fire source. This scale was used to characterize the air entrainment of the ejected flames along the facade, and it was further employed to determine the temperature and velocity profiles in his study. Yokoi's model assumed the neutral plane was positioned at the centre of the opening, and the equivalent radius is defined by the **Equation (10)**:

$$r_0 = \sqrt{\frac{HW}{2\pi}} \quad (10)$$

where H and W are the height and width of the opening.

Building upon this, a more recent study conducted by Delichatsios and Lee et al. [35] proposed a theoretical framework to characterize the ejected plume. Their model approximates the ejected plume as originating from a rectangular fire source located at the neutral plane height $H_n = 0.4H$, where H represents the window height. The dimensions of this rectangular fire source are represented by the length scales l_1 and l_2 , which are derived from the window area (A) and height (H), using the **Equations (11) and (12)**:

$$l_1 = \left(A \sqrt{H} \right)^{2/5} \quad (11)$$

$$l_2 = \left(AH^2 \right)^{1/4} \quad (12)$$

The length scale l_1 is associated with convective flow at the enclosure exit, while l_2 determines the transition from horizontal to vertical flow orientation. These two length scales collectively describe the development of flames emerging from an opening, significantly influencing flame shape and behaviour.

Delichatsios and Lee [36] revised the length scale proposed by Yokoi [4], and found that their proposed length scale was more appropriate, as the results from this revised length scale accurately matched Yokoi's experimental data.

3.3.2. Flame Height

Lee and Delichatsios et al. [35] conducted an experimental study to investigate the characteristics of flame height and heat fluxes in under-ventilated fire enclosures. Their research aimed to address inconsistencies and gaps in previous studies concerning the behaviour of ejected flames and associated heat fluxes, with the objective of developing validated correlations for predicting these parameters.

The study used enclosures with a front face dimension of $0.5 \text{ m} \times 0.5 \text{ m}$ and varying depths (0.5 m, 1 m, and 1.5 m), with openings of different sizes to analyse the influence of opening size on ejected flame behaviour. The key parameters investigated include flame height and

heat flux correlation with the non-dimensional excess HRR ($\dot{Q}_{ex}^*$) and characteristic length scale (l_1).

The non-dimensional excess HRR ($\dot{Q}_{ex}^*$) characterizes fire plume behavior, distinguishing between buoyancy-driven and momentum-driven plumes. It is defined by **Equation (13)**:

$$\dot{Q}_{ex}^* = \left(\frac{\dot{Q}_{ex}}{\rho_{\infty} c_p T_{\infty} \sqrt{g} l_1^{5/2}} \right) \quad (13)$$

where $\dot{Q}_{ex}$ is the excess HRR, ρ_{∞} is the ambient air density, c_p is the specific heat capacity of ambient air, T_{∞} is the ambient air temperature, g is the gravitational acceleration and l_1 is the characteristic length scale.

The study developed a correlation relating the ejected flame height (Z_f) to the non-dimensional excess HRR ($\dot{Q}_{ex}^*$) and the characteristic length scale (l_1).

$$\frac{Z_f}{l_1} = fcn[\dot{Q}_{ex}^*] \quad (14)$$

The results presented in **Figure 9** indicate two distinct flame regimes [31] : for smaller fire ($\dot{Q}_{ex}^* \leq 1.3$), the flame height follows a two-dimensional behaviour, with a power dependence of 2/3 on $\dot{Q}_{ex}^*$, resembling a line plume where entrainment occurs from the front. For larger fires ($\dot{Q}_{ex}^* > 1.3$), the flames become three-dimensional with a power dependence of 2/5 on $\dot{Q}_{ex}^*$, forming a half-axisymmetric plume where air entrainment occurs from both the sides and the front.

This correlation is presented by **Equation (15)** [37]:

$$Z_f = \begin{cases} 3.2 \dot{Q}_{ex}^{*2/3} l_1 & \text{when } \dot{Q}_{ex}^* \leq 1.3 \\ 3.5 \dot{Q}_{ex}^{*2/5} l_1 & \text{when } \dot{Q}_{ex}^* > 1.3 \end{cases} \quad (15)$$

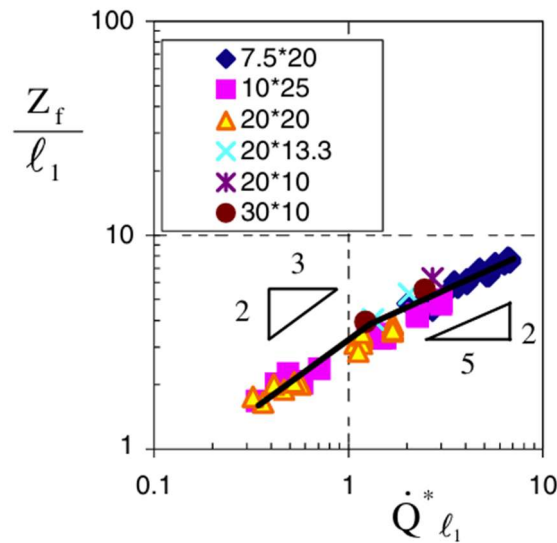


Figure 9 - Flame height correlation proposed by Lee et.al. Markers represent opening sizes (width × height in cm). (Reprinted from [35] with permission from Elsevier).

As shown in **Figure 10**, Sun et al. [37] conducted a comparative analysis between experimental studies at various scales—small, medium, and large—and the predictions of the established correlation proposed by Lee et al. [35]. The study involved data from ([35], [38], [39], [40]) for small-scale experiments, ([41], [42], [43], [44]) for medium-scale tests, and ([45], [46], [47], [48], [5]) for large-scale fire scenarios. The findings demonstrated a strong agreement between experimental results and the correlation, with prediction errors remaining below 25%.

Expanding on this validation of the correlation, Guoxiang et al. [49] conducted CFD simulations to evaluate flame height predictions in fire scenarios, using the experimental data from Lee et al. [35] for validation against FDS results. Two approaches were employed to define flame height in FDS: (1) a temperature-based method, where the flame tip was identified at a reference temperature of 520 °C, and (2) an HRRPUV-based approach, in which the flame was considered present when HRRPUV exceeded predefined thresholds of 0.5 MW/m³ and 1.2 MW/m³. The study found that FDS overpredicted external flame height compared to Lee et al.'s results, with an overestimation of 17.85% using the temperature-based method 24.51% using the HRRPUV threshold of 1.2 MW/m³. The HRRPUV threshold of 0.5 MW/m³ resulted in even greater discrepancies, with overpredictions reaching up to 56%. Despite this discrepancy, the results showed good agreement with experimental data, confirming the 2/3 power dependence of flame height on excess HRR established in the correlation. Additionally, the height of the neutral plane, defined as 0.4H in Lee et al.'s study, was assessed in the CFD simulations, which demonstrated strong alignment with the theoretical model proposed by Delichatsios and Lee [35].

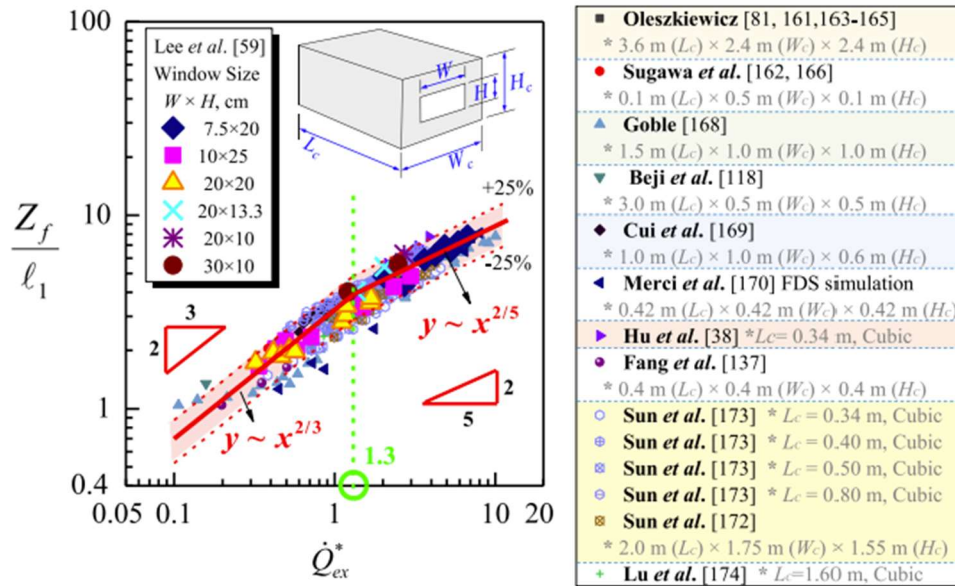


Figure 10 - Validation of Lee et al. [35] correlation using multi-scale experimental and numerical data [37].

3.3.3. Flame Extension Beneath a Horizontal Projection

Lu et al. [50] investigated the behaviour of flame extension beneath horizontal projections caused by ejected fire plumes using small-scale experiments. Their study involved cubic

compartments measuring 0.4 m, with variations in opening dimensions, projection height, and HRR. The horizontal projection used in the experiments was non-combustible.

Experimental observations revealed that flames beneath horizontal projections spreads in a half-circle pattern as illustrated in **Figure 11**. While Delichatsios [35] modeled the ejected fire plume as originating from a rectangular fire source at the neutral plane level, Lu et al. [50] focused on the resulting flame impingement beneath projections and proposed modelling it as a half-circle fire source with a radius R_0 , as expressed in **Equation (16)**.

$$R_0 = \sqrt{\frac{2}{\pi}} l_1 l_2 \quad (16)$$

where l_1 and l_2 are the characteristic length scales introduced in [35].

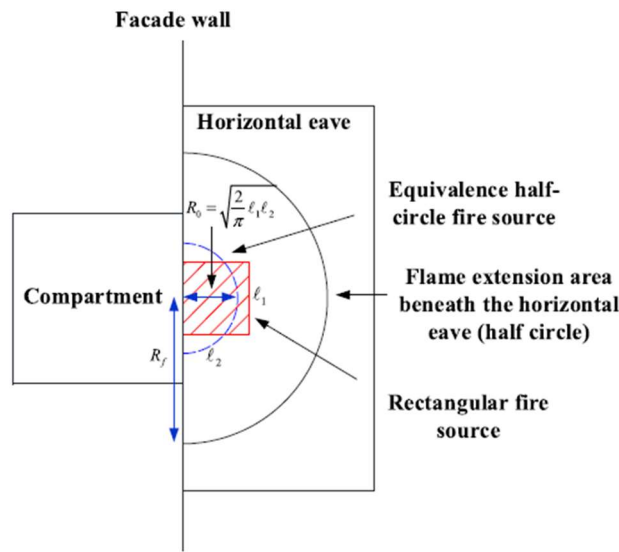


Figure 11 - Flame extension beneath horizontal projection in half-circle pattern. (Reprinted from [50] with permission from Elsevier).

The experimental results showed that flames extended beneath the horizontal projection only when the projection was positioned below the free facade flame height. However, when the flame height was lower than the projection, the plume could not reach the surface, and the extension disappeared. Increasing the HRR led to longer flame extensions beneath the projection, while raising the projection height reduced the extent of the extension. Additionally, smaller window openings resulted in longer flame extensions due to an increase in the excess HRR.

Based on their experimental findings, Lu et al. [50] developed a dimensionless correlation to predict flame extension length (R_f) beneath the horizontal projections. This correlation accounts for the excess HRR ($\dot{Q}_{ex}$), the vertical distance between the neutral plane and the horizontal projection ($H_e - H_n$), and the intersected volume ratio (ϕ) representing the proportion of the flame volume intercepted by the horizontal projection. The correlation is expressed by **Equation (17)**:

$$R_f = 0.0283 \left(\frac{\phi \dot{Q}_{ex}}{\sqrt{H_e - H_n}} \right)^{1/2} \quad (17)$$

The presence of a horizontal projection causes the ejected flames to divide into two distinct portions: the intercepted flame volume above the eave, and the impinging flame on the underside of the horizontal projection (Figure 12b).

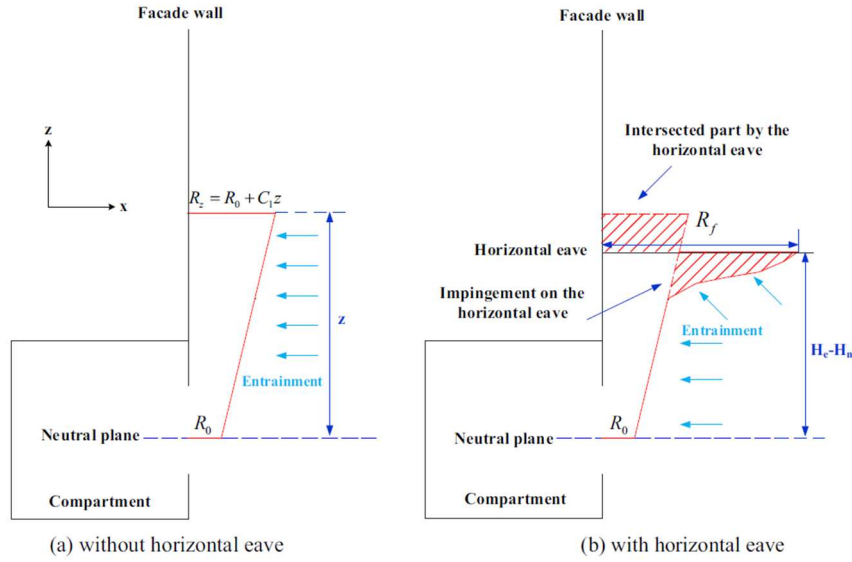


Figure 12 - Simplified model illustrating fire plume with and without horizontal eave conditions. (Reprinted from [50] with permission from Elsevier).

The intersected volume ratio (ϕ) quantifies the relationship between the intercepted flame portion and the total flame volume. It is calculated using Equation (18):

$$\phi = \frac{R_0^2(H_f - H_e) + R_0 C_1 ((H_f - H_n)^2 - (H_e - H_n)^2) + \frac{1}{3} C_1^2 ((H_f - H_n)^3 - (H_e - H_n)^3)}{R_0^2(H_f - H_n) + R_0 C_1 (H_f - H_n)^2 + \frac{1}{3} C_1^2 (H_f - H_n)^3} \quad (18)$$

where H_f is the free facade flame height (in the absence of a horizontal projection), R_0 is the fire source radius, H_e is vertical height of the horizontal projection from the floor, H_n is the height of the neutral plane and C_1 is a constant originally defined by Quintiere [51] where $C_1 = 0.179$ for axisymmetric fire source.

Lu et al. [23] identified three distinct stages of flame behaviour in the presence of horizontal projections. The first stage, referred to as the "free flame stage", is characterized by flames that remain below the projection, behaving similarly to a free facade fire scenario without projections. The second is the "flame horizontal spread stage", occurs when the flame reaches and spreads along the horizontal projection. Finally, the "flame overflow stage" arises when the flames extend beyond the horizontal projection and are redirected upward due to buoyancy effects, which occurs when the projection length is insufficient.

During the flame overflow stage, the flame extension zone is divided into two regions: S_1 , located closer to the facade wall where the flame continues its extension, and S_2 , where

flames are redirected upward due to buoyancy. These two regions, S_1 and S_2 , are illustrated in Figure 13.

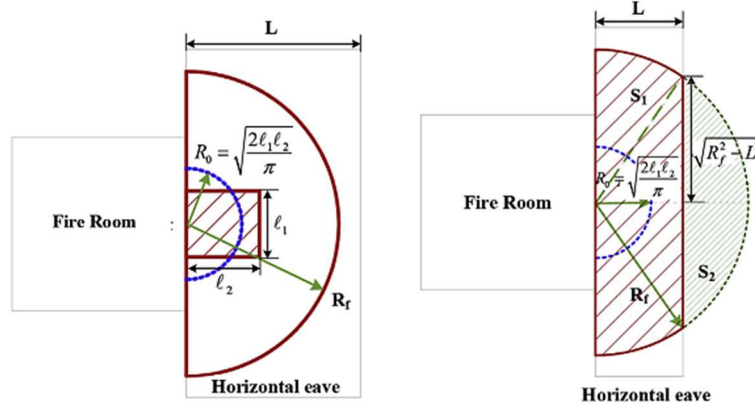


Figure 13 - Flame extension in presence of different projection length. Adapted from [23] with permission from Elsevier.

To predict the extension of the flame in region S_1 , Lu et al. developed a correlation expressed as:

$$S_1 \sqrt{g(H_e - H_n)} = 0.1455 \phi_1 \left(\frac{\dot{Q}_{ex}}{\rho_f \Delta H_c} \right)^{1/2} \quad (19)$$

where H_e is vertical height of the horizontal projection from the floor, H_n is the height of the neutral plane, ϕ_1 is the intersected volume ratio (see Equation (18)), $\dot{Q}_{ex}$ is the excess HRR, ρ_f is the density of the fuel and ΔH_c is the heat of combustion of the fuel.

3.4. Flame Spread on Facade Wall

Heat flux received by a facade wall is a critical parameter in predicting fire spread, particularly when combustible materials are used. While surface exposure is typically the main concern, in ventilated facade systems, flames may also enter cavities behind the cladding, contributing to vertical fire spread under certain conditions.

Understanding this process requires examining how flames interact with the facade and how the heat flux to the surface can be estimated.

When flames are ejected from an opening, their behaviour relative to the facade wall is strongly influenced by the geometry of the opening. The shape of the opening determines how closely the flame attaches to the wall [4] : For narrow openings (where vertical height exceeds horizontal width), the hot gases rise more freely away from the wall, and air can easily be entrained from the sides, which tends to keep the flame detached from the surface. In contrast, wide openings (with greater horizontal width) limit side air entrainment. This results in a stronger flame attachment to the facade wall.

When attachment occurs, the flames transmit both radiative and convective heat to the facade surface, preheating the wall material. As the surface temperature rises, it eventually reaches the pyrolysis temperature, at which combustible gases are released and ignited by the flame front. This defines the pyrolysis region, where the flame front continues to propagate by heating the unburned fuel within the preheating zone.

The preheating zone, located between x_p and x_f , experiences a heat flux of approximately 20-30 kW/m² from the flames [52]. In facade scenarios, the heat flux can be considerably higher, often exceeding 90 kW/m² [48]. Above x_f , the buoyant plume region extends upward, where the visible flame is no longer present. Flame spread can be understood as a series of piloted ignitions, with each step in the process contributing to the sustained propagation of fire along the facade.

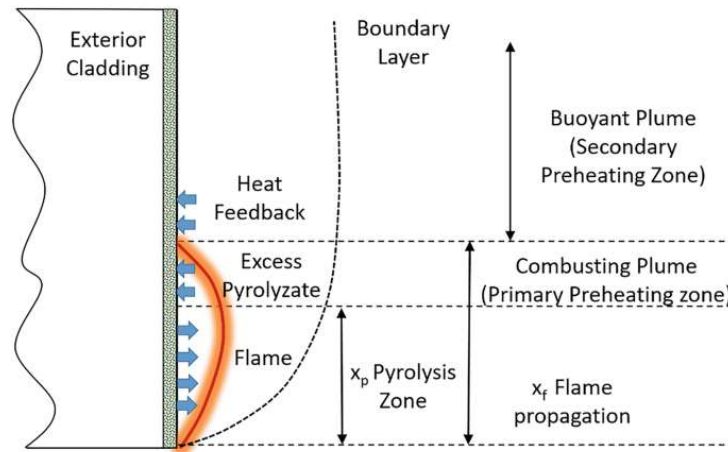


Figure 14 - Flame spread along the exterior surface of the façade. Reprinted from [53], licensed under [CC BY 4.0](#).

The rate at which fire spreads along a facade cladding is primarily influenced by heat transfer mechanisms and material properties. Among different flame spread orientations, upward propagation is the most rapid, as its growth follows an exponential pattern. This acceleration is driven by concurrent flow dynamics, where buoyancy enhances the spread rate as flames and hot gases rise in the same direction. In this scenario, heat transfer occurs through a combination of radiation and convection, with both mechanisms preheating the surface ahead of the fire. Additionally, the accumulation of hot gases within the boundary layer adjacent to the facade intensifies heat transfer, further facilitating the rapid spread of the flame front [32].

The behaviour of flame spread varies significantly between thermally thin and thermally thick materials, largely due to differences in heat transfer mechanisms and thermal properties [32]. In thin fuels, where the entire thickness can heat uniformly (as described by the lumped thermal capacity model), there is minimal temperature difference across the material. As a result, the rate of flame spread is inversely proportional to the thickness meaning that thinner materials burn more rapidly. In contrast, thick materials exhibit more complex behaviour. As thickness increases beyond a certain point, the flame spread rate gradually becomes less sensitive to further increases in thickness. Eventually, it reaches a constant value. For very thick materials, heat transfer within the solid becomes dominant, and the fuel behaves as "thermally thick."

Once the material is considered thermally thick, thermal inertia, represented by the parameter $(k\rho c)$, plays a significant role in determining flame spread characteristics. Where ρ is the density of the material, c is its specific heat capacity and k is its thermal conductivity. These characteristics determine how rapidly heat is taken in and dissipated throughout the material, which in turn influences ignition delays and flame spread rate [52].

Materials with high thermal inertia absorb heat more, leading to a slower increase in surface temperature. This delays ignition and reduces flame spread rate. Conversely, materials with low thermal inertia experience rapid surface heating, resulting in faster ignition and more rapid flame propagation.

When present, horizontal projections deflect flames and enhance lateral radiative heating ahead of the burning front. Buoyancy forces contribute to keeping the flames closer to the surface beneath the projection, thereby enhancing heat transfer and accelerating the spread rate. Consequently, flame spread can be more rapid on the underside of the projection compared to its top surface [32].

The rate at which flames spread over a facade is primarily determined by the heat flux received by the facade material. Heat transfer from ejected flames to the exterior facade wall occurs through both radiation and convection. Thermal exposure from the flames ejected from the opening can be characterized in terms of sum of radiative and convective heat flux, as described by **Equation (20)** [54]:

$$\dot{q}_{total}'' = \underbrace{\epsilon_s (\dot{q}_{inc}'' - \sigma T_s^4)}_{radiation} + \underbrace{h(T_g - T_s)}_{convection} \quad (20)$$

where ϵ_s is the emissivity of the surface, $\dot{q}_{inc}''$ is the incident radiative heat flux received by the surface, σ is the Stefan-Boltzmann constant, T_s is the surface temperature, h is the convective heat transfer coefficient, and T_g is the gas temperature.

The heat flux received on the surface will depend on the location of the surface in relation to the flames and hot gases. Flames emit radiative heat to all surfaces within the view factor, while convection is received on the surface where hot gases are in contact with the surface. In the case where horizontal projections are present, the flames extend horizontally and the wall surface directly below the projection experiences intense convective and radiative heat. In areas significantly below horizontal projections, the influence of convective heat transfer may be reduced due to the buoyancy-driven upward movement of hot gases. Nevertheless, these regions can still experience convective heating depending on the flow dynamics near the façade. Radiative heat transfer, particularly at high flame temperatures, remains a dominant contributor to the overall heat flux in these lower zones.

The incident radiative heat flux received by the surface is primary dependent on the flame temperature and its emissivity. The incident radiative heat flux can be expressed as:

$$\dot{q}_{inc}'' = \sum_i^{\infty} \epsilon_{f,i} F_i \sigma T_{f,i}^4 \quad (21)$$

where $\epsilon_{f,i}$ represents the emissivity of the flame, F_i is the view factor, σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$), and $T_{f,i}$ is the flame temperature.

The emissivity of the flame can be estimated through the **Equation (22)** given by [55] :

$$\varepsilon_f = 1 - e^{-\kappa_m S} \quad (22)$$

where κ_m is the absorption coefficient of the fuel and S is the flame thickness.

The view factor depends on the distance separating the flame from the target surface, the relative orientation between the flame and the target, as well as the shape and size of the flame itself. Methodologies for estimating view factors under different configurations are presented in the literature [28], [32].

4. Methodology

This chapter outlines the methodology used to investigate the influence of horizontal projections on lateral fire spread along building façades. Numerical simulations were performed using Fire Dynamics Simulator (FDS) version 6.9.1 [56], validated against experimental data from the SP Fire 105 façade fire test [57], conducted by the SP Technical Research Institute of Sweden (now known as RISE).

The methodology is divided into two main phases:

1. Development and validation of the numerical model using data from the SP Fire 105 experiment.
2. Comparative analysis to assess the effect of horizontal projections on lateral flame spread and heat flux distribution.

4.1. Numerical Model Validation: SP Fire 105

The first phase focuses on validating the baseline FDS model using results from the SP Fire 105 test. The façade configuration made of lightweight concrete [57] was chosen to isolate the effects of geometry without the added complexity of combustible materials.

Key model parameters such as burner dimensions, facade materials, ambient conditions, and measurement locations (e.g., thermocouples, heat flux gauges, and plate thermometers) were set according to the experimental setup. Validation compared simulation outputs (temperature, heat flux, flame shape) to experimental data to confirm model reliability. No sensitivity analysis was performed; the focus was to establish general agreement between the simulation and experimental results, rather than quantifying numerical uncertainty.

4.1.1. Experimental Setup

4.1.1.1. Background on SP Fire 105 Façade Test

The SP Fire 105 test method is a standardized large-scale fire test designed to evaluate the fire performance of façade cladding materials and external wall assemblies. This test method originated in the 1950s when the SP Technical Research Institute of Sweden conducted initial large-scale façade fire experiments, using a 7.6 m high and 4 m wide test rig to study façade fire behaviour. However, the influence of unpredictable weather conditions on outdoor testing led to the development of controlled laboratory-scale methods [58].

During the 1970s and 1980s, researchers at Lund University conducted major studies that refined the test method. These investigations examined the fire performance of various thermal insulation systems and window frames, helping establish critical exposure conditions for façade fire testing. The first official version of the SP Fire 105 test was published in 1985, with a test rig measuring 6 m high and 4 m wide, exposed to a heptane fire source (**Figure 15**). Further refinements were made in the early 1990s, reducing the air inlet area by 18% and slightly decreasing the height of the fire room opening from 0.8 m to 0.71 m. The test lasts between 15 and 20 minutes [58].

The test evaluates key aspects of façade fire performance, such as [18]:

- Fire spread on surface and within the facade system.
- Temperature measurement under the eave (shown in **Figure 17**)
- Heat flux to the centre of the first fictitious window.
- Falling parts and burning droplets

According to the test method [18], flame spread must not extend beyond the lower part of the upper fictitious window opening, and there must be no large falling debris from the façade. Additionally, temperatures at the eave must not exceed 500°C for more than 2 minutes and 450°C for more than 10 minutes. In some cases, the heat flux at the centre of the first window above the fire room should not exceed 80 kW/m².

4.1.1.2. Fire Source

The fire source consisted of a rectangular burner tray measuring 500 mm × 2000 mm × 100 mm, which was filled with 60 litres of heptane. A flame suppressor was mounted on the top edges of the tray, consisting of a perforated steel sheet with pipes of 25 mm diameter is placed on the fire tray (**Figure 16**) [59]. An air intake opening measuring 3140 mm x 300 mm was positioned centrally, 50 mm from the back wall of the fire room, and located directly behind the fire tray.

The fire room opening, located at the base of the façade wall, had dimensions of 3 m in width and 0.71 m in height. This opening allowed the flame and hot gases from the heptane pool fire to directly impinge on the façade system during the test. The experimental setup is illustrated in **Figure 15**.

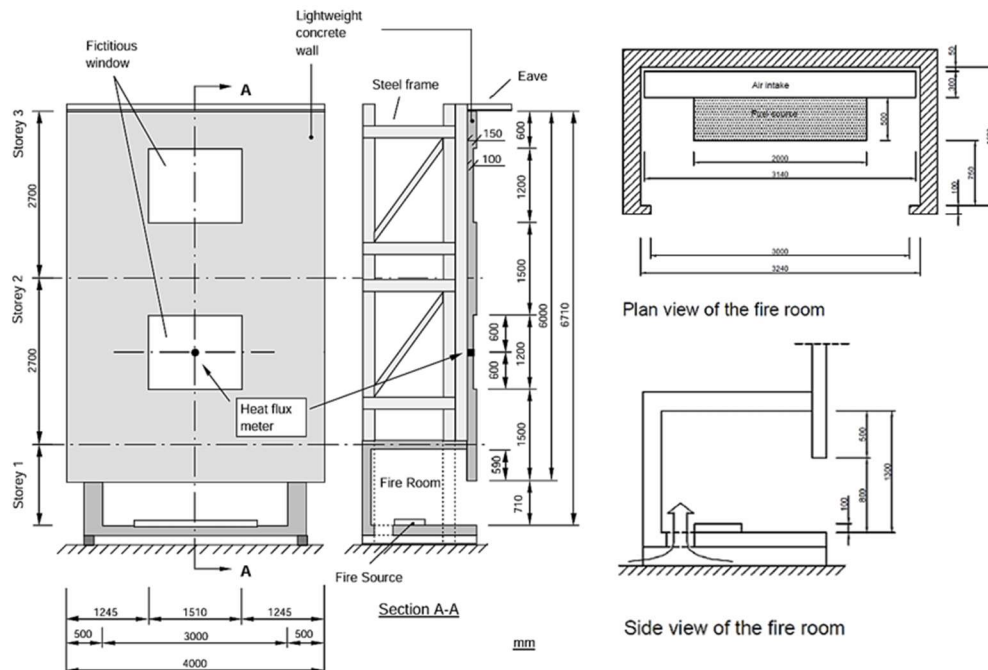


Figure 15 - SP Fire 105 fire test rig [57].



Figure 16 - Flame suppressing lattice used in SP Fire 105 test [59].

4.1.1.3. Test Specimen

This façade, as tested in the experiment, consists of a 6 m high by 4 m wide lightweight concrete structure with a thickness of 150 mm. The lightweight concrete used has a density of 550 kg/m³ and a relative humidity of 50%.

4.1.1.4. Measurements

▪ Thermocouples

The test rig was equipped with type K thermocouples with a 0.5 mm diameter, and these thermocouples were positioned on the facade wall at locations C1-C19. The measurements obtained from these thermocouples were intended to represent the surface temperature of the facade. Additionally, more type K thermocouples with a 0.5 mm diameter were placed 100 mm and 200 mm away from the facade wall to measure gas temperature. These thermocouples were positioned at the same locations as C2, C3, C6, C7, C13, C14, C17, and C18. Furthermore, two more 0.5 mm type K thermocouples were installed 100 mm below the eave at the top of the facade rig, with one positioned 100 mm and the other 400 mm away from the facade surface, both centred on the facade wall. The locations of these thermocouples are shown in Figure 19.

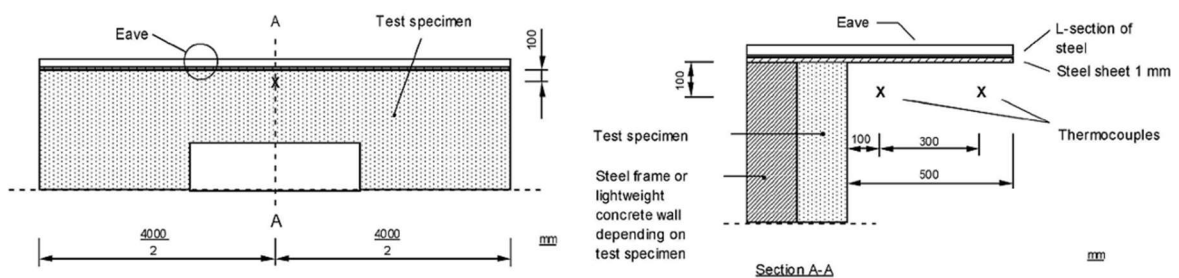


Figure 17 - Position of thermocouples below the eave [18].

▪ Heat Flux Meter

The total heat flux, including both radiant and convective components, is measured using a heat flux gauge (HF1) positioned on the fictitious window of the second storey, directly above the fire room (Figure 19). The heat flux meter used in this experiment is a Schmidt-Boelter heat flux sensor, a water-cooled device designed to measure heat flux levels. This sensor is capable of accurately measuring heat flux up to 120 kW/m² [18].

▪ Plate Thermometers

The test used six plate thermometers, each measuring 100 mm × 100 mm × 10.7 mm. These plate thermometers were identical to those specified in the EN 1363-1 standard for fire resistance furnace tests. Each plate thermometer featured a 0.7 mm thick Inconel front plate, with the backside being 10 mm thick and insulated to minimize heat loss. A thermocouple was securely attached to the plate to monitor its temperature, which represented the adiabatic surface temperature within the test environment [54].

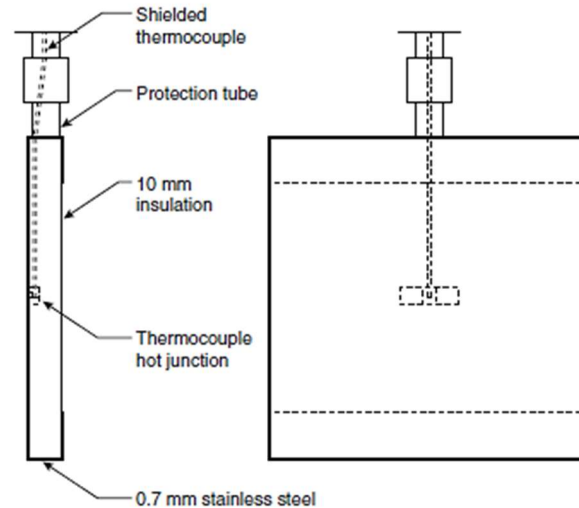


Figure 18 - The plate thermometer according to EN 1363-1 [54].

The plate thermometers PT1-PT3 are situated 500 mm away from the fire room, oriented towards the fire. Meanwhile, PT4-PT6 are mounted on the facade surface, facing outwards. The positioning of these plate thermometers is illustrated in Figure 19.

4.1.1.5. Test Conditions

The test was carried out indoors at the SP Fire Research facility in Borås, Sweden, within a controlled test hall environment. The initial ambient conditions recorded prior to the test were:

- Air temperature: 18.8°C
- Relative humidity: 38%

The test hall's ventilation system produced an airflow with velocities ranging from 0.1-0.5 m/s. This airflow was directed parallel to the facade rig, flowing from right to left, simulating an easterly wind.

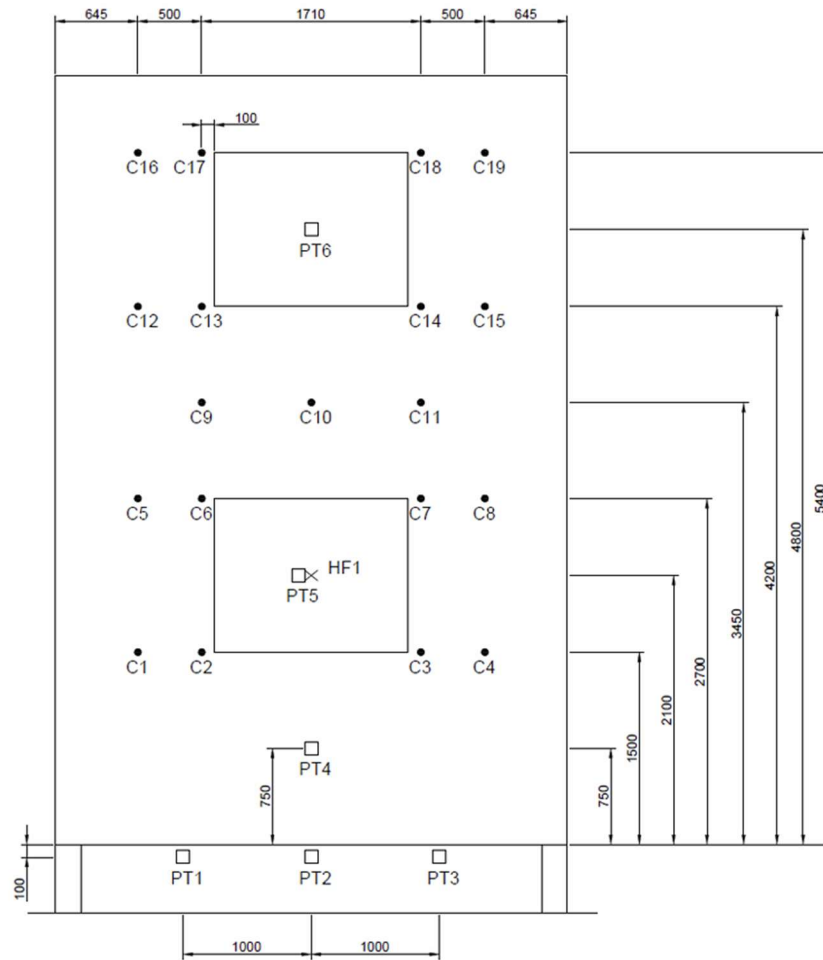


Figure 19 - Position of the measurements used during the experiment [57].

4.1.2. FDS Modelling of SP Fire 105

FDS has consistently demonstrated effectiveness in modelling SP Fire 105 fire behaviour, particularly when guided by measured HRRs and accurate material properties ([60], [61], [59], [62]).

Numerical results have generally shown good agreement with experimental data, particularly for temperature predictions at shielded locations and measurements farther from the fire source [59]. A grid resolution of 5 cm has been found sufficient for capturing relevant features of fire dynamics [61], [62]. However, recurring limitations have been reported in near-source regions, where FDS tends to overpredict temperatures. These discrepancies are often attributed to localized combustion effects, such as those caused by the flame-suppressing lattice in the fire tray, which are not fully resolved with simplified fire source modelling. Despite its limitations, the consistent results across FDS versions (5.5.3, 6.0, and 6.2.0) show its reliability as a simulation tool, provided its limitations are understood and supported by experimental validation.

4.1.2.1. Design Fire

To accurately replicate the experimental setup, n-heptane, the same fuel used during the tests, was employed in the numerical simulations. The fuel source was assigned a heat of

combustion of 44,400 kJ/kg [30], along with a soot yield of 0.037 g/g [63] and a carbon monoxide yield of 0.006. The burner geometry ($2000 \times 500 \times 100$ mm) matched the experimental tray. For simplification purposes, the flame suppressor present in the experimental test was excluded from the numerical model.

The HRR was prescribed based on experimental data, using an HRR per unit area (HRRPUA) of $2,400 \text{ kW/m}^2$, coupled with a ramp-up function to simulate the fire's growth, steady state, and decay (see **Figure 27** and **Appendix A**).

4.1.2.2. Computational Domain

The computational domain was designed to include both the fire room and the external environment to capture the interaction between the fire plume and facade. As shown in **Figure 20**, the domain is divided into two meshes, which was done to enable parallel processing and thus optimize computational time:

- The lower mesh measured $4.0 \text{ m} \times 4.0 \text{ m} \times 1.9 \text{ m}$. It includes the fire room and extends 1.9 m outward from the façade into the exterior.
- The upper mesh measured $2.1 \text{ m} \times 4.0 \text{ m} \times 5.4 \text{ m}$. It extends vertically from the top boundary of the lower mesh up to the eaves of the structure.

To allow the free flow of hot gases and smoke and simulate an open-air environment, open boundary conditions were applied on all external faces of the computational domain.

4.1.2.3. Grid Resolution

A grid resolution of 5 cm was selected for the simulation. This grid size has been validated in [61], [62] and [59], where 5 cm mesh effectively captured the fire behaviour in simulations of the SP Fire 105 test. While finer meshes can improve the resolution of flow structures, they significantly increase the number of computational cells, leading to longer simulation times and higher computational costs. Therefore, a 5 cm grid was deemed appropriate for this study, as it provides sufficient detail for capturing key fire phenomena while maintaining manageable computational demands.

The selected grid configuration resulted in a total of 606,080 computational cells across the entire domain. The simulation took approximately 100 hours and 41 minutes.

To further validate the chosen grid cell size, the non-dimensional resolution parameter $D^*/\delta x$ was calculated, as recommended in the FDS User Guide [56]. This parameter is commonly used as a rule of thumb to assess mesh adequacy in fire simulations. The aim was to ensure that the mesh was sufficiently refined to capture the essential fire dynamics and provide reliable numerical results.

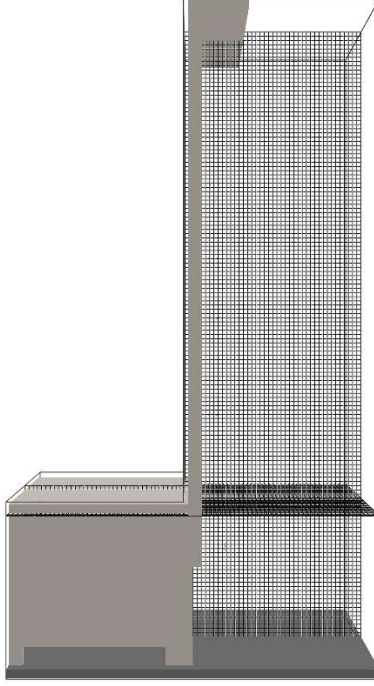


Figure 20 - Computational domain and mesh configuration for SP Fire 105 FDS model.

The characteristic fire diameter D^* was calculated using **Equation (23)**:

$$D^* = \left(\frac{\dot{Q}}{\rho_{\infty} c_p T_{\infty} \sqrt{g}} \right)^{2/5} \quad (23)$$

where $\dot{Q}$ is the total heat release rate (kW), ρ_{∞} is the ambient density (kg/m³) taken as 1.2 kg/m³, c_p is the specific heat capacity (kJ/kg.K), assumed to be 1 kJ/kg.K, T_{∞} is the ambient temperature (K), taken as 293 K and g is the acceleration due to gravity (m/s²), taken as 9.81 m/s².

The characteristic fire diameter for the simulated case is:

$$D^* = \left(\frac{2400}{1.2 \times 1 \times 293 \times \sqrt{9.81}} \right)^{2/5} = 1.37 \text{ m}$$

The corresponding resolution ratio $D^*/\delta x$ was calculated for the selected grid size of 5 cm as follows:

$$\frac{D^*}{\delta x} = \frac{1.37}{0.05} = 27.4$$

This value suggests that the simulation resolution is likely sufficient, as practical experience indicates that a $D^*/\delta x$ ratio between 4 and 16 is considered acceptable for capturing key fire dynamics. However, it is important to note that this grid resolution assessment alone does not guarantee overall simulation accuracy.

4.1.2.4. Model Geometry

The test rig was modelled based on the dimensions presented in **Figure 15** and **Figure 19**. The geometry includes a non-combustible facade wall made of lightweight concrete, a fire room, and an opening located beneath the facade wall. The model geometry is illustrated in **Figure 21**.

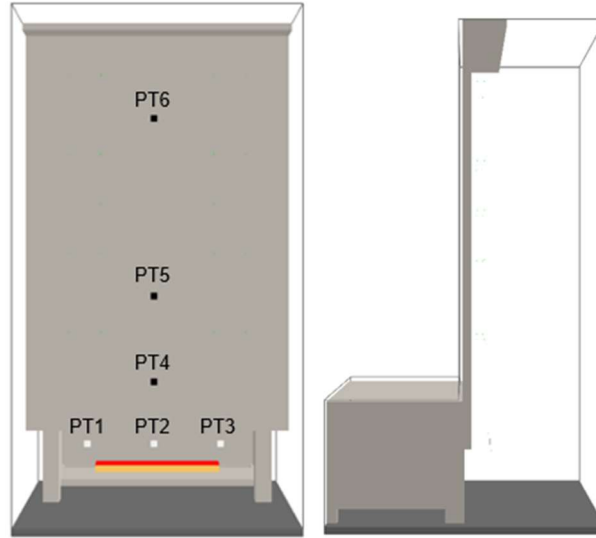


Figure 21 - Geometry of the SP Fire 105 FDS model.

4.1.2.5. Material Properties

The lightweight concrete used for the façade wall in the experiment had a measured density of 550 kg/m^3 , as reported in the test report [57]. This material was also assumed for the walls, ceiling, and floor of the fire room. The structural floor of the test rig was modelled using high-density concrete. Thermal properties were sourced from experimental data and established literature [32].

The plate thermometer was modelled as a thin, layered solid obstruction, consisting of a 0.7 mm front layer of Inconel 600 and a 10 mm rear layer of insulation material. The thermal properties of these materials were obtained from the validation study presented in Chapter 3.74 of the *FDS Validation Guide: SP Adiabatic Surface Temperature Experiments* [64]. Additionally, the specific heat and thermal conductivity for the Inconel were implemented with a ramp function. The details of this ramp function are provided in the FDS input file (**Appendix A**).

A summary of all material properties used in the simulation is presented in **Table 2**.

Table 2 - Properties of material used in the simulation:

Material	Density (kg/m^3)	Specific heat ($\text{kJ}/(\text{kg}\cdot\text{K})$)	Conductivity ($\text{W}/(\text{m}\cdot\text{K})$)	Emissivity	Ref
Lightweight concrete	550	1.0	0.15	0.9	[65]
Concrete	2,300	1.05	1.4	0.85	[32]
Inconel600	8,470	Ramp up	Ramp up	0.85	[64]
Insulation	280	1.0	0.1	0.9	[64]

4.1.2.6. Devices and Outputs

All experimental devices (thermocouples, heat flux gauges, and plate thermometers) were reproduced in the simulation using FDS measurement quantities and dimensions consistent with the test (see **Appendix A**). Surface temperature of the plate thermometers was recorded using a 'WALL TEMPERATURE' device positioned on the front face of each plate thermometer.

4.1.2.7. Simulation Parameters

The simulation parameters presented in **Table 3**, matched the test conditions described in **Section 4.1.1.5**. The wind speed was set to 0.3 m/s, representing the average value observed in the variable wind conditions of the experiment (ranging from 0.1 to 0.5 m/s). For radiation calculations, the default setting of 100 discrete angles was used, consistent with [59]. Although a higher number of angles could yield more accurate results, it would also significantly increase computational cost. The radiative fraction was set to 0.35, the default value in FDS. This is in close agreement with experimentally measured values, such as 0.33 for well-ventilated heptane fires [66]. Since the primary objective of this thesis is to investigate the impact of horizontal projection on lateral flame spread, no sensitivity analysis was conducted on these parameters.

Table 3 - Summary of simulation parameters:

Parameter	Value
Simulation duration	1,080 s
Ambient temperature	18.80 °C
Relative humidity	38%
Wind speed	0.3 m/s
Wind direction	90°
Radiation angles	100 (default)
Radiative fraction	0.35 (default)

Note: Wind parameters were applied only during the validation experiment and were excluded from the simulations involving horizontal projections to isolate the effect of geometric variation. This allowed the influence of projection depth on flame behaviour to be assessed without additional complexity introduced by wind.

4.2. Comparative Study on Horizontal Projections

This phase investigates the influence of horizontal projections on lateral and vertical thermal exposure using a modified version of the SP Fire 105 façade test. The primary objective is to evaluate the impact of varying projection depths on flame spread behaviour, façade surface temperatures, and incident heat flux.

The flame shape was identified using established criteria from the literature. In this study, the flame region is defined using a temperature threshold of 550 °C. According to previous studies, the average flame height, as defined by Zukoski et al., typically corresponds to temperatures in the range of 500–600 °C, with 550 °C often used to define the maximum vertical flame reach [32]. Similarly, Seigel [67] proposed 550 °C as a representative threshold for identifying the luminous flame region. Another criterion used in this study to characterize the flame shape is the Heat Release Rate Per Unit Volume (HRRPUV). This parameter is

commonly employed in numerical simulations to identify regions where combustion reactions are taking place. Specifically, areas where the HRRPUV exceeds a predefined threshold are considered to represent the presence of flame. The literature suggests a range of reference values for this threshold, with 500 kW/m^3 and $1,200 \text{ kW/m}^3$ being commonly cited [49]. In this study, a more conservative threshold of 500 kW/m^3 is adopted to identify the flame regions within the computational models. This relatively low value (compared to $1,200 \text{ kW/m}^3$) would capture a broader portion of the combustion zone and results in larger flame volumes.

The impact of projection geometry is assessed by comparing simulation results across a range of projection depths, evaluating effects on flame deflection, lateral spread, and façade exposure.

In addition to varying projection depth, two distinct design fire scenarios are considered to assess how fire intensity influences heat flux and temperatures distributions.

4.2.1. Design Fire

All scenarios used a 1 m^2 burner, with Scenario 1 employing a baseline HRR of 2.4 MW, consistent with the validated model. To evaluate the influence of a more intense fire condition, Scenario 2 applied an elevated HRR of 3.5 MW. The 3.5 MW value was selected based on the test presented in [57], where it was representative of the heat release rate produced by a combustible façade system (plywood test). In both cases, the HRR ramped linearly over 10 seconds to reach a steady state (**Appendix C**). The prescribed HRR used in the simulations are illustrated in **Figure 22**.

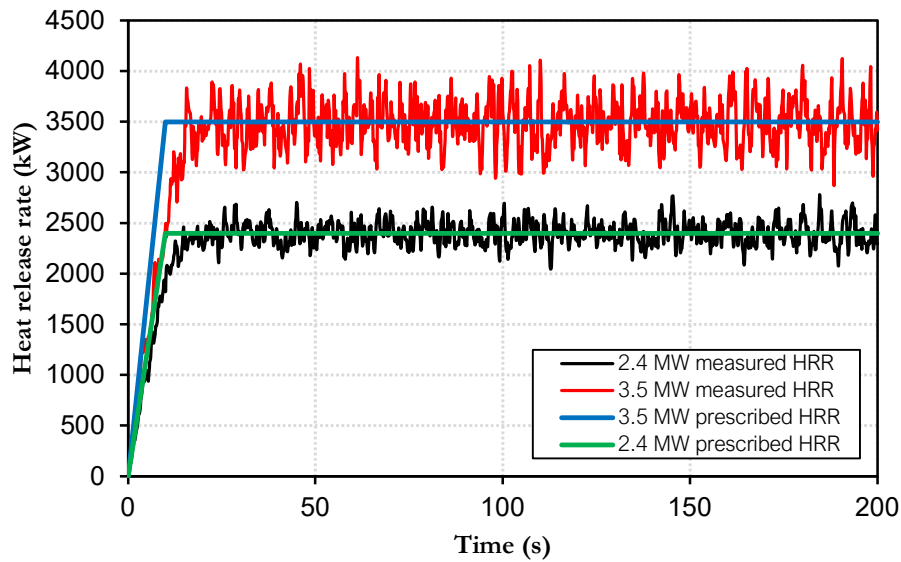


Figure 22 - Prescribed HRR for the comparative analysis.

4.2.2. Computational Domain and Grid Resolution

The domain was adapted for the new geometry, with three meshes (5 cm resolution) used to optimize simulation time.

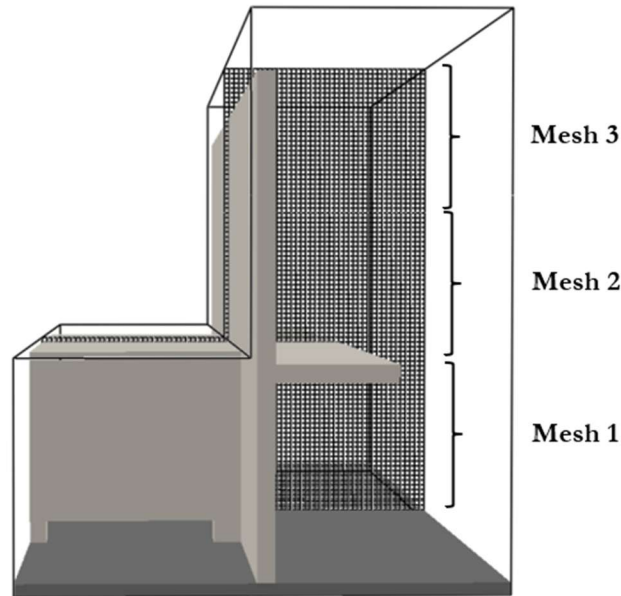


Figure 23 - Computational domain and mesh configuration for the comparative study.

4.2.3. Model Geometry

To capture both lateral and vertical flame spread and heat transfer effects, walls were added on both sides of the façade opening. These represent the continuation of the building façade and allow for the assessment of horizontal flame extension. The model also includes sufficient vertical extent to evaluate upward heat transfer along the façade. The original model height was reduced to improve computational efficiency, while still capturing the essential heat transfer dynamics.

Horizontal projections were incorporated into the model as open-ended elements, with a uniform thickness of 13 cm. Three projection depths were examined: 30 cm, 60 cm, and 100 cm, allowing for comparative analysis of their influence on both vertical and lateral thermal exposure.

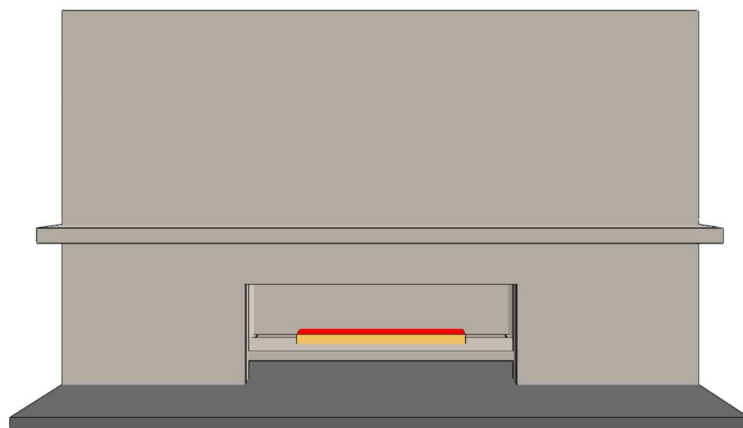


Figure 24 - Model geometry used for the comparative study.

4.2.4. Material Properties

All thermal material properties remained consistent with the validated scenario, except for the specific heat capacity of lightweight concrete that was reduced by a factor of 10 to accelerate its thermal response. The projection was also modelled as a lightweight concrete element, using the same adjusted thermal properties.

4.2.5. Devices and Outputs

Sensor arrays were placed vertically and laterally to capture heat flux and wall temperature variations (Figure 25):

- **Vertical array:** devices measuring incident heat flux and wall temperature were positioned along the vertical centreline of the façade. Sensors were placed at intervals of 500 mm, starting from the top of the horizontal projection up to the top of the façade, with additional sensors at 100 mm and 300 mm below the projection.
- **Lateral array:** devices were positioned horizontally at 500 mm intervals along the façade wall, extending from the edge of the opening to the façade end. Each lateral line of sensors was located at 100 mm, 500 mm, and 1,000 mm below the horizontal projection.

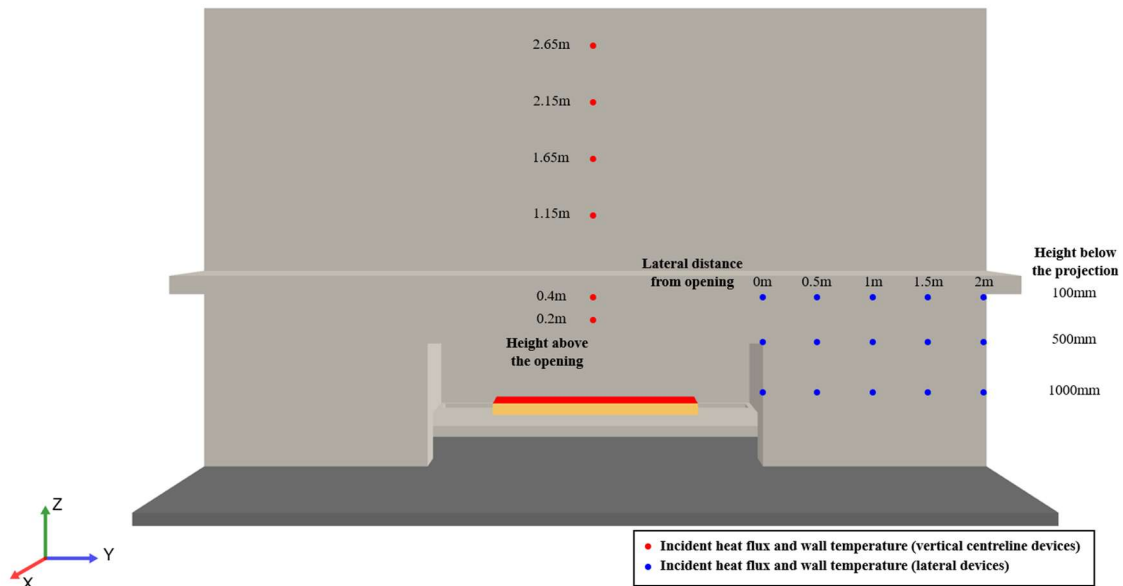


Figure 25 - Positions of devices of incident heat flux and wall temperatures used in the comparative simulations.

Flame regions were defined using two established criteria from the literature. Isosurfaces were generated and visualized based on a temperature threshold of 550 °C and a heat release rate per unit volume (HRRPUV) of 500 kW/m³ to define flame shape.

Boundary quantities such as wall temperature and incident heat flux were recorded at the façade surface to evaluate their distribution patterns.

Velocity fields were visualized using 2D slice data extracted from FDS and rendered in Smokeview. Two primary vertical planes were analysed:

- **Y = 2.0 m:** A vertical slice positioned through the centre of the façade opening.
- **X = 0.2 m:** A vertical slice positioned close to the façade surface.

4.2.6. Simulation Parameters

Simulations were conducted under consistent boundary conditions (**Section 4.1.2.7**), with external wind effects excluded to allow a controlled assessment of horizontal projection influences. Each simulation was run for 200 seconds, which was sufficient for the heat flux and wall temperature measurements to reach steady-state behaviour.

4.2.7. Summary of Simulation Scenarios

Eight simulation cases were developed to assess the impact of varying horizontal projection depths and heat release rates, as summarized in **Table 4**.

Table 4 - Summary of the simulations:

Case	HRR (MW)	Projection depth (m)
1	2.4	No projection (free façade)
2	2.4	0.3
3	2.4	0.6
4	2.4	1.0
5	3.5	No projection (free façade)
6	3.5	0.3
7	3.5	0.6
8	3.5	1.0

4.2.8. Data Analysis Approach

Wall temperature and incident heat flux measurements were time-averaged over the 50–200 s interval, corresponding to the period where the thermal response—defined by stable wall temperature and incident heat flux readings—was steady.

The visual analysis was performed using Smokeview, where isosurfaces were generated to represent key fire dynamics variables. Temperature isosurfaces are illustrated in pink, while heat release rate per unit volume (HRRPUV) isosurfaces are shown in orange.

A Python script, detailed in **Appendix D**, was used to process visual data from the 50–200 second interval. This script extracts contours from the isosurfaces and calculates flame height and horizontal flame extension, for each frame within the time window. The script then computes the mean values of these parameters across all frames to obtain time-averaged results. An example of how flame height and horizontal extension are measured is illustrated in **Figure 26**.

For comparative analysis, the time-averaged values of surface temperature and incident heat flux were evaluated at different vertical heights and lateral distances from the opening. The comparison was conducted using both absolute average values and percentage differences, with the free façade scenario used as the reference case.

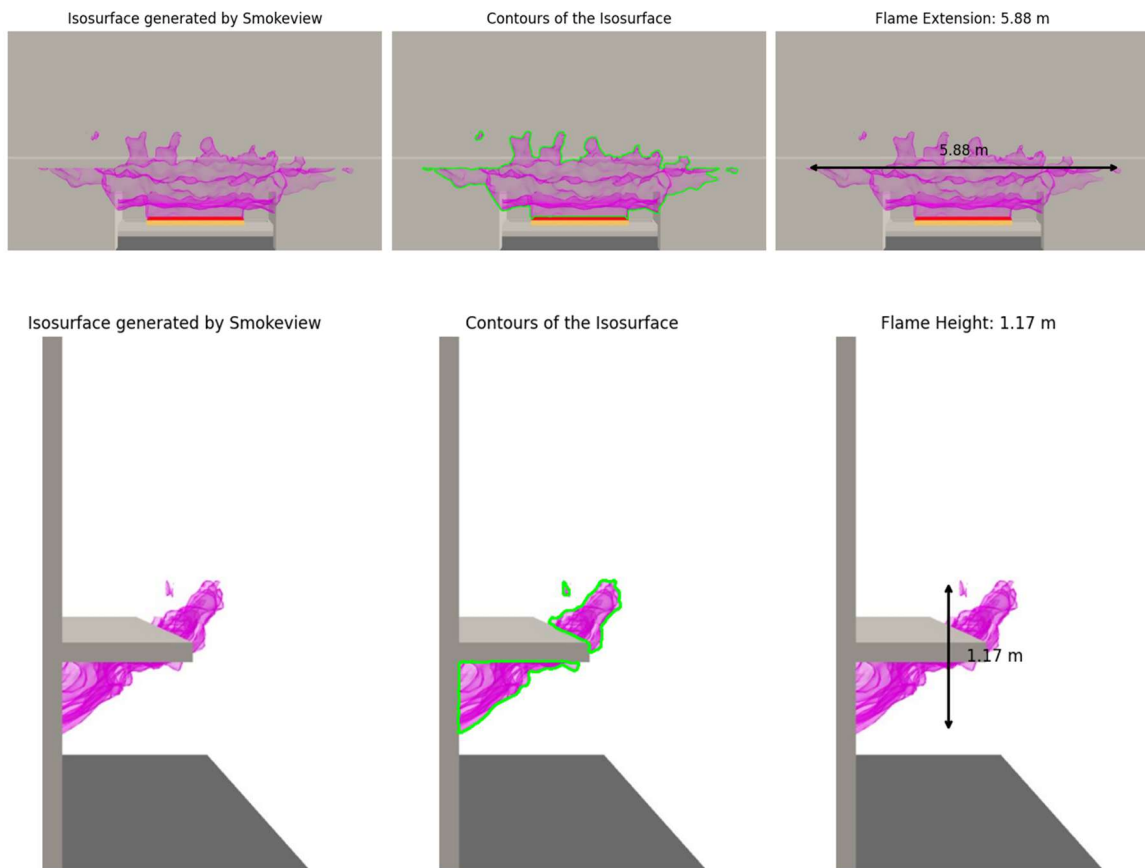


Figure 26 - Measurement of flame height and horizontal extension from temperature isosurface using contour extraction with Python.

5. Results

5.1. Validation of Numerical Model (SP Fire 105 Test)

This section presents the results obtained from the simulation of the SP Fire 105 test of the lightweight concrete façade described in **Section 4.1**. The outputs from the simulations are referenced as (FDS), while the experimental measurements are referenced as (EXP) throughout this section.

5.1.1. Heat Release Rate

In the simulation, the experimentally measured HRR was prescribed as an input for the simulation to accurately replicate the fire behaviour observed in the experiment. The HRR was measured by analysing the exhaust gases collected in the hood above the facade rig.

Figure 27 below compares the measured experimental HRR with the input HRR used in the simulation. The HRR initially increases, reaching approximately 2,000 kW at around 8 minutes, and then continues to rise until reaching a peak of approximately 2,400 kW between 10 and 15 minutes, before decreasing towards the end of the experiment.

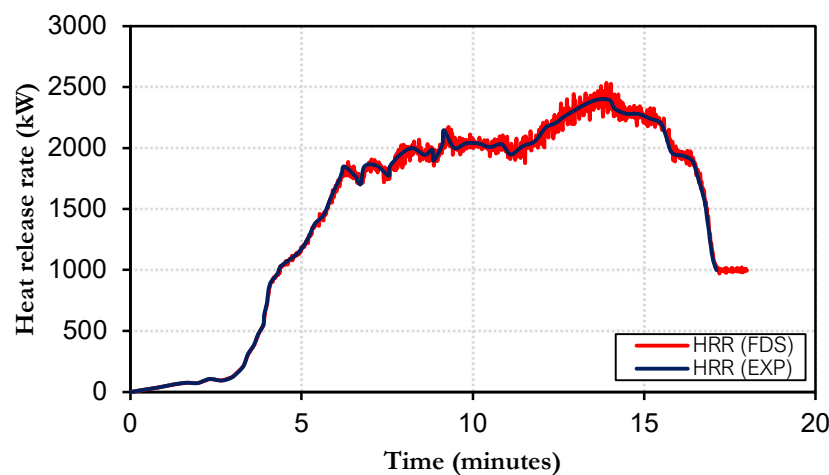


Figure 27 - Measured and simulated HRR.

5.1.2. Gas Temperatures

Figure 28 illustrates the evolution of gas temperatures measured 100 mm from the façade during the experiment, compared with the corresponding values predicted by FDS. The simulation underestimates temperatures near the fire source, particularly at 1,500 mm above the fire room opening, where the discrepancy reaches 200-300 °C. However, this difference decreases further up the façade, where the simulation results more closely align with the experimental data. The simulated gas temperature profile mirrors the pattern observed in the experimental measurements.

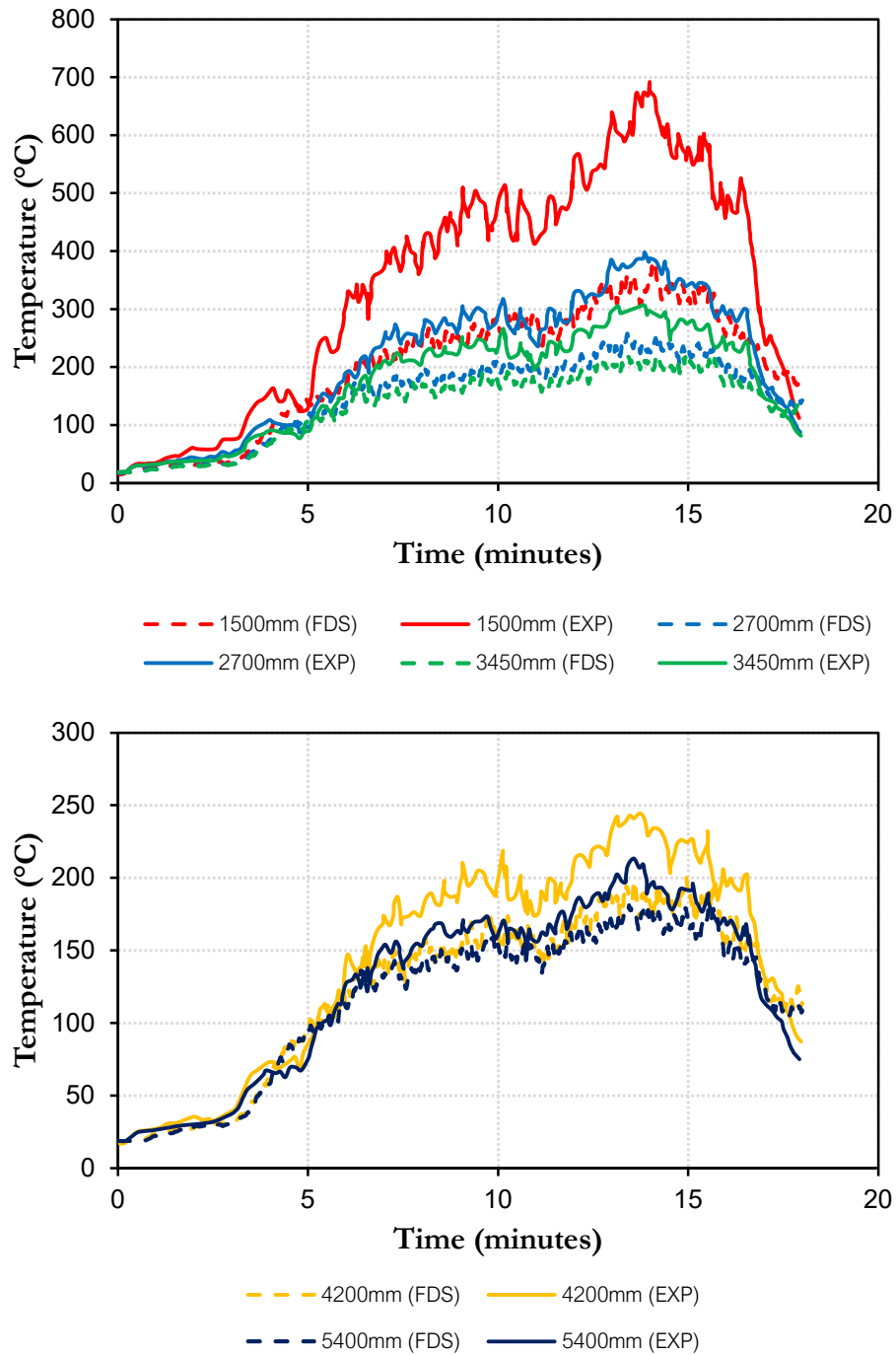


Figure 28 - Measured and simulated gas temperatures 100 mm from the façade at various heights.

Figure 29 shows gas temperatures measured and simulated 200 mm from the façade. The overall trends remain consistent with those seen at 100 mm (**Figure 28**), with FDS underestimating peak temperatures, especially at 1,500 mm. Agreement improves with height, and the model continues to capture the overall temperature profile well.

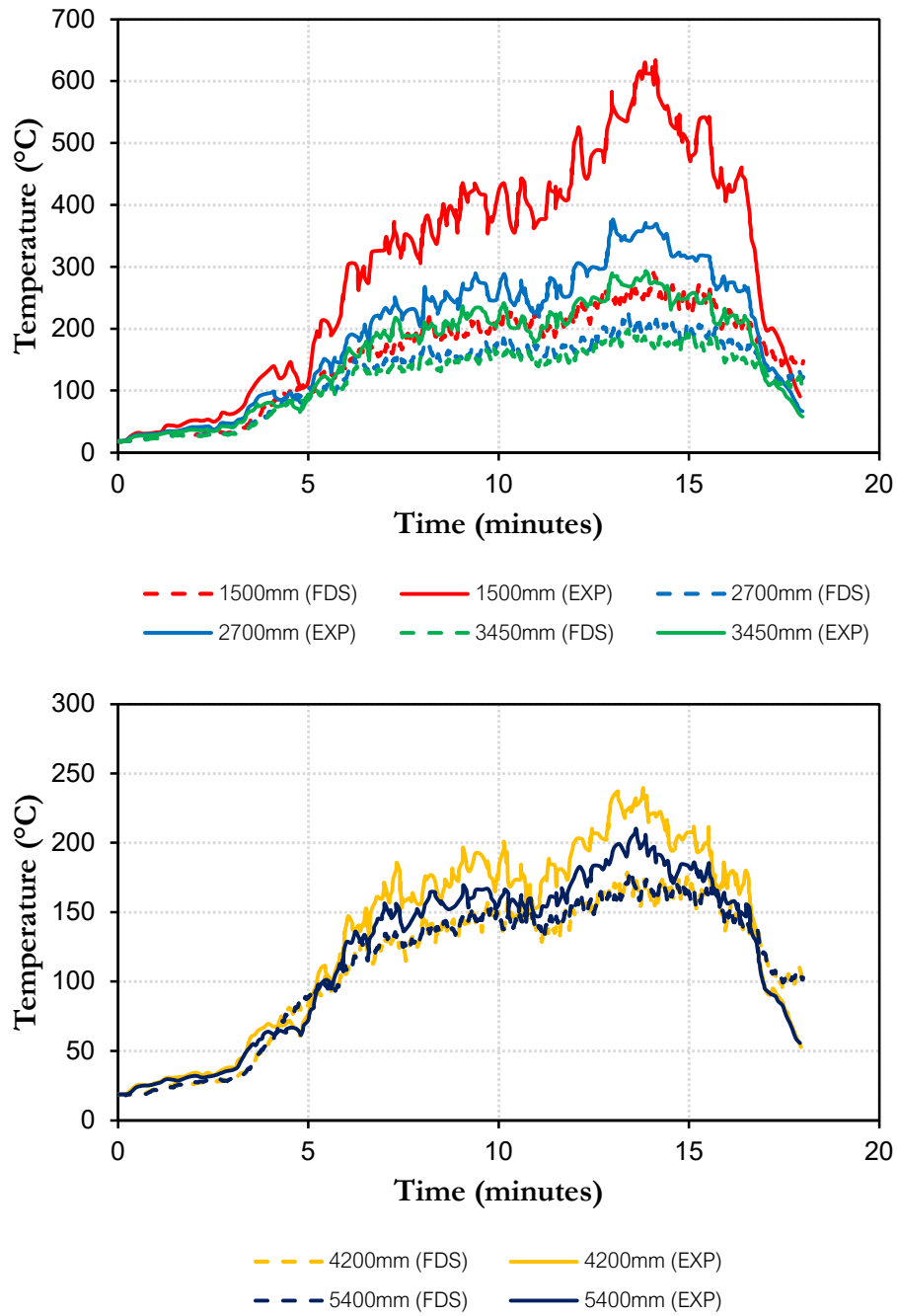


Figure 29 - Measured and simulated gas temperatures 200 mm from the façade at various heights.

The results presented in **Figure 30** demonstrate a strong agreement between the measured and simulated gas temperatures below the eave (shown in **Figure 17**). The FDS measurements slightly underestimated the experimental results, by around 40 °C for the measurement located 100 mm from the façade, and 20-30 °C for the measurement positioned 400 mm from the façade. This finding is consistent with the results reported in [68], where temperature measurements near the eave closely matched the experimental data.

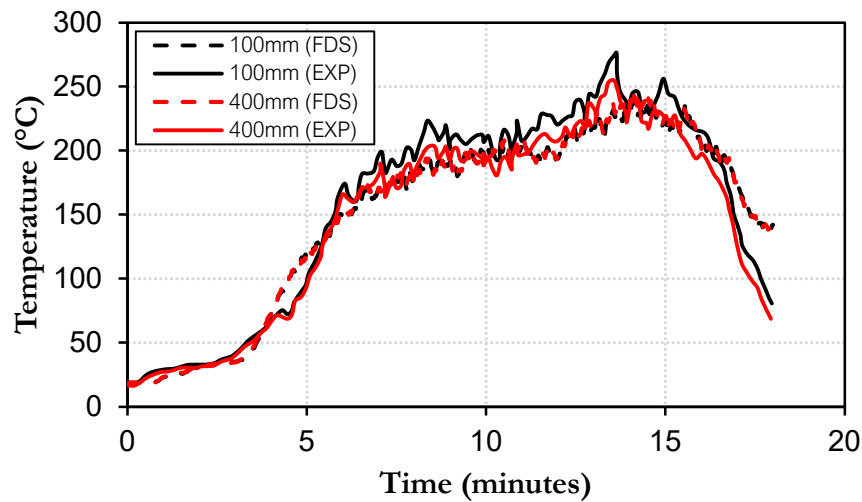


Figure 30 - Measured and simulated temperatures below the eave at 100 mm and 400 mm from the façade.

5.1.3. Surface Temperatures

Figure 31 presents a comparison between the experimentally measured and numerically predicted surface temperatures at various heights above the opening. The temperature values shown represent averages from thermocouples placed at the same heights in both the experimental configuration and the FDS simulations. The exact placement of these thermocouples is detailed in Figure 19.

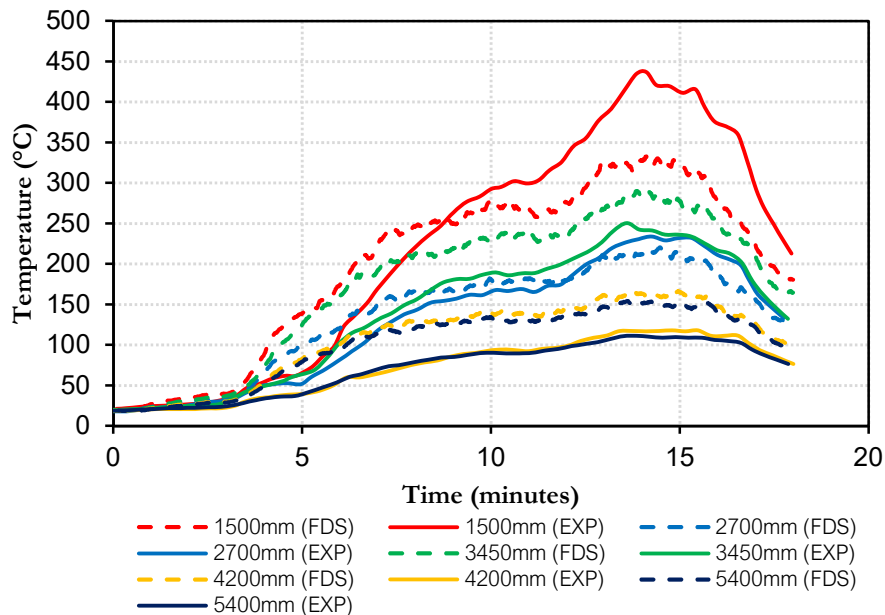


Figure 31 - Measured and simulated surface temperatures at various heights.

The model's predictions align well with the experimental data, effectively capturing the overall temperature trends across different heights. However, some local discrepancies are observed and discussed below.

At 1,500 mm, the model tends to predict a faster temperature rise compared to the experimental results, which show a delayed response. Furthermore, the FDS simulation

underestimates surface temperatures at this height by 50–120 °C during the 10–16 minutes period. At 2,700 mm, the model appears to reproduce the experimental trend, where mean surface temperatures are slightly lower than those recorded at 3,450 mm. The error percentage at this height is 16.25%, indicating a moderate level of deviation.

From 3,450 mm upward, the FDS model begins to overestimate temperatures with an error percentage of 28.71%. The overprediction becomes more pronounced at higher elevations, with an average deviation of approximately 50 °C at 4,200 mm and 5,400 mm, corresponding to error percentages of 45.80% and 40.15%, respectively.

These observations indicate that while FDS partially replicates the general thermal behaviour along the façade, it tends to underpredict temperatures near the fire source and increasingly overpredict them at higher elevations. The average error across all measured heights is 31.77%.

5.1.4. Temperature at Plate Thermometers

Figure 32 illustrates the comparison between measured and simulated mean temperatures recorded by plate thermometers PT1, PT2, and PT3, each positioned 500 mm from the combustion chamber. FDS overestimates the temperatures in proximity to the combustion chamber, with 120–200 °C compared to the experimental measurements.

Previous studies ([59],[68]) have reported similar findings of overpredicted temperatures near the fire source. For instance, in [68], FDS was shown to overestimate the temperature of the plate thermometer in front of the combustion chamber by approximately 300 °C.

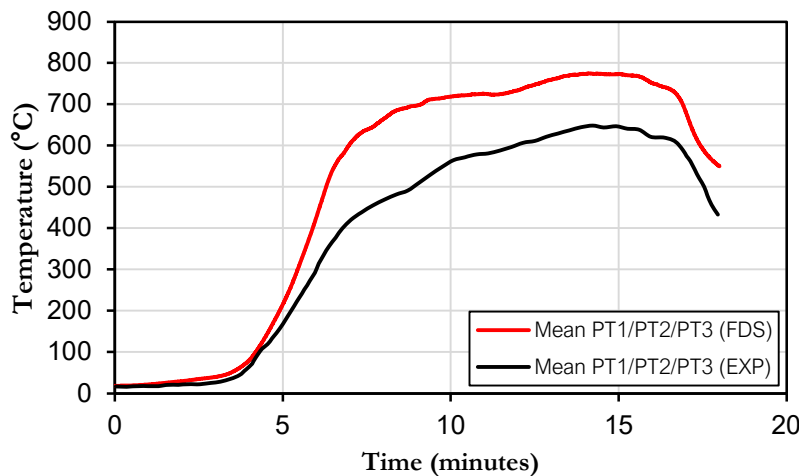


Figure 32 - Measured and simulated temperatures of plate thermometers PT1, PT2 and PT3.

The inconsistency observed in **Figure 32** might be attributed to the influence of the flame-suppressing lattice used in the experimental setup, which was not represented in the FDS model for simplification purposes. This lattice, modifies the combustion dynamics by introducing localized combustion effects, deviating from the typical behaviour of an unobstructed liquid pool fire. Consequently, the FDS model, which relies on a prescribed heat release rate (HRR), cannot fully capture the complex interaction introduced by the lattice [60].

Furthermore, inaccuracies in the material properties assigned to the plate thermometers within the simulation could also contribute to discrepancies. Specifically, imprecise or

oversimplified values for thermal conductivity, emissivity, or specific heat can affect the FDS-predicted temperatures, potentially exacerbating the disparity with experimental results.

Figure 33 presents the temperatures recorded by plate thermometers PT4, PT5, and PT6, positioned at distances of 750 mm, 2,100 mm, and 4,800 mm from the façade, respectively. The experimental measurements (solid lines) are compared with FDS predictions (dashed lines).

For PT4, located closest to the opening, FDS significantly underestimated the temperature peaks observed in the experimental data. The first peak reached approximately 800 °C, while the simulation predicted only 600 °C, resulting in a 200 °C discrepancy. A similar underestimation of roughly 150 °C was observed during the second peak. The predicted temperatures by PT4 corresponds to a mean percentage error of 32.27%, indicating a significant difference between simulation and experiment in the near-field region.

For PT5 and PT6, the discrepancies were less severe but still evident. At PT5, the simulation underestimated the temperature by approximately 150 °C and 100 °C during the first and second peaks, respectively, yielding a mean percentage error of 21.88%. At PT6, positioned furthest from the fire source, the deviation remained consistently around 50 °C, with a lower mean percentage error of 17.54%.

Averaged across all three positions, the model produced a mean percentage error of 23.89%, suggesting improved agreement with distance from the fire opening. While the FDS simulation underpredicted the peak temperatures, it captured the overall trends and timing of the thermal response reasonably well, suggesting a moderate level of agreement with the experimental data.

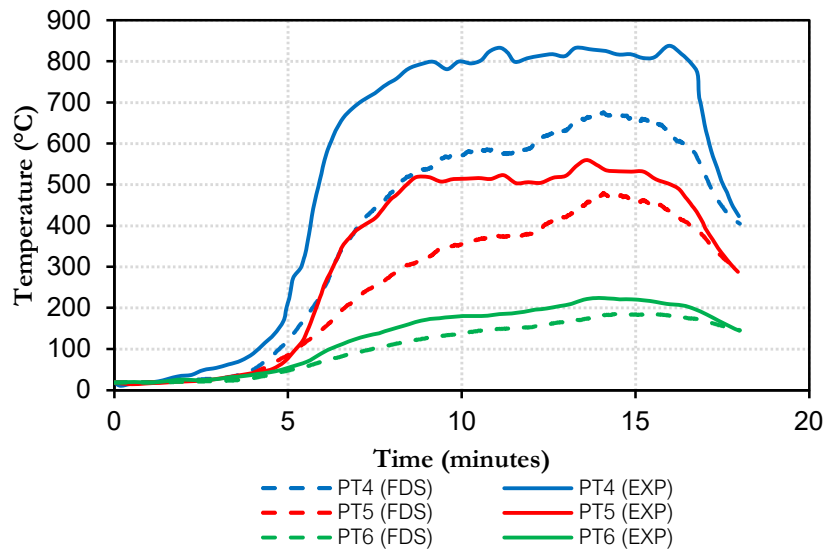


Figure 33 - Measured and simulated temperatures of plate thermometers PT4, PT5 and PT6.

These findings highlight that FDS struggles to accurately capture the rapid thermal rise near the fire room opening, particularly during peak periods. However, its performance improves with increasing distance, showing better agreement at higher locations. This behaviour aligns with previous observations reported in [60], where temperature of the plate thermometer

positioned 2.1 m above the fire room—corresponding to the location of PT5 in this study—was also significantly underestimated by the FDS model.

5.1.5. Heat Flux

Figure 34 illustrates the measured and simulated heat flux on the facade surface at a height of 2,100 mm above the opening. Both the experimental and numerical results exhibit a similar trend, characterized by three distinct peaks. However, the FDS consistently underestimates the heat flux compared to the experimental measurements.

To enable a consistent comparison, the FDS results were evaluated at the same time points as the experimental peak heat flux values, specifically at 7, 8, and 14 minutes. At 7 minutes, the experimentally measured heat flux reached 32 kW/m², whereas the FDS simulation predicted only 14 kW/m², corresponding to a 56.25% underestimation. Similarly, at 8 minutes, the experimental value was 35 kW/m², while the simulation produced 15 kW/m², resulting in a 57.14% underestimation. At 14 minutes, the experimental heat flux peaked at 40 kW/m², with the FDS model predicting 29 kW/m², an underestimation of 27.5%. On average, the heat flux predicted by FDS was 18.84 kW/m², whereas the experimentally measured average was 31.07 kW/m², representing a 39.36% underestimation in the simulation.

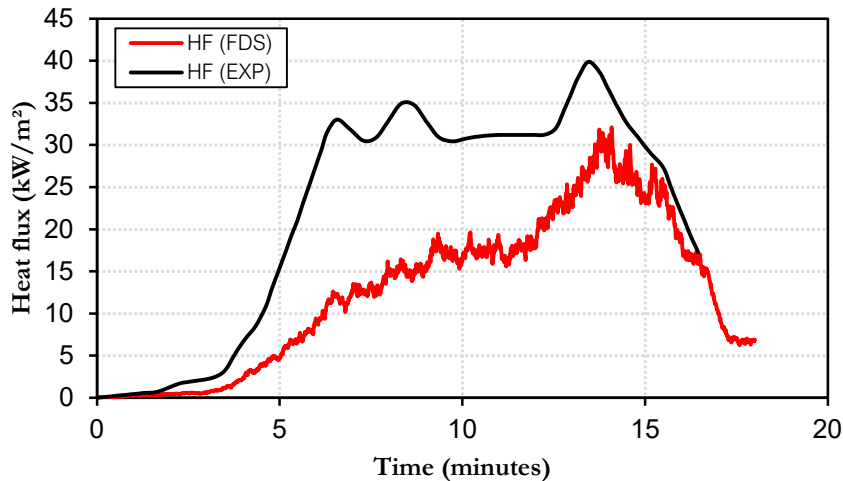


Figure 34 - Measured and simulated heat flux at 2.1m above the opening.

This discrepancy can be attributed to two key factors. First, measurements obtained using water-cooled heat flux meters during experiments are subject to substantial uncertainties [60], with large variations within the same test. Additionally, the underestimation in the FDS simulation may be due to its treatment of convective heat transfer. The Schmidt-Boelter water-cooled heat flux meter has a short length scale, which can lead to higher convective heat flux measurements. However, this effect is not fully accounted for in the convective heat transfer coefficient calculations performed by FDS [68].

5.1.6. Flame Shape

Figure 35 compares the fire progression at $t = 9$ min, $t = 12$ min, and $t = 15$ min from the start of the test between the experimental data and the FDS model. In this analysis, flames are represented by the 550 °C isosurface. The default HRRPUV setting in FDS produced

weaker flame predictions that did not closely resemble the observed fire behaviour. However, using the 550 °C isosurface as a flame criterion provided a better visual agreement with the experimental results, closely representing the observed flame spread and intensity.

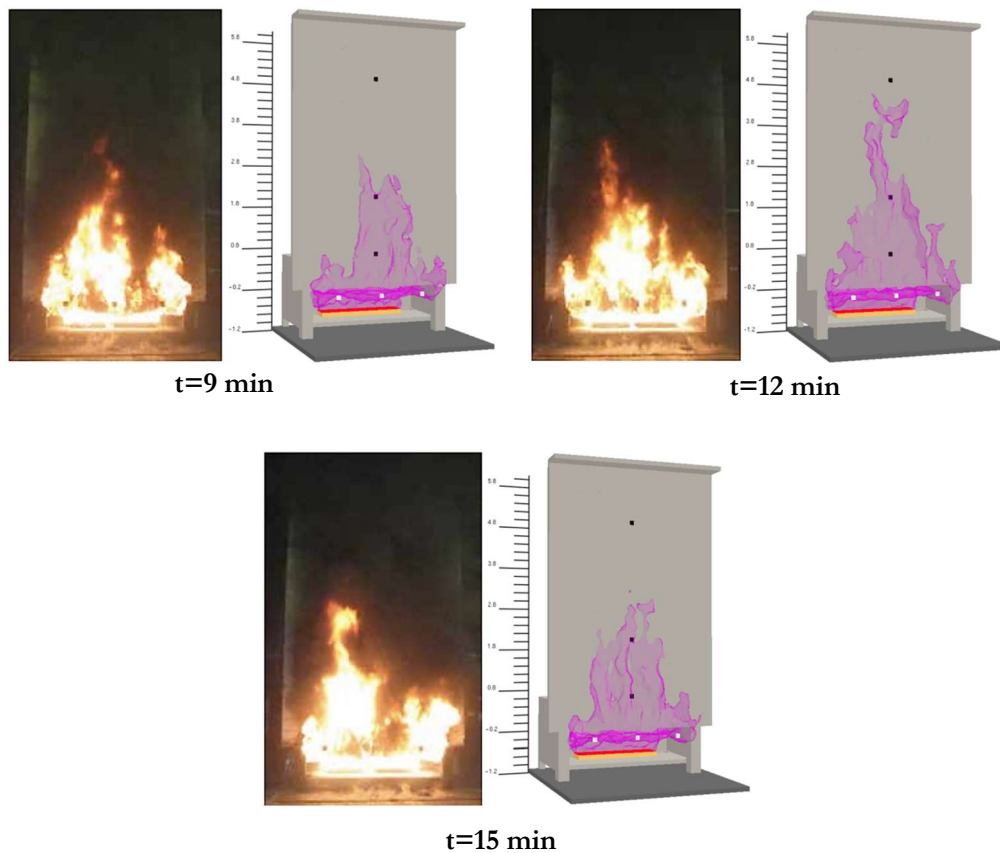


Figure 35 - Comparison of flame spread between the experiment (left) and the FDS model (right) at $t=9$ min, $t=12$ min and $t=15$ min.

5.1.7. Summary of Validation and Model Limitations

The validation indicated that the FDS model (version 6.9.1) was able to reasonably reproduce the general fire behaviour observed in the SP Fire 105 façade fire test using lightweight concrete. While the model did not achieve exact agreement with all experimental results, it captured key trends in temperature and heat flux, providing a useful reference case for further analysis.

Several modelling simplifications contributed to the observed discrepancies between simulation and experiment. These include the omission of the flame suppression lattice used in the test, the use of default radiation parameters (e.g., 100 radiation angles and a radiative fraction of 0.35), and reliance on literature values for material and fuel properties. Wind effects were also simplified through a constant velocity input, which does not fully reflect the dynamic nature of the experimental setup and may have influenced plume development. Mesh resolution was another factor affecting accuracy. Although finer meshes can improve precision, a 5 cm grid size was chosen to balance computational cost with performance. This resolution provided a slight improvement over the 10 cm mesh and was deemed sufficient for the goals of this study. Specifically, the 5 cm mesh yielded better agreement with experimental data in terms of surface temperatures, the temperature of plate thermometers

mounted on the façade wall, and the heat flux. A detailed comparison of the results predicted by 5 cm and 10 cm grid size is presented in **Appendix B**.

However, it is important to acknowledge that the validation shows the greatest uncertainties at lower measurement heights, near the combustion chamber opening. These discrepancies may arise from localized phenomena, such as strong flame-wall interactions, which are challenging to capture accurately with the current model configuration. This limitation represents a key constraint and introduces uncertainty in interpreting the results in these regions.

Although the model has limitations, it was considered adequate for the intended purpose of investigating the influence of horizontal projections on façade fire behaviour. The goal was not to perfectly replicate the test results, but to establish a computationally efficient and representative model. Future work should include detailed uncertainty quantification and sensitivity analysis to improve the robustness and reliability of the simulation outcomes.

5.2. Numerical Study of Horizontal Projections

This section presents the results of the comparative analysis that examined the impact of horizontal projection depth on façade thermal exposure. Two design fire scenarios were considered:

- **Scenario 1: a baseline fire with a heat release rate (HRR) of 2.4 MW, and**
- **Scenario 2: a higher-intensity fire with a HRR of 3.5 MW.**

Results presented in **Sections 5.2.1 to 5.2.3** are based on Scenario 1. Results from Scenario 2 are introduced in **Sections 5.2.4** (Heat Flux) and **5.2.5** (Wall Temperature), where a direct comparison was conducted to evaluate how increased fire intensity affects thermal exposure to the façade.

5.2.1. Flame Trajectory

The external flame trajectory from side and front view is presented in **Figure 36** and **Figure 37**, respectively, for four scenarios: a free façade (a), and façades with horizontal projections of 30 cm (b), 60 cm (c), and 100 cm (d).

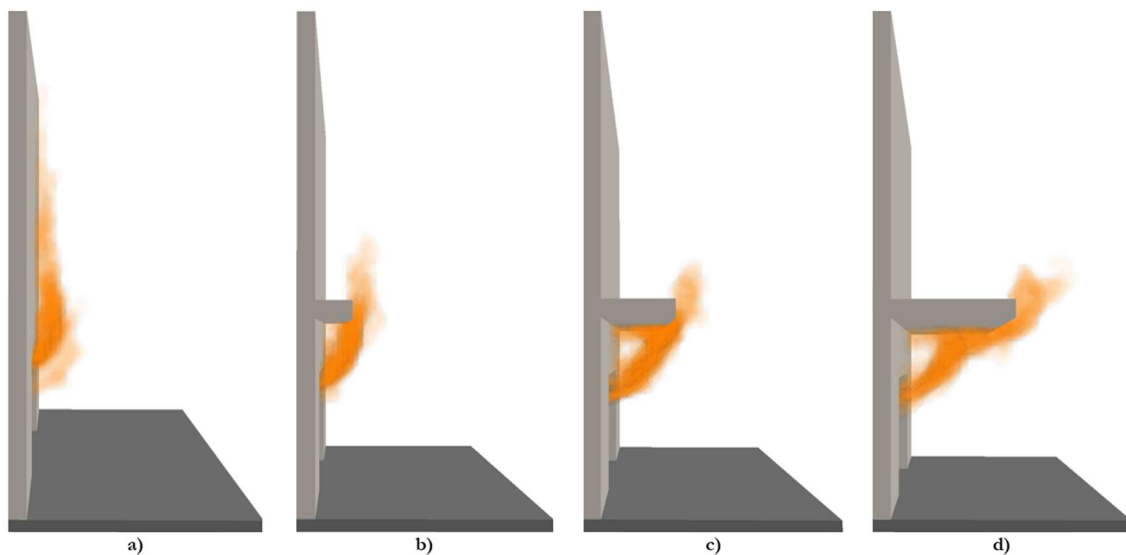


Figure 36 - External flame trajectory (side view) under 2.4 MW fire scenario: a) No projection (free façade), b) 30 cm projection, c) 60 cm projection, d) 100 cm projection.

In the free façade scenario (**Figure 36a**), the flame remains closely attached to the wall, rising directly upward. This configuration poses the highest risk due to direct flame impingement. As the projection depth increased, the flames were increasingly deflected outward. The 100 cm projection results in the most pronounced deflection, minimizing contact with the façade and reducing upward fire spread.

All projection cases show a small air gap between the underside of the projection and the base of the flame, due to the deflection of the flame. The gap widened with projection depth, showing more effective disruption of the vertical flame path.

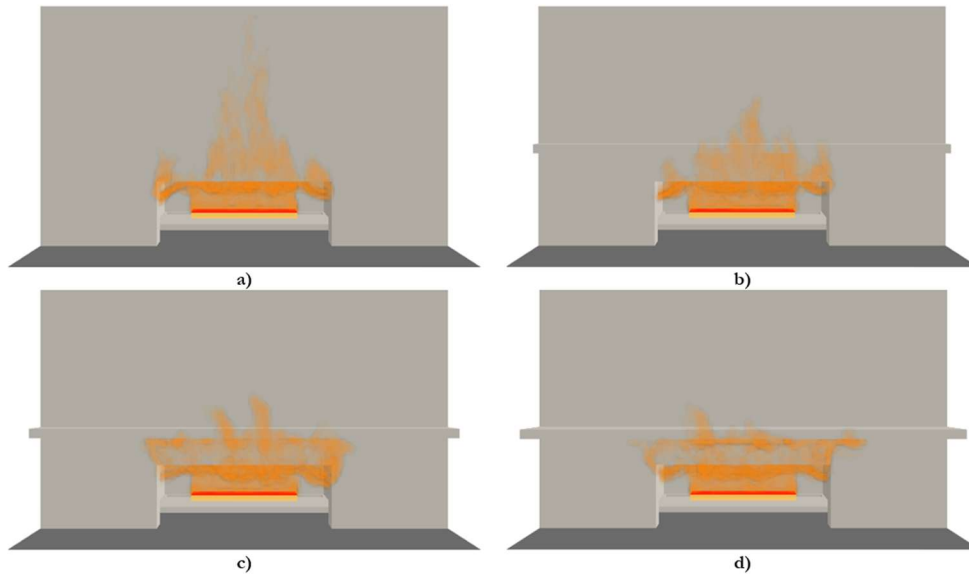


Figure 37 - External flame trajectory (front view) under 2.4 MW fire scenario: a) No projection (free façade), b) 30 cm projection, c) 60 cm projection, d) 100 cm projection.

The front view (Figure 37) shows the lateral spread introduced by the projections. In the free façade case (a), the flame rises narrowly above the opening. However, as projection depth increases, the flame begins to spread more laterally. This suggests a redistribution of heat from the vertical to the horizontal surfaces. This lateral extension increases the potential for flame spread to nearby elements on the sides of the opening.

5.2.2. Flame Shape

5.2.2.1. Temperature Isosurface (550 °C)

▪ Flame height

Figure 38 illustrates the influence of façade projection on flame height, using a temperature threshold of 550 °C at a simulation time of 167 seconds.

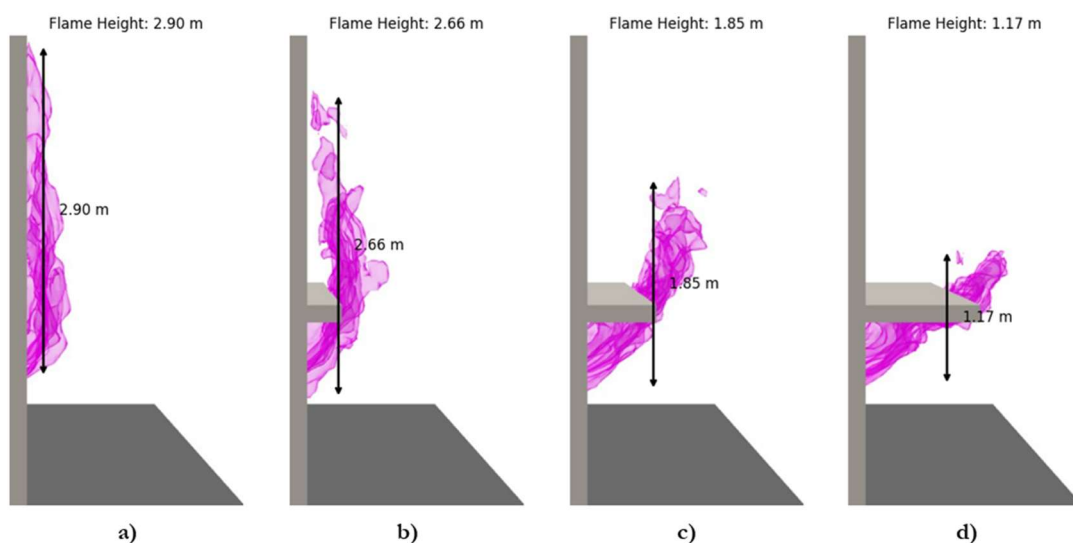


Figure 38 - Flame height based on 550 °C temperature isosurface at $t=167$ s under 2.4 MW fire scenario: a) No projection (free façade), b) 30 cm projection, c) 60 cm projection, d) 100 cm projection.

The figure shows that increasing projection depth correlates with reduced flame height. The scenario without any projection resulted in the greatest flame height, measuring approximately 2.90 m. Introducing a modest 30 cm projection reduced the flame height to 2.66 m, representing an 8.3% decrease. Increasing the depth to 60 cm produced a more pronounced effect, with flame height dropping to approximately 1.85 m—a 36.2% reduction. The maximum projection of 100 cm yielded the lowest flame height at around 1.17 m, corresponding to a 59.7% decrease relative to the no-projection case. These results clearly demonstrate that deeper projections significantly reduce upward flame propagation.

▪ Horizontal Flame Extension

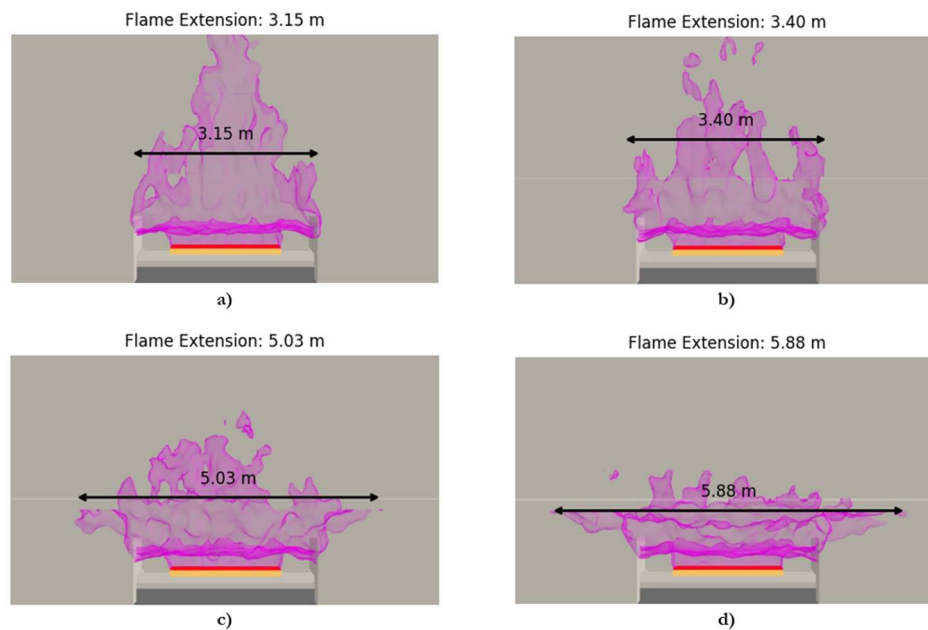


Figure 39 - Flame horizontal extension based on 550 °C temperature isosurface at $t=167$ s under 2.4 MW fire scenario: a) No projection (free façade), b) 30 cm projection, c) 60 cm projection, d) 100 cm projection.

Figure 39 illustrates the flame horizontal extension at $t = 167$ s using the 550 °C temperature threshold for different façade projections. The horizontal flame extension progressively increased with deeper projections: from 3.15 m with no projection (free façade) to 5.88 m with a 100 cm projection, representing an 86.7% increase.

The flame heights and horizontal flame extensions were computed from transient data recorded between 50 s and 200 s, using a temperature threshold of 550 °C. Representative transient graphs for the free façade scenario (no projection) are provided in **Figure 40** and **Figure 41**.

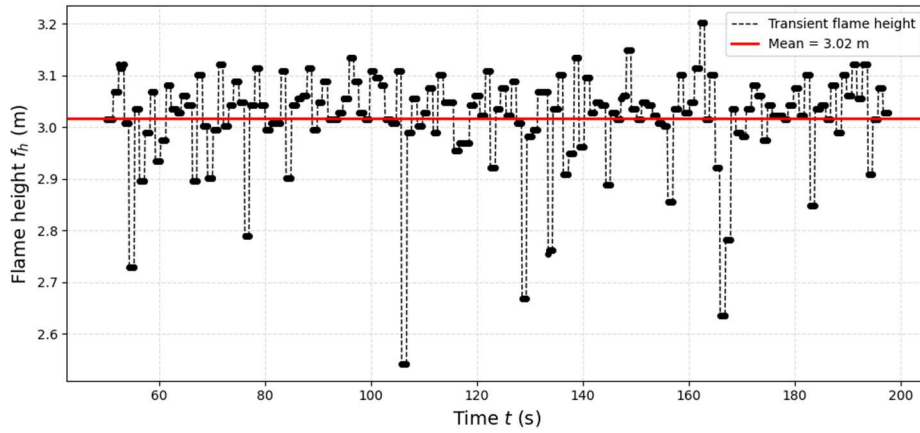


Figure 40 - Flame height over time and average flame height for the free façade (no projection) using temperature isosurface of 550 °C under 2.4 MW fire scenario.

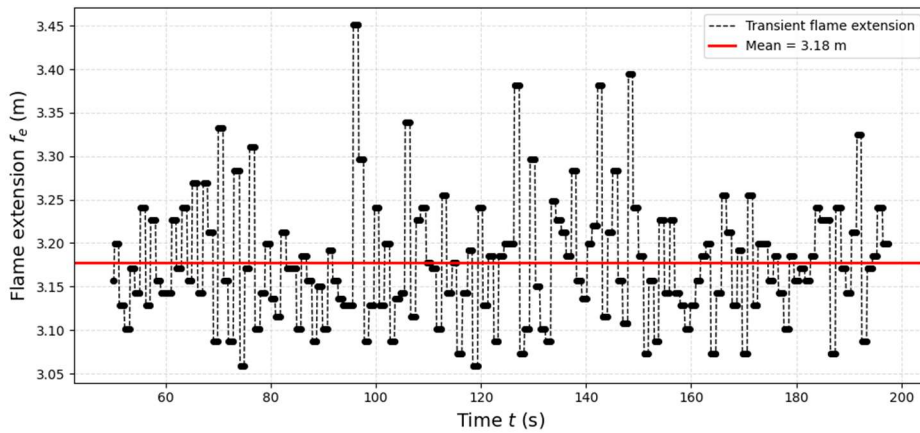


Figure 41 - Flame horizontal extension over time and average flame extension for the free façade (no projection) using temperature isosurface of 550 °C under 2.4 MW fire scenario.

Detailed transient flame height and horizontal flame extension graphs, along with their corresponding mean values for all façade projection scenarios, are provided in **Appendix E**.

Table 5 presents the average flame height and horizontal extension at the 550 °C isosurface for different projection configurations. To better illustrate the impact of projections, percentage differences are included relative to the free façade scenario. As projection depth increases, there is a noticeable reduction in flame height (up to 38.41% for 100cm depth) accompanied by a significant increase in horizontal spread (up to 68.55% for 100cm depth). **Table 5 - Summary of average flame height and horizontal extension using temperature isosurface of 550 °C under 2.4 MW fire scenario:**

Projection configuration	Mean flame height (m)	Mean horizontal extension (m)	% Diff in Flame Height	% Diff in Horizontal Extension
Free façade	3.02	3.18	-	-
30 cm	2.96	3.28	-1.99%	+3.14%
60 cm	2.47	4.38	-18.21%	+37.74%
100 cm	1.86	5.58	-38.41%	+68.55%

5.2.2.2. HRRPUV Isosurface (500 kW/m^3)

■ Flame height

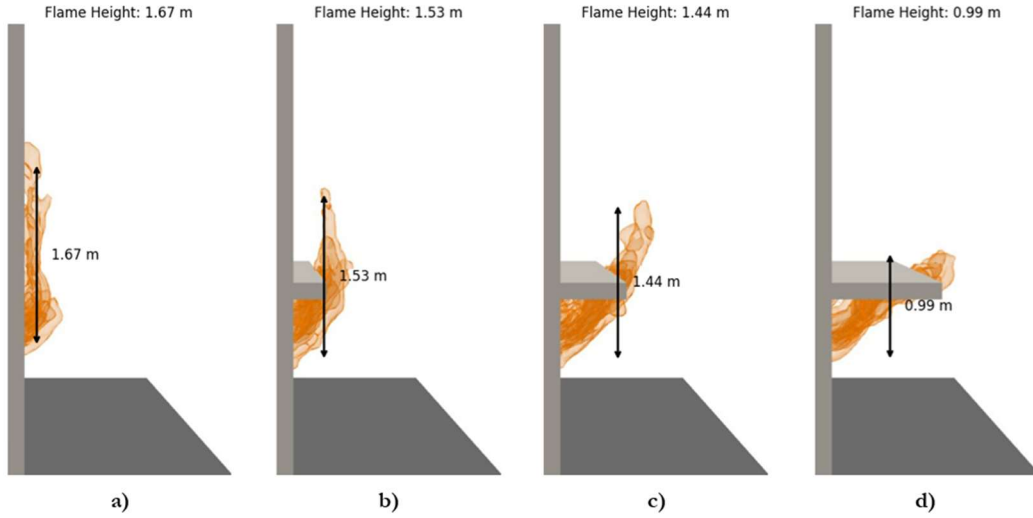


Figure 42 - Flame height based on 500 kW/m^3 HRRPUV isosurface at $t=167 \text{ s}$ under 2.4 MW fire scenario: a) No projection (free façade), b) 30 cm projection, c) 60 cm projection, d) 100 cm projection.

Figure 42 presents the flame height at $t = 167 \text{ s}$ based on the 500 kW/m^3 HRRPUV isosurface. The flame behaviour observed under this criterion mirrors the trend seen with the temperature isosurface. As the depth of the horizontal projection increases, the vertical extent of the flame decreases progressively. In the free façade case, the flame height reaches 1.67 m . Introducing a 30 cm projection causes a slight reduction to 1.53 m . Further increases in projection depth yield more significant reductions: 1.44 m for the 60 cm projection and a minimum of 0.99 m for the 100 cm projection.

■ Horizontal Flame Extension

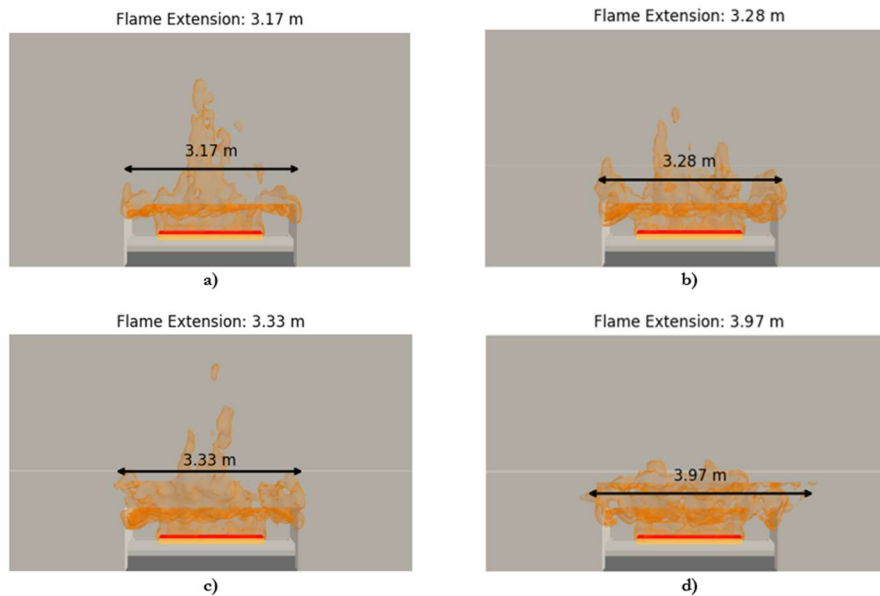


Figure 43 - Flame horizontal extension based on 500 kW/m^3 HRRPUV isosurface at $t=167 \text{ s}$ under 2.4 MW fire scenario: a) No projection (free façade), b) 30 cm projection, c) 60 cm projection, d) 100 cm projection.

Figure 43 illustrates the influence of horizontal projections on lateral flame extension, using a 500 kW/m^3 HRRPUV isosurface at $t = 167 \text{ s}$. The results follow a similar trend to the temperature-based isosurface data, where increased projection depth leads to greater horizontal flame extension. The free façade case shows a flame spread of 3.17 m , while the 30 cm and 60 cm projections extend to 3.28 m and 3.33 m , respectively. The 100 cm projection results in the widest horizontal spread of 3.97 m , highlighting the enhanced lateral dispersion caused by deeper projections.

The same post-processing methodology was applied to the HRRPUV isosurfaces as was used for the temperature threshold analysis. Flame height and horizontal extension were extracted from isosurface data recorded between 50 and 200 seconds of simulation time. Results for the free façade configuration are shown in **Figure 44** and **Figure 45**, while detailed data for all projection scenarios are included in **Appendix E**.

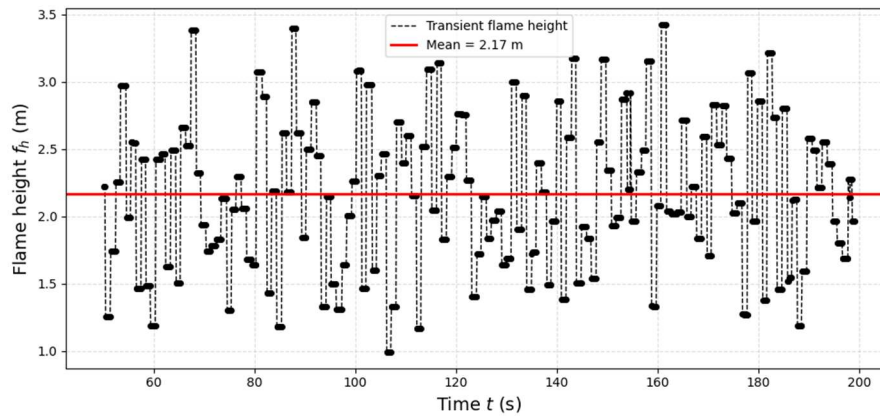


Figure 44 - Flame height over time and average flame height for the free façade (no projection) using HRRPUV isosurface of 500 kW/m^3 under 2.4 MW fire scenario.

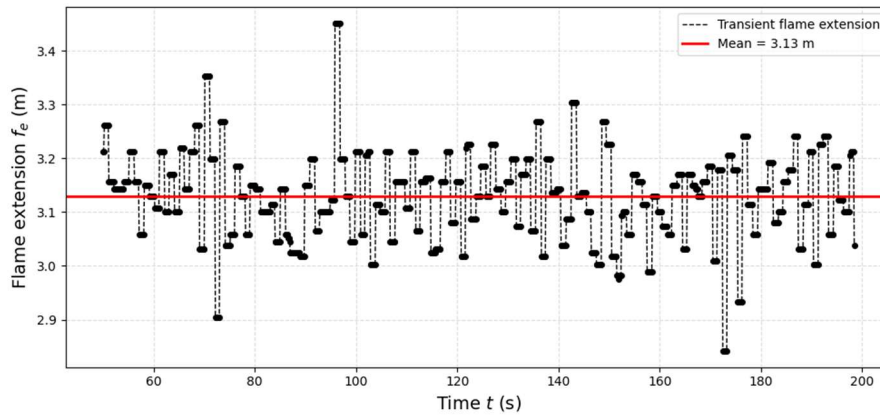


Figure 45 - Flame extension over time and average flame extension for the free façade (no projection) using HRRPUV isosurface of 500 kW/m^3 under 2.4 MW fire scenario.

Table 6 summarizes the average flame height and horizontal flame extension calculated using the HRRPUV isosurface at a threshold of 500 kW/m^3 for each projection configuration under a 2.4 MW fire scenario. The table presents the average values for both flame height and horizontal extension, as well as their percentage differences relative to the free façade case, which serves as the baseline.

The data show a progressive reduction in flame height as the depth of the projection increases. Compared to the free façade, flame height decreases by 24.88% for the 30 cm projection, 31.80% for the 60 cm projection, and 47.93% for the 100 cm projection. This trend indicates that deeper projections more effectively deflect the vertical flame spread, reducing upward flame propagation.

In contrast, horizontal flame extension increases with projection depth. Relative to the free façade, horizontal extension increases by 1.28% for the 30 cm projection, 7.02% for 60 cm, and 20.45% for 100 cm. This suggests that while vertical flame spread is reduced, the flame tends to spread laterally along the façade due to the obstructing geometry.

Table 6 - Summary of average flame height and horizontal extension using HRRPUV isosurface of 500 kW/m³ under 2.4 MW fire scenario:

Projection configuration	Mean flame height (m)	Mean horizontal extension (m)	% Diff in Flame Height	% Diff in Horizontal Extension
Free façade	2.17	3.13	-	-
30 cm	1.63	3.17	-24.88%	+1.28%
60 cm	1.48	3.35	-31.80%	+7.02%
100 cm	1.13	3.77	-47.93%	+20.45%

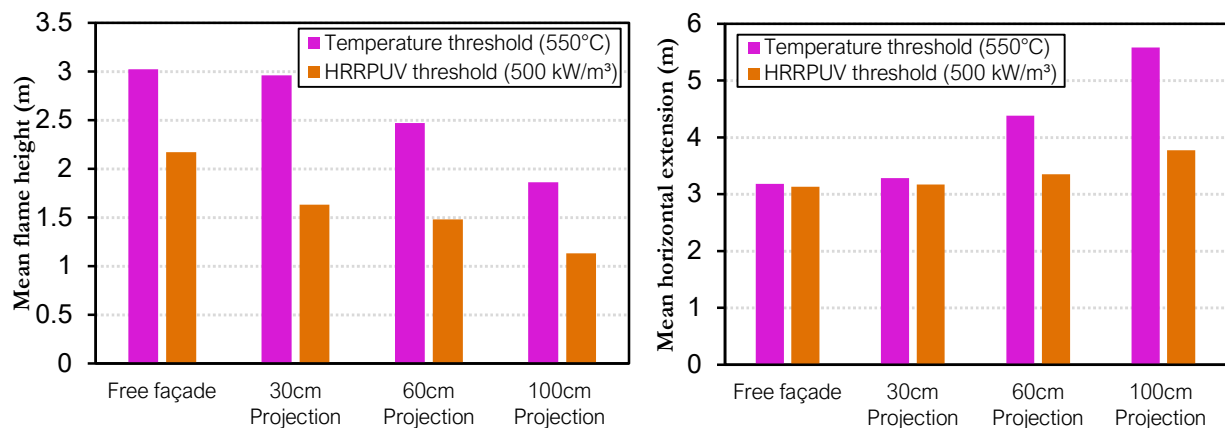


Figure 46 - Comparison of mean flame height and horizontal extension using temperature and HRRPUV isosurfaces for various projection depths under 2.4 MW fire scenario.

Results based on the 500 kW/m³ HRRPUV threshold exhibit similar trends to the temperature-based analysis, but with lower magnitudes. On average, the flame height predicted using the HRRPUV criterion underestimates the flame height derived from the temperature criterion by 38.10%, while the horizontal flame extension is lower by an average of 15.22%. As seen in Figure 46, the temperature threshold consistently produces higher flame heights and greater horizontal extensions than the HRRPUV threshold. This is expected, as the 550 °C temperature isosurface captures the broader thermal envelope of the flame, including areas with lower combustion intensity but still elevated temperatures. Conversely, the HRRPUV isosurface isolates regions of high combustion activity, where the heat release rate is most concentrated, leading to more compact flame shapes.

Results confirm that deeper horizontal projections significantly lower flame height while increasing lateral flame extension. This is because the projection serves as a physical barrier, interrupting the buoyant upward flow and redirecting flames laterally. As the projection depth increases, this redirection becomes more pronounced, increasing the horizontal component of the flame beneath the projection.

Deeper horizontal projections limit upward heat transfer, reducing the risk of flames reaching higher façade levels. However, this also increases the potential for lateral flame spread, which could expose adjacent façade components. Thus, while horizontal projections are effective in suppressing vertical flame spread, simultaneously elevate the possibility of horizontal flame exposure.

5.2.2.3. Theoretical Flame Height

Based on the theoretical correlation proposed by Lee et al. [35], the expected flame height for the free façade configuration was calculated using a characteristic length scale l_1 derived from the window dimensions (0.71 m × 3.0 m). The resulting l_1 was calculated according to **Equation (11)** as 1.26 m.

To calculate the excess heat release rate $\dot{Q}_{ex}$, the value was obtained by subtracting the HRR measured by a device positioned inside the fire compartment from the total HRR measured in the computational domain. This approach isolates the portion of the heat release contributing to the external flame, as defined in Lee et al.'s model. For the free façade scenario, the average excess HRR was found to be **698 kW**.

The non-dimensional excess HRR ($\dot{Q}_{ex}^*$) was then calculated using **Equation (13)** :

$$\dot{Q}_{ex}^* = \left(\frac{\dot{Q}_{ex}}{\rho_{\infty} c_p T_{\infty} \sqrt{g} l_1^{5/2}} \right)$$

where:

$$\dot{Q}_{ex} = 698 \text{ kW}, \rho_{\infty} = 1.2 \text{ kg/m}^3, c_p = 1 \text{ kJ/kg}\cdot\text{K}, T_{\infty} = 293 \text{ K}, g = 9.81 \text{ m/s}^2, l_1 = 1.26 \text{ m}$$

This gives a non-dimensional excess HRR of:

$$\dot{Q}_{ex}^* \approx 0.35$$

Since $\dot{Q}_{ex}^* < 1.3$, the fire is within the two-dimensional flame regime, and the theoretical flame height Z_f is estimated using **Equation (15)**:

$$\begin{aligned} Z_f &= 3.2 \dot{Q}_{ex}^{*2/3} l_1 \\ Z_f &= 3.2 \times (0.35)^{2/3} \times 1.26 \approx 2 \text{ m} \end{aligned}$$

Therefore, the theoretical flame height predicted by Lee et al.'s correlation for the free façade case is approximately 2 m.

In contrast, the simulated flame height obtained from the 550 °C temperature isosurface was 3.02 m, which is approximately 51% higher than the theoretical prediction. The flame height based on the 500 kW/m³ HRRPUV isosurface was 2.17 m, representing a smaller

overprediction of 8.5% compared to the theoretical value. The closer agreement of the HRRPUV method with theory suggests it may be a more physically consistent metric for external flame characterization in this setup.

5.2.2.4. Theoretical Flame Horizontal Extension

In this section, we evaluate the horizontal flame extension beneath projections using the empirical correlation developed by Lu et al. [50] and compare the results with numerical simulations. The theoretical correlation, defined in **Equation (17)**, estimates the radius of flame extension (R_f) under a horizontal projection:

$$R_f = 0.0283 \left(\frac{\phi \dot{Q}_{ex}}{\sqrt{H_e - H_n}} \right)^{1/2}$$

where:

- ϕ is the intercepted flame volume ratio
- $\dot{Q}_{ex}$ is the excess heat release rate (kW)
- H_e is the height of the projection from the floor (m)
- $H_n = 0.4H$ is the height of the neutral plane (m)

For this study, the following parameters were used:

- $H = 0.71$ m (window opening height)
- $H_n = 0.284$ m
- $H_e = 1.315$ m (measured from the numerical model)
- $H_f = 2$ m (estimated free-facade flame height)
- $C_1 = 0.179$ (empirical constant)

Using **Equation (18)**, the intercepted volume ratio was calculated as:

$$\phi = \frac{R_0^2(H_f - H_e) + R_0 C_1((H_f - H_n)^2 - (H_e - H_n)^2) + \frac{1}{3} C_1^2((H_f - H_n)^3 - (H_e - H_n)^3)}{R_0^2(H_f - H_n) + R_0 C_1(H_f - H_n)^2 + \frac{1}{3} C_1^2(H_f - H_n)^3}$$

With characteristic length-based fire source radius $R_0 = \sqrt{\frac{2}{\pi} l_1 l_2}$, the intercepted volume fraction ϕ was found to be 0.47, indicating that 47% of the total flame volume was intercepted by the projection.

Theoretical R_f values were then computed for each projection depth using the respective $\dot{Q}_{ex}$:

Table 7 - Comparison of theoretical and simulated flame extension radius beneath horizontal projections:

Projection depth	$\dot{Q}_{ex}$ (kW)	Theoretical Rf (m)	Rf (550°C) (m)	Rf (500 kW/m ³) (m)
30 cm	721	0.52	1.64	1.58
60 cm	767	0.53	2.19	1.67
100 cm	804	0.55	2.79	1.88

As shown in **Table 7**, the theoretical flame extensions remain relatively constant, ranging from 0.52 to 0.55 m, due to the small variation in the excess heat release rate. In contrast, the simulated flame extensions increase considerably with projection depth, indicating that deeper projections lead to greater lateral extension. At 30 cm, the simulated extensions are 1.64 m and 1.58 m for the temperature and HRRPUV criteria, respectively, both exceeding the theoretical estimate by a factor of approximately three. For the 60 cm projection, the simulated extensions increase to 2.19 m and 1.67 m, showing an even larger deviation from the predicted value of 0.53 m. The greatest discrepancy is observed at the 100 cm depth, where the temperature-based extension reaches 2.79 m and the HRRPUV-based value is 1.88 m, compared to a theoretical prediction of only 0.55 m.

These results indicate that Lu et al.'s empirical model underestimates the actual flame extension beneath projections, particularly for larger projections. The simplified model does not fully capture the complex flame deflection occurring in the simulations.

5.2.3. Plume Velocity

Figure 47 and **Figure 48** show the external flame velocity fields captured at two different planes: $Y = 2.0$ m (**Figure 47**) represents a vertical slice at the centreline of the opening, while $X = 0.2$ m (**Figure 48**) represents a slice closer to the façade, just in front of the opening. Both figures compare four scenarios: no projection (free façade), and horizontal projections of 30 cm, 60 cm, and 100 cm.

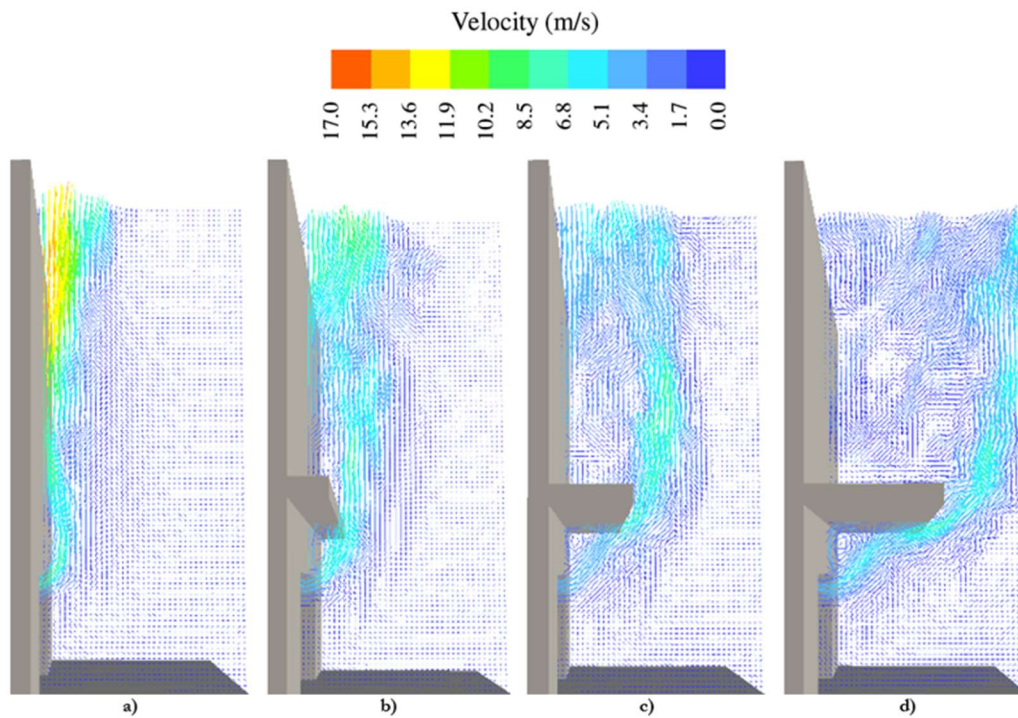


Figure 47 - External flame velocity slice ($Y=2.0$ m) under 2.4 MW fire scenario: a) No projection (free façade), b) 30 cm projection, c) 60 cm projection, d) 100 cm projection.

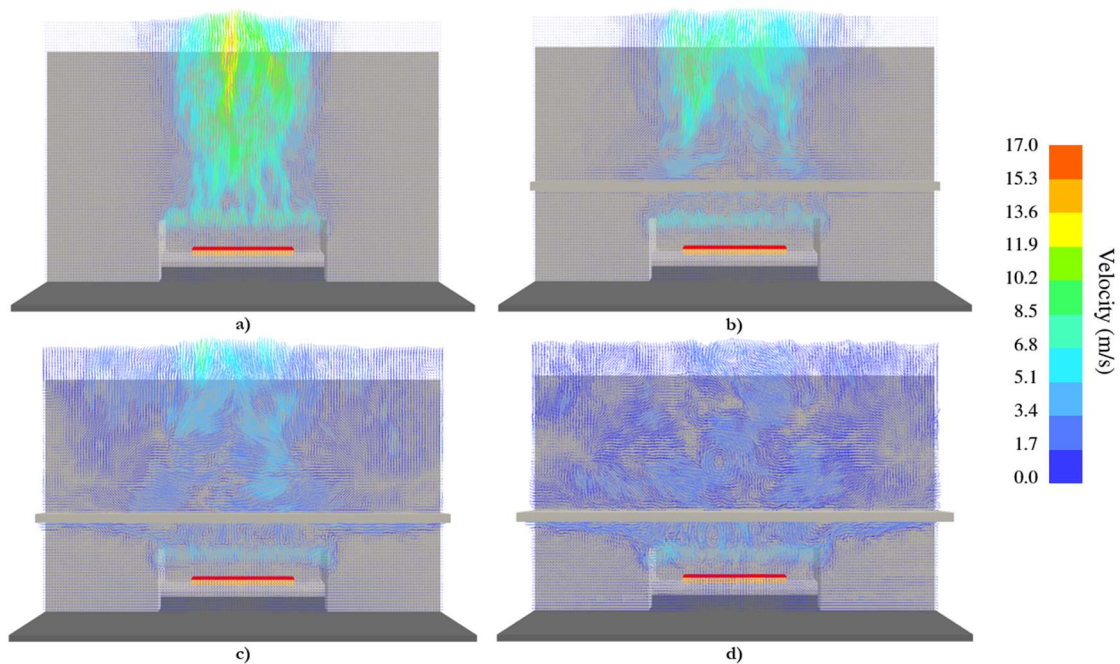


Figure 48 - External flame velocity slice ($X=0.2$ m) under 2.4 MW fire scenario: a) No projection (free façade), b) 30 cm projection, c) 60 cm projection, d) 100 cm projection.

In the free façade configuration (Figure 47a and Figure 48a), the flame exhibits a strong, vertically oriented plume that remains closely attached to the façade surface. The velocity fields show a narrow, high-intensity upward flow, with peak velocities ranging between 15–17 m/s.

This indicates intense buoyancy-driven convection, with no obstruction to the vertical movement of hot gases. As a result, the flame directly impinges on the upper portions of the façade, significantly increasing the thermal exposure on exterior elements like windows and

cladding. This configuration represents the most critical scenario in terms of vertical fire spread.

As horizontal projections are introduced and increased in depth, the flame velocity fields show significant changes. The 30 cm projection (**Figure 47b**) modestly disrupts the upward flame movement, partially separating the flow and reducing its attachment to the façade, while also slightly lowering the vertical velocity compared to the free façade scenario.

In the cases with 60 cm (**Figure 47c**) and 100 cm (**Figure 47d**) horizontal projections, vertical flame velocity decreases significantly, and the plume deflects more noticeably away from the facade. For the 60 cm projection, vertical velocities range from 6–8 m/s, while in the 100 cm case, they decline further to approximately 5–6 m/s. This reduction reflects the projection's disruption of the buoyant upward flow and promotion of lateral dispersion. Correspondingly, horizontal velocity components become more dominant, particularly beneath the projections. In the 100 cm case, the region where lateral velocities range between 1–5 m/s is notably more extensive than in the 60 cm case, indicating greater outward flame spread and enhanced plume deflection.

These results indicate that increasing the depth of the horizontal projection effectively reduces the vertical flow velocity of the external flame while simultaneously expanding the region where lateral velocity components are dominant. Additionally, the entrainment of cooler air diminishes the flame's vertical momentum, resulting in wider lateral flame spread.

5.2.4. Heat Flux

Figure 49 illustrates how projection depth alters the intensity and distribution of radiative heat exposure at $t=167s$ under the baseline 2.4 MW scenario. In the free façade configuration, the plume rises vertically, concentrating a significant amount of thermal energy above the opening. The upper wall experiences the highest heat flux values, exceeding 45–50 kW/m², due to direct flame contact and proximity to the ejected flames. The lateral surfaces remain relatively unaffected, as the flames are narrowly focused along the vertical axis. With a 30 cm projection, the heat flux distribution starts to change. The projection slightly disrupts the plume, reducing heat exposure to the upper façade. However, significant heat concentrations persist just below and around the projection edge. With deeper projections of 60 cm and 100 cm, a significant redistribution of heat occurs. The heat flux zone expands horizontally, with pronounced concentrations beneath the projections and along the lower facade. In the 100 cm case, a distinct heat trapping effect is observed, where hot gases accumulate under the projection, maintaining high heat flux values over a wider lateral area. Vertical heat transfer is reduced on the façade above the projection, but this redirection increases the thermal load on the surfaces directly under and adjacent to the projection.

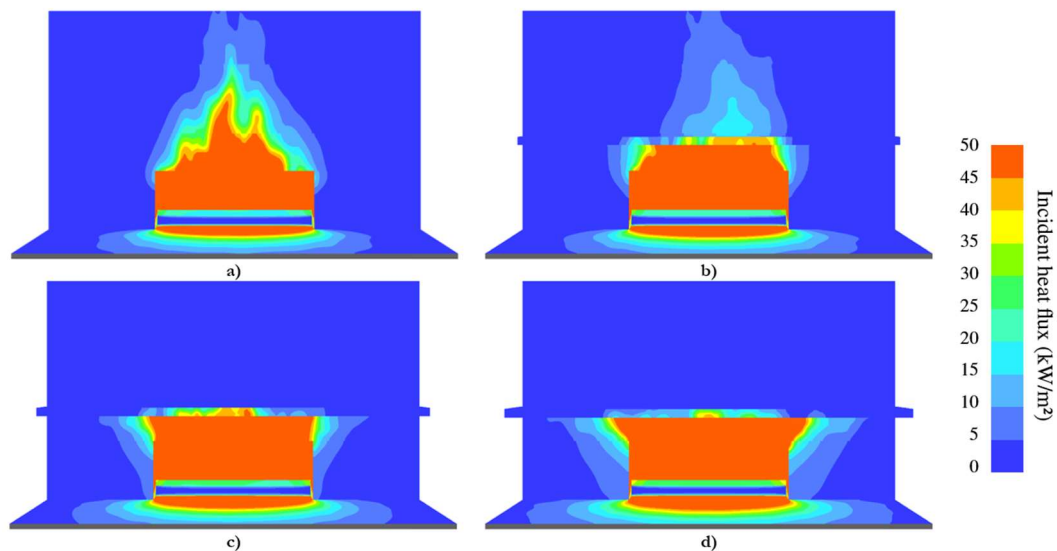


Figure 49 - Incident heat flux distribution under 2.4 MW fire scenario: a) No projection (free façade), b) 30 cm projection, c) 60 cm projection, d) 100 cm projection.

Figure 50 presents the average vertical incident heat flux profiles for different projection depths under both the 2.4 MW and 3.5 MW fire scenarios.

For the 2.4 MW case, the maximum heat flux at 2.15 m height is approximately 22 kW/m² for the free façade. This value progressively decreases with deeper projections: to approximately 7 kW/m² with a 30 cm projection, 3 kW/m² with a 60 cm projection, and 1.25 kW/m² with a 100 cm projection—corresponding to reductions of 68%, 86%, and 94%, respectively. Under the 3.5 MW scenario, the same trend is observed, though with higher heat flux values. As shown in Figure 50, at 2.15 m height, the 30 cm, 60 cm, and 100 cm projections reduce vertical heat flux by approximately 39.8%, 78.2%, and 91.7%, respectively, compared to the free façade case. These results confirm that deeper projections remain highly effective in limiting upward thermal exposure, even under more severe fire conditions.

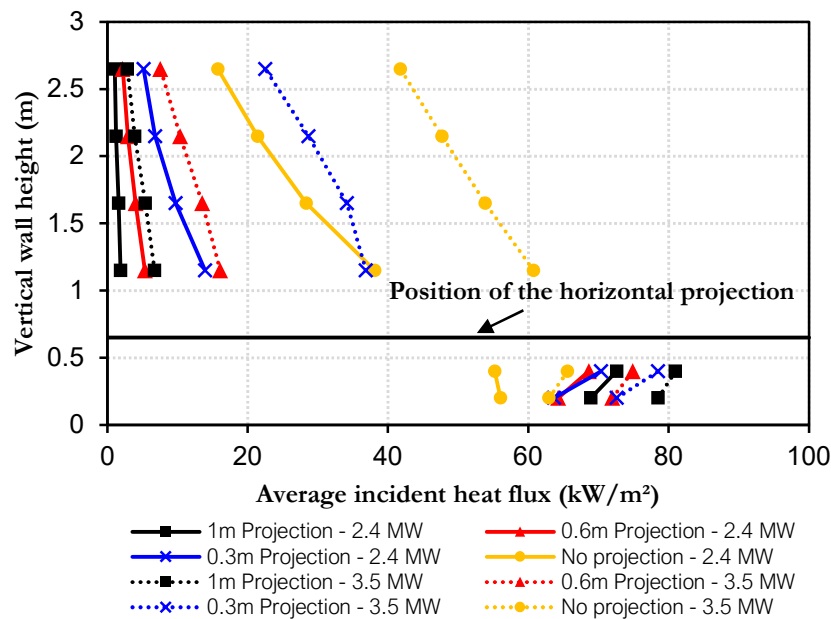


Figure 50 - Average incident heat flux predictions along vertical façade height for different horizontal projections depths under 2.4 MW and 3.5 MW.

However, below the horizontal projection, an opposite trend is observed. As the depth of the projection increases, the incident heat flux in the lower façade region also rises. This effect is most pronounced in cases with deeper projections. This rise is primarily due to a heat trapping effect, in which flames and radiant energy are deflected laterally and become concentrated beneath the projection. As a result, the area immediately beneath the projection is subjected to intensified thermal exposure, potentially accelerating ignition and increasing the risk of façade material degradation. This could lead to the detachment of façade components, which is undesirable as it poses hazards during evacuation and compromises firefighter safety.

Figure 51 presents the average lateral distribution of incident heat flux at a height of 100 mm below the horizontal projection, for various projection depths under both the 2.4 MW and 3.5 MW fire scenarios. In the free façade and 30 cm projection cases, lateral heat flux remains minimal. For the 2.4 MW scenario, values stay below 3 kW/m² at 50 cm from the edge of the opening, and under 5 kW/m² for the 3.5 MW scenario. Starting from the 60 cm projection, lateral thermal exposure increases significantly. Under the 2.4 MW scenario, the 10 kW/m² heat flux threshold is observed at a lateral distance of approximately 0.5 m from the opening, while for the 100 cm projection, this threshold extends to about 1.0 m. Under the 3.5 MW scenario, the spread increases further, reaching approximately 1.0 m for the 60 cm projection and up to 1.5 m for the 100 cm projection.

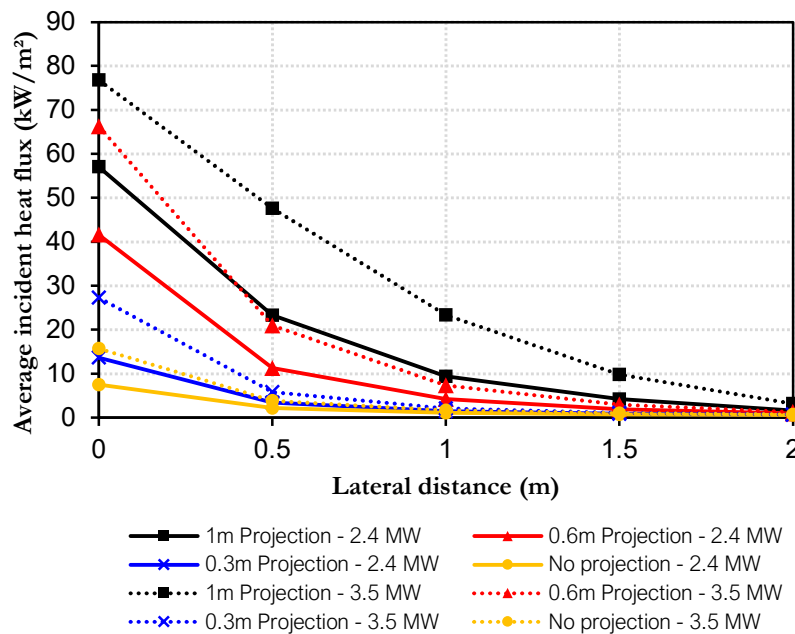


Figure 51 - Average lateral heat flux predictions at 100 mm below horizontal projections for various projection depths under 2.4 MW and 3.5 MW.

Peak heat flux near the edge of the opening (at 0 m lateral distance) increases from 7.5 kW/m² in the free façade case to 13, 41.65, and 57 kW/m² for the 30 cm, 60 cm, and 100 cm projections, respectively. These values are approximately 1.7, 5.6, and 7.6 times higher than the free façade configuration. Similarly, under the 3.5 MW fire scenario, the peak

heat flux rises from 15.73 kW/m² (free façade) to 27.30, 66.27, and 76.80 kW/m² for the 30 cm, 60 cm, and 100 cm projections, corresponding to increases of approximately 1.7, 4.2, and 4.9 times, respectively.

At a lateral distance of 0.5 m from the opening, a similar pattern is observed: under the 2.4 MW scenario, heat flux increases from 2.17 kW/m² in the free façade case to 3.40, 11.26, and 23.28 kW/m² for the 30 cm, 60 cm, and 100 cm projections, respectively. These values are approximately 1.6, 5.2, and 10.7 times higher than the free façade configuration. For the 3.5 MW scenario, the heat flux at 0.5 m rises from 3.86 kW/m² (free façade) to 5.79, 20.94, and 47.63 kW/m² for the same projection depths, corresponding to increases of approximately 1.5, 5.4, and 12.3 times, respectively.

These findings indicate that deeper projections not only redirect the flame but significantly intensify lateral thermal exposure, especially at increased fire intensities and distances from the opening.

The results demonstrate that horizontal projections significantly influence the distribution of incident heat flux on building façades during fires. As projection depth increases, vertical heat transfer decreases—particularly above the projection, where deeper elements effectively shield the upper façade and reduce upward flame spread. This confirms their effectiveness as passive fire protection features in mitigating vertical fire propagation.

However, this benefit comes at the cost of intensified heat accumulation below the projection. Flames and radiant energy are deflected downward and laterally, resulting in elevated incident heat fluxes directly beneath and beside the projection. This redirection effect becomes especially pronounced in the 60 cm and 100 cm cases and is further amplified under the 3.5 MW fire scenario. Results from 500 mm and 1000 mm below the projection (Figure 52 and Figure 53) confirm this pattern.

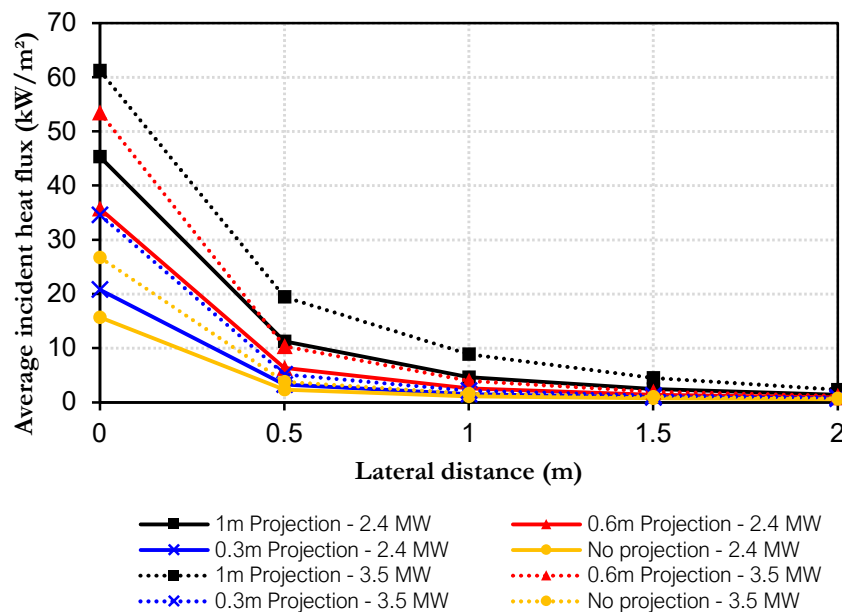


Figure 52 - Average lateral heat flux predictions at 500 mm below horizontal projections for various projection depths under 2.4 MW and 3.5 MW.

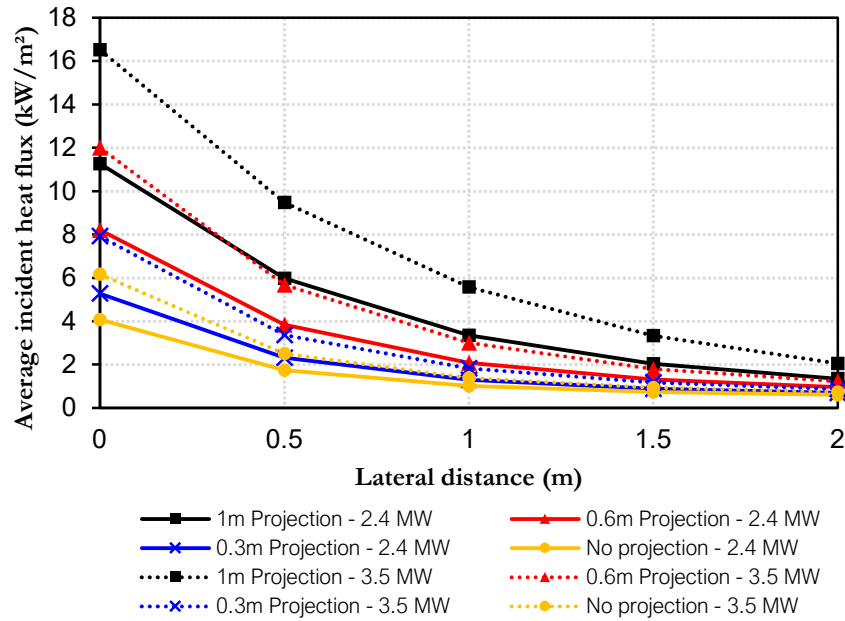


Figure 53 - Average lateral heat flux predictions at 1000 mm below horizontal projections for various projection depths under 2.4 MW and 3.5 MW.

5.2.5. Wall Temperature

Figure 54 presents the wall surface temperature distribution under 2.4 MW fire scenario for varying horizontal projection depths: no projection, 30 cm, 60 cm, and 100 cm.

In the free façade case (a), the flame plume rises vertically and adheres closely to the wall, resulting in widespread high-temperature zones extending far above the window opening. Maximum temperatures are 600-800 °C directly above the fire source, with elevated heat spreading vertically along the façade.

The introduction of a 30 cm projection (b) reduces vertical spread slightly. High temperatures are observed beneath the horizontal projection reaching 700-800 °C, however temperatures in the upper part of the façade above the projection are lower than previous case reaching 400-500 °C. With a 60 cm projection (c), the temperature profile changes more significantly. Vertical heat exposure is reduced to a small zone where the temperature reaches 200-300 °C. However, the region beneath the projection shows higher concentrations of heat expanding laterally. In the 100 cm projection case (d), this effect is most pronounced. The area above the projection remains at much lower temperatures, typically below 200 °C, due to effective shielding by the deeper projection. However, the heat distribution shifts further horizontally, with high temperatures spreading more laterally.

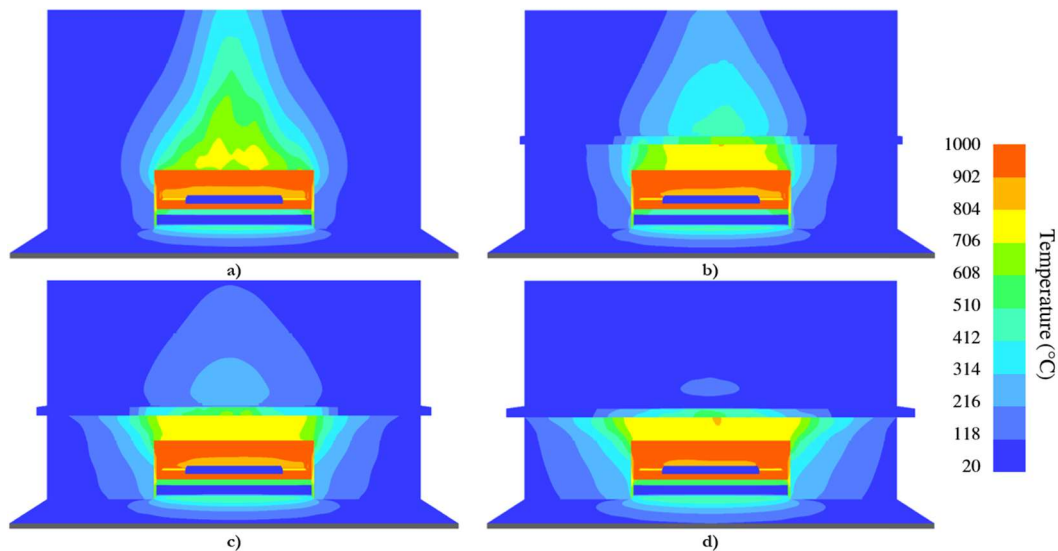


Figure 54 - Wall temperature distribution under 2.4 MW fire scenario: a) No projection (free façade), b) 30 cm projection, c) 60 cm projection, d) 100 cm projection.

Figure 55 illustrates the variation in average wall temperature along the vertical façade height for different horizontal projection depths under both the 2.4 MW and 3.5 MW fire scenarios. For the 2.4 MW case, the wall temperature without any projection reaches approximately 610 °C at 1.15 m above the opening and remains around 480 °C at 2.15 m. Introducing a 30 cm projection lowers the temperature at 2.15 m to about 275 °C, representing a 42% reduction compared to the free façade. With deeper projections of 60 cm and 100 cm, temperatures further decline to approximately 157 °C and 75 °C, reflecting reductions of 67% and 84%, respectively, relative to the no-projection scenario.

Under the 3.5 MW fire scenario, the same trend is observed: At 2.15 m, wall temperatures are reduced by approximately 18% with the 30 cm projection, 48% with the 60 cm projection, and 71% with the 100 cm projection, when compared to the free façade configuration.

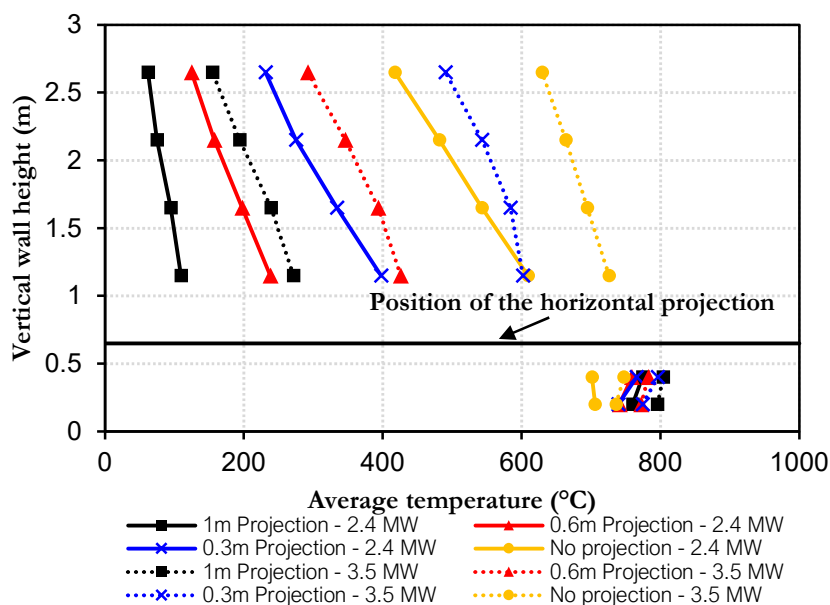


Figure 55 - Average wall temperature predictions along vertical façade height for different horizontal projections depths under 2.4 MW and 3.5 MW.

Figure 56 shows the average lateral wall temperature distribution measured 100 mm below the horizontal projection for different projection depths under both the 2.4 MW and 3.5 MW fire scenarios.

For the 2.4 MW case, the wall temperature without a projection is approximately 300 °C at the edge of the opening and decreases to about 125 °C at 0.5 m laterally. Adding a 30 cm projection raises the temperature near the opening to 400 °C, with a value of 173 °C at 0.5 m lateral distance. Increasing the projection depth to 60 cm results in a temperature of 630 °C at the edge and 358 °C at 0.5 m. For the 100 cm projection, temperatures rise further to 710 °C at the edge and 500 °C at 0.5 m. At 0.5 m lateral distance, wall temperatures increase by approximately 1.4, 2.9, and 4.0 for the 30 cm, 60 cm, and 100 cm projections, respectively, compared to the free façade case.

Under the 3.5 MW scenario, temperatures are notably elevated across all cases. The 100 cm and 60 cm projections reach approximately 800 °C and 747 °C at the edge of the opening, respectively, compared to 420 °C in the free façade case. This indicates a 1.78 increase for the 60 cm projection and nearly 1.9 for the 100 cm projection relative to the free façade. These results clearly demonstrate that deeper projections amplify lateral heat accumulation.

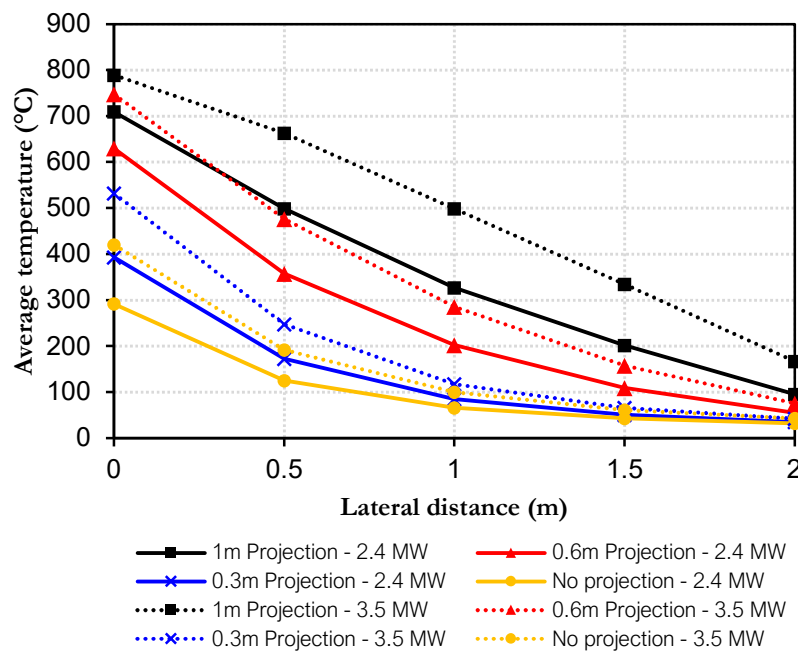


Figure 56 - Average lateral wall temperatures predictions at 100 mm below horizontal projections for various projections depths under 2.4 MW and 3.5 MW.

As shown in **Figure 57** and **Figure 58**, the average lateral wall temperatures at 500 mm and 1,000 mm below the projection confirm the previously observed trend: increasing the depth of the horizontal projection results in greater heat accumulation, leading to significantly higher wall temperatures—even at larger lateral distances from the opening.

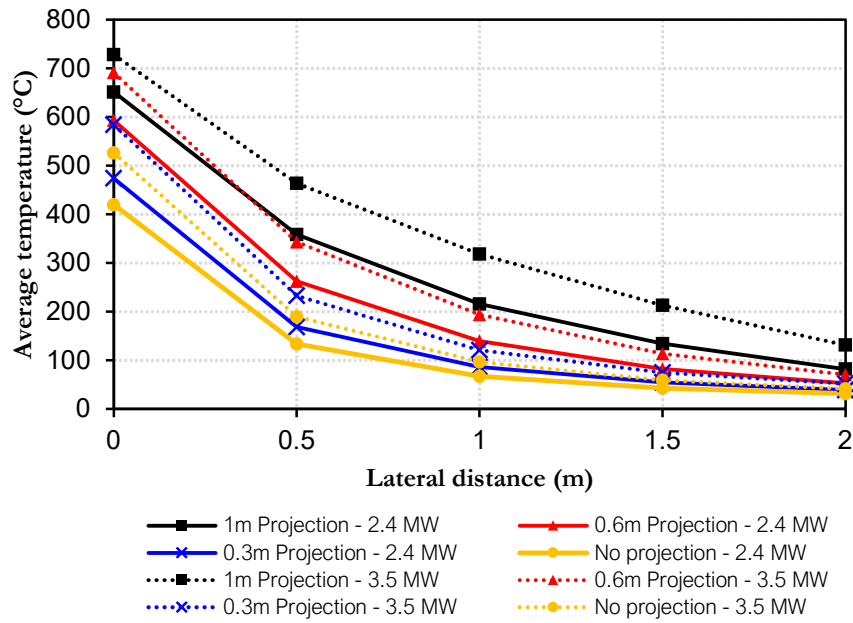


Figure 57 - Average lateral wall temperatures predictions at 500 mm below horizontal projections for various projection depths under 2.4 MW and 3.5 MW.

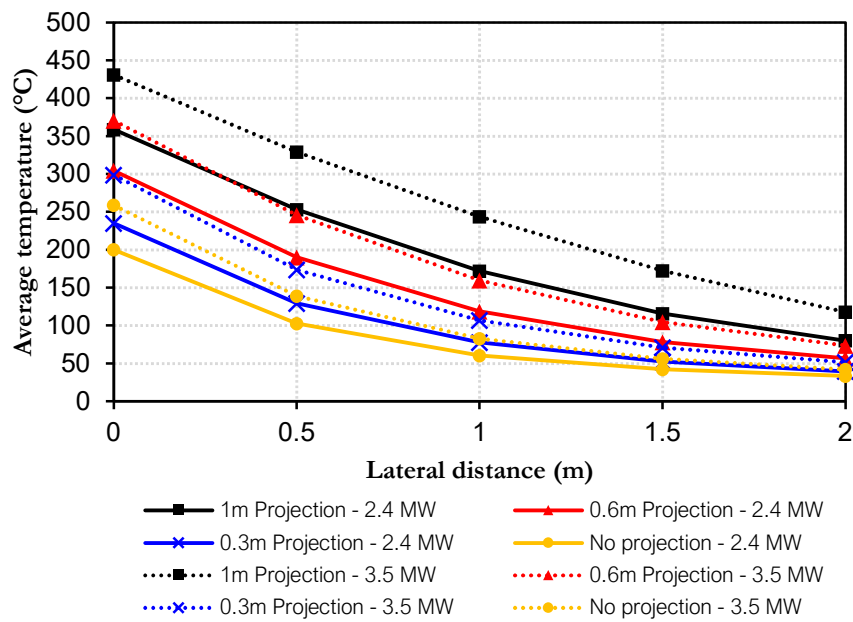


Figure 58 - Average lateral wall temperatures predictions at 1000 mm below horizontal projections for various projection depths under 2.4 MW and 3.5 MW.

6. Discussion

This study examined the impact of horizontal projection depth on the thermal exposure of building façades during fire scenarios using numerical simulations conducted in FDS version 6.9.1. The findings highlight that horizontal projections significantly alter fire dynamics on building exteriors, producing both beneficial and adverse effects depending on their depth.

Based on the model validated against SP Fire 105, the trends observed in this parametric study are considered reliable for comparative assessment.

The results show that deeper projections—specifically 60 cm and 100 cm—effectively reduce upward flame propagation and vertical thermal exposure in the investigated scenarios (HRR of 2.4 MW and 3.5 MW). These projections deflect the rising plume of hot gases away from the upper façade, thus reducing direct flame impingement. This was evidenced by substantial reductions in flame height, incident heat flux, and wall surface temperature above the projection. For instance, a 60 cm projection reduced heat flux above the projection by approximately 86% and surface temperatures by 67%, while a 100 cm projection yielded reductions of 94% and 84%, respectively compared to the free façade under 2.4 MW fire scenario. These outcomes support the role of horizontal projections as a passive fire protection feature, shielding upper façade regions from vertical fire spread within the limits of the specific plume and geometry conditions studied.

However, this beneficial effect is counterbalanced by a notable redistribution of thermal exposure laterally and downward. As projection depth increases, flames and hot gases are increasingly deflected beneath the projection, forming a zone of intensified thermal radiation. The study revealed that a 60 cm projection increased lateral incident heat flux beneath the projection by a factor of 4 and wall temperatures by 2.9 times compared to a free façade. The 100 cm projection intensified this effect even further, increasing heat flux by a factor of 7.6 and temperatures by 4 times. This suggests that deeper projections trap more heat beneath them, amplifying thermal exposure in the lower façade and adjacent horizontal areas. A comparative analysis using a higher design fire scenario (3.5 MW) further confirmed these trends, demonstrating that while deeper projections enhance vertical shielding, they simultaneously heighten the risk of lateral fire spread and localized heat accumulation below the projection. Together, these findings underscore the dual effect of horizontal projections: while they serve as effective passive fire protection for upper façades by limiting vertical flame spread, they also generate zones of elevated lateral and downward thermal exposure due to plume deflection and heat entrapment. This dual behaviour must be carefully considered in façade design, particularly in buildings with combustible claddings such as timber. In such cases, the intensified lateral heat flux may accelerate façade ignition, increase the heat release rate (HRR), and raise the risk of integrity failure of the external wall, especially near openings. Furthermore, elevated thermal exposure can contribute to the degradation and detachment of façade elements, posing additional safety risks due to falling construction parts. While the potential for lateral flame spread toward adjacent compartments exists, further investigation is needed to assess whether such flames can be self-sustained and propagate significant distances horizontally.

The observed reduction in thermal exposure due to horizontal projections aligns well with findings from previous studies. Oleszkiewicz [5] reported that a 60 cm deep projection reduced heat exposure above the projection by approximately 60%, while a 100 cm projection achieved an 85% reduction compared to the no-projection case. Similarly, Nilsson et al. [26], [27] found that a 60 cm projection significantly lowered both incident heat flux and wall temperatures in the region above the projection. However, it is worth noting that their study employed a façade setup identical to the current work (SP Fire 105 test), which may partly explain the alignment in outcomes. These findings support the results of the current study, where the 60 cm and 100 cm deep projections effectively reduced both heat flux and façade temperatures above the opening, reinforcing the projection's role in mitigating vertical thermal exposure.

In contrast, the increase in lateral heat flux observed beneath projections in this study is consistent with findings reported by McKeen and Liao [6]. Although their study did not explicitly specify the projection depths used, their numerical simulations revealed that horizontal projections deflect the fire plume radially, redistributing thermal energy laterally and thereby increasing the heat flux along adjacent façade sections. For example, in one of their simulations involving a 10.3 MW fire, the 20 kW/m² heat flux contour extended over 3.5 m laterally with a projection, compared to only approximately 0.7 m in the free façade scenario. This trend was similarly observed in the current study, particularly with deeper projections (60 cm and 100 cm) which resulted in significant increases in lateral thermal exposure.

This thesis contributes to existing knowledge by systematically comparing the effects of different projection depths on vertical and lateral thermal exposure. By quantifying how varying depths influence heat flux intensity and distribution, this work offers further insight into the dual role of horizontal projections as both vertical fire barriers and potential enhancers of lateral fire spread risk.

Based on the findings of this thesis, a 60 cm deep horizontal projection was found to be effective in reducing vertical heat flux and wall temperatures above the projection. Although this configuration increases lateral thermal exposure, the extent of this increase is notably less severe compared to the 100 cm projection. These results emphasize the dual role of horizontal projections: while they serve to shield upper façade regions from vertical flame impingement, they can also promote lateral heat transfer and flame spread.

It is important to acknowledge that these findings are derived from specific simulation scenarios with defined setup parameters and design fire conditions. In real-world applications, the dual effect of projections must be considered within the broader context of building design and fire safety strategy. An appropriate façade configuration should be informed by a design fire scenario that reflects realistic fire loads and burning behaviour associated with the building's intended use. In residential buildings, for example, design fires should consider typical fuel loads, compartment geometry, and fire growth rates to accurately assess the effectiveness of projections.

The use of CFD modelling is a valuable tool in façade fire safety assessments, as it enables the prediction of flame behaviour and thermal exposure under varying projection depths and fire conditions. However, it is important to recognise the limitations of such simulations. CFD results rely heavily on assumptions related to fire growth, boundary conditions, and material properties, and may not fully capture complex fire dynamics—particularly near the fire source or in regions such as the lower façade, where deviations from experimental data are often observed [60].

The accuracy of CFD predictions is also sensitive to uncertainties in input data, which may arise from natural variability in material properties and environmental conditions. Additionally, simulation time constraints limit the number of scenarios that can be practically explored, making comprehensive uncertainty analyses challenging to perform. Radiation heat transfer remains another computationally demanding aspect of fire simulations, with radiation calculations accounting for approximately 20% of total CPU time [60], even when using modern modelling techniques.

Another significant source of uncertainty, as observed during the validation of the SP Fire 105 test presented in **Section 5.1**, is wind. Wind effects were included only for the validation case and removed in the comparative analysis. In [60], wind led to deviations in predicted temperatures both in front of the fire source and on the façade. In real experimental settings, wind behaviour is inherently more complex and difficult to replicate accurately in simulations. These limitations highlight the importance of using CFD in conjunction with experimental testing and engineering judgement, rather than relying on CFD as a standalone solution. A combined approach ensures a more robust and reliable assessment of façade fire performance.

To mitigate the lateral fire hazard introduced by projections—especially in buildings with adjacent openings or combustible cladding—additional fire protection measures may be necessary. One such solution could be the incorporation of vertical fire-resistant barriers between compartments, limiting lateral heat transfer and flame spread. This is particularly critical when façade openings such as closely spaced windows, open windows, or ventilation openings are present, as they can allow flames and hot gas to enter adjacent compartments and increase the risk to occupant safety.

In cases where combustible cladding materials, such as timber, are used, the inclusion of fire retardants or the strategic use of non-combustible cladding beneath projections may be considered to reduce the likelihood of façade ignition. Combustible cladding can significantly increase the heat release rate (HRR), as surface ignition can occur rapidly under radiant heat fluxes from around 10-12 kW/m².

Current building codes primarily focus on limiting vertical fire spread by requiring the use of non-combustible or limited-combustibility materials, based on standard fire tests. While deeper architectural projections may be used to reduce vertical flame spread, their impact on lateral fire exposure is often overlooked. This thesis highlights the importance for fire safety engineers to consider the potential for increased lateral thermal hazard, especially when evaluating alternative designs or deviations from prescriptive requirements. A more comprehensive engineering approach that accounts for both vertical and lateral fire dynamics is crucial for robust façade fire safety.

7. Conclusion

This thesis aimed to explore the impact of horizontal projections on the thermal exposure of building façades, examining both vertical and lateral effects. To achieve this, the study compared different projection depths and evaluated how these elements influenced the heat exposure above and below the projections.

As part of the methodology, FDS version 6.9.1 was validated against the SP Fire 105 test. The simulations showed good agreement in predicting general fire behaviour, including temperature and heat flux trends, though FDS tended to overpredict temperatures directly in front of the combustion chamber while underpredicting those at the façade wall. On average, the predicted surface temperatures and plate thermometer temperatures deviate from the experimental data by 31.77% and 23.89%, respectively. This discrepancy is likely due to simplifications in the modelling of certain combustion dynamics or localized heat transfer phenomena not fully captured by the model. Despite these limitations, the model was considered reliable for the scope and objectives of this study.

The research was guided by the following questions:

- 1. How do different horizontal projection depths affect the heat flux and surface temperatures on building façades, both above and below the projection?**
- 2. To what extent can varying the projection depth help reduce vertical thermal exposure, and what implications might this have for the risk of lateral fire spread?**

In addressing the first question, the simulations revealed that increasing projection depth can effectively mitigate vertical flame spread by reducing incident heat flux and surface temperatures on the upper façade. However, deeper projections also led to increased lateral heat flux and temperatures beneath the projection, due to horizontal flame deflection and the accumulation of hot gases.

With regard to the second question, the findings suggest that while deeper projections, such as the 60 cm case, can significantly reduce vertical thermal exposure, they may simultaneously introduce lateral fire hazards. For instance, the 60 cm projection achieved a notable reduction in upward heat transfer with less lateral impact than the 100 cm projection.

However, no single "optimal" projection depth was identified. The effectiveness of horizontal projections is influenced by several factors, such as the projection geometry, the design fire scenario, the cladding material used, the spacing of façade openings, and the applicable fire performance criteria. In summary, deeper projections reduced vertical exposure but increased lateral risk, highlighting the need for a balanced design approach.

The findings presented in this study are based on a specific, simplified geometry: a setup with fixed opening dimensions and a non-combustible, open-ended projection with a uniform thickness. While this configuration facilitated controlled comparisons, it does not capture the full complexity of real-world building façades. To gain a more comprehensive understanding, further studies should consider:

- Alternative projection geometries, such as balconies with solid wall balustrades, as well as scenarios involving multiple projections.
- Variations in window and door dimensions, which may influence thermal behaviour and interaction with projections.
- The impact of façade cladding and typologies, particularly combustible materials, and ventilated façade systems.
- Incorporating experimental validation using reduced-scale or full-scale façade test rigs to compare results with numerical data.

This study excluded wind effects to isolate the impact of projection depth. However, in real-world scenarios, wind can significantly influence fire dynamics, either hindering or accelerating flame spread depending on its direction and intensity [69], [70]. Future research should incorporate wind factors to provide a more comprehensive understanding of how projection geometry and environmental conditions interact during façade fires.

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Appendix

Appendix A: Validation of SP Fire 105 FDS input file

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REMOVABLE=F /
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&OBST ID='Floor', XB=-1.9,-0.3,0.4,3.6,-0.9,-0.8, SURF_ID='concretewall'/
&OBST ID='Obstruction', XB=-0.3,-0.2,0.5,3.5,0.52,0.62125, SURF_ID='concretewall'/
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Appendix B: Mesh Resolution Sensitivity for Validation of the Numerical Model – SP Fire 105

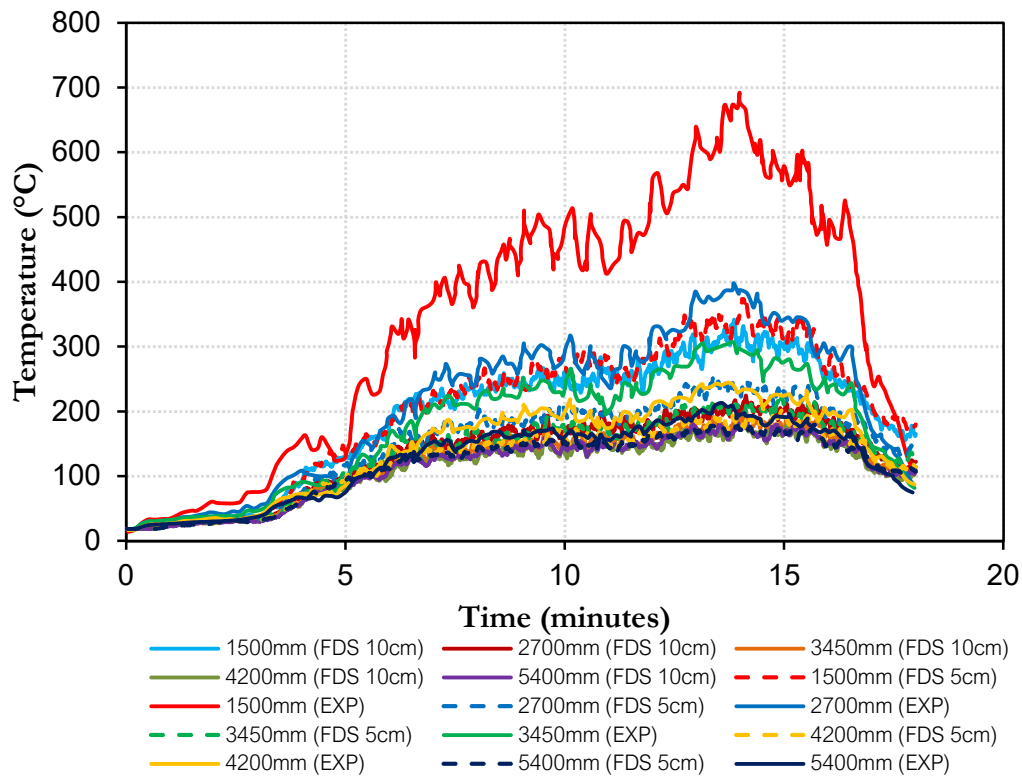


Figure 59 - Comparison of experimental and simulated gas temperatures 100 mm from the façade at various heights with varying mesh resolutions (5 cm and 10 cm).

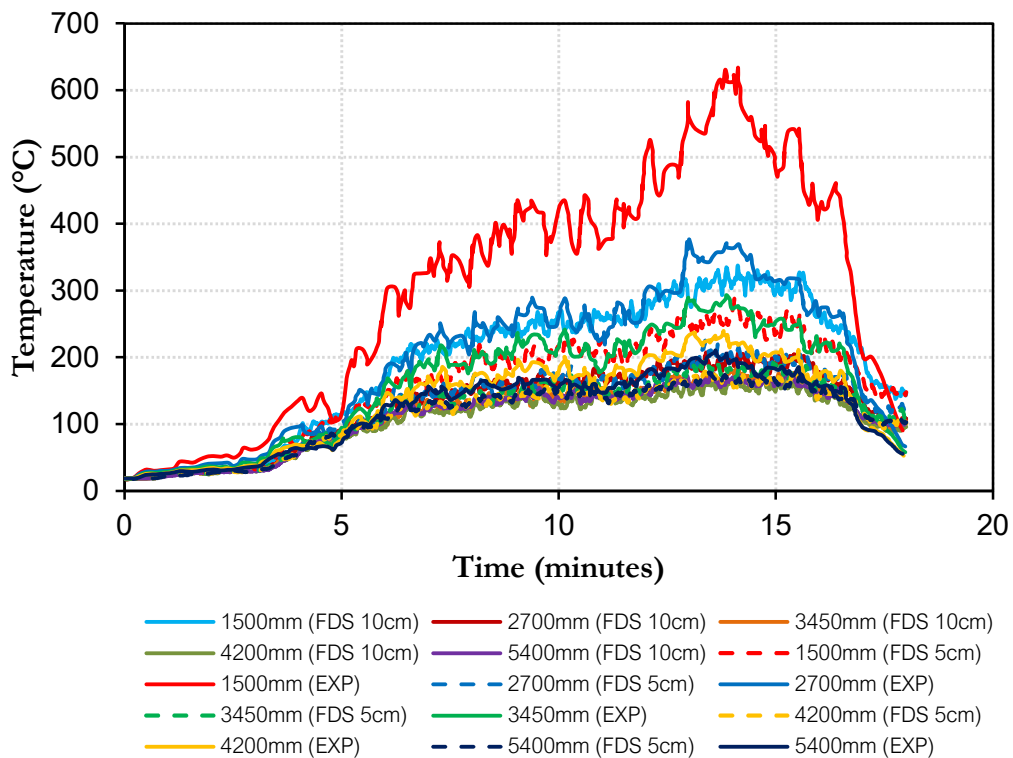


Figure 60 - Comparison of experimental and simulated gas temperatures 200mm from the façade at various heights with varying mesh resolutions (5 cm and 10 cm).

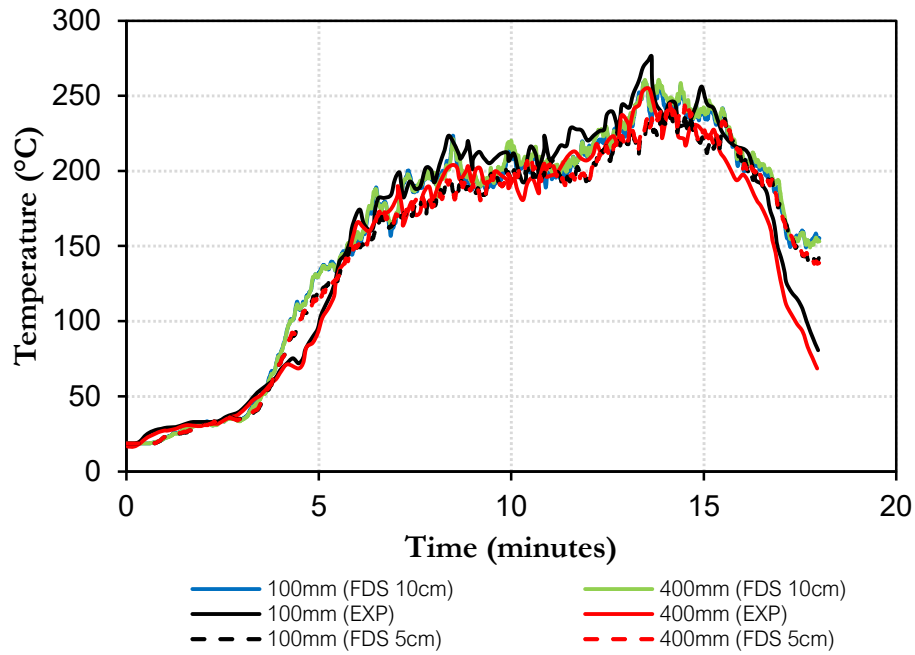


Figure 61 - Comparison of experimental and simulated temperatures below the eave at 100 mm and 400mm from the façade with varying mesh resolutions (5 cm and 10 cm).

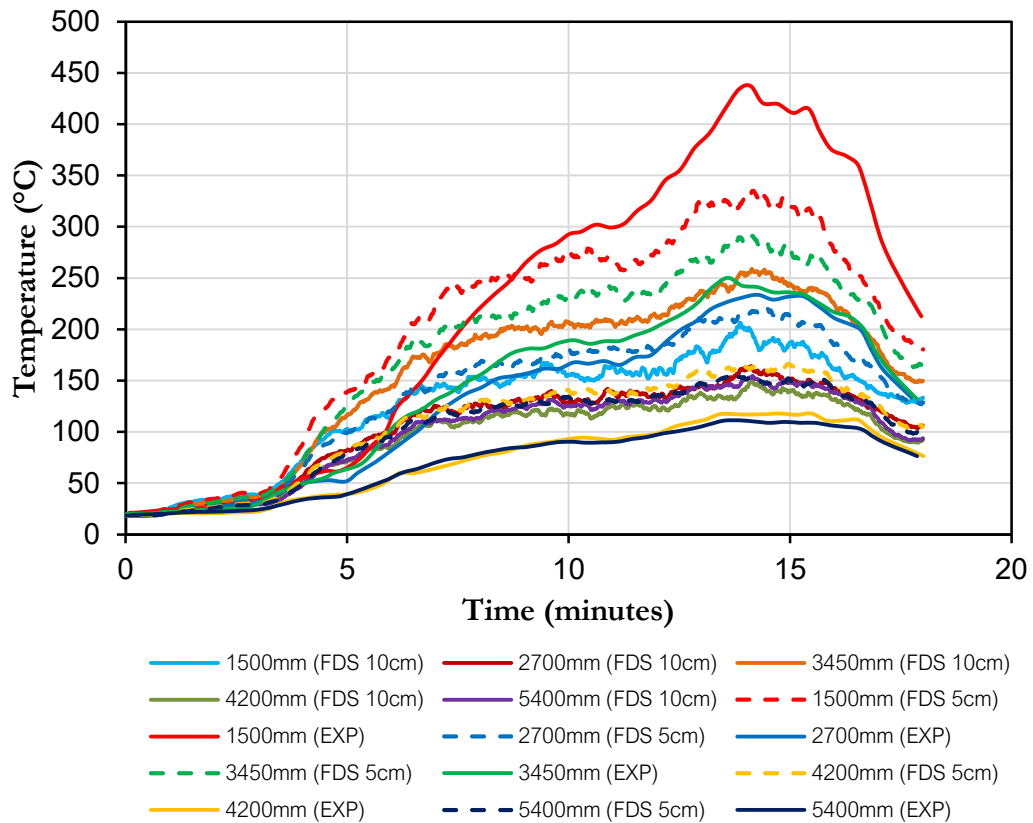


Figure 62 - Comparison of experimental and simulated surface temperatures at various heights with varying mesh resolutions (5 cm and 10 cm).

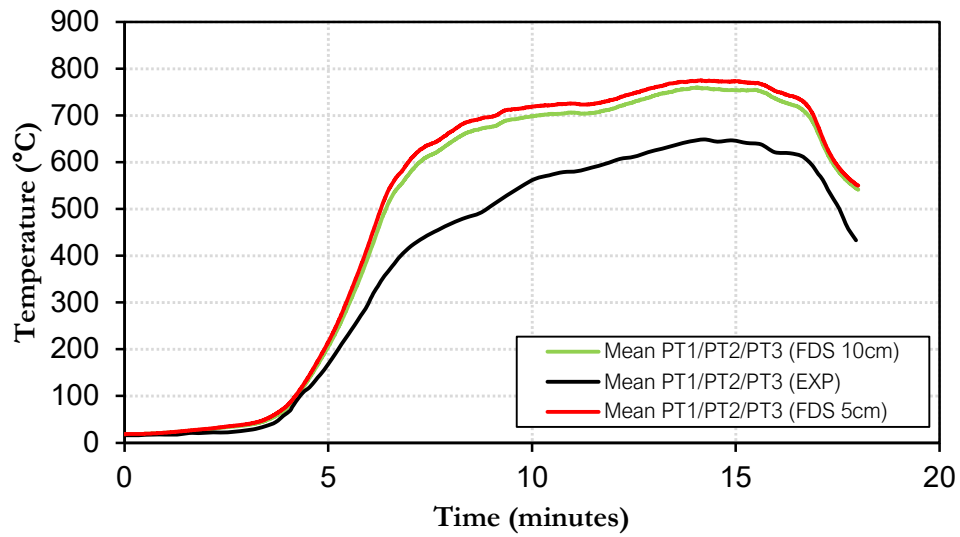


Figure 63 - Comparison of experimental and simulated temperatures of plate thermometers PT1, PT2 and PT3 with varying mesh resolutions (5 cm and 10 cm).

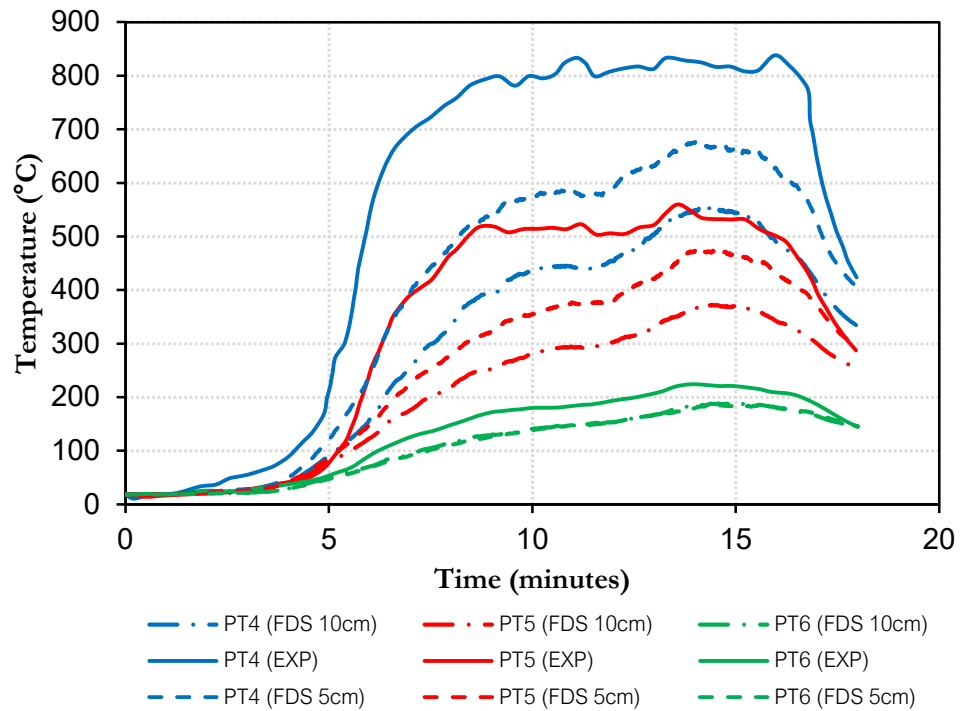


Figure 64 - Comparison of experimental and simulated temperatures of plate thermometers PT4, PT5 and PT6 with varying mesh resolutions (5 cm and 10 cm).

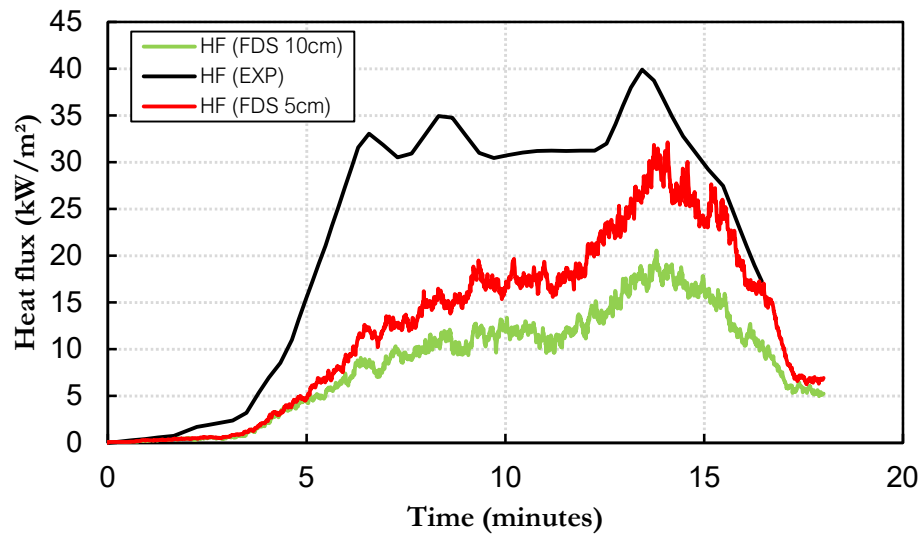


Figure 65 - Comparison of experimental and simulated heat flux at 2.1 m with varying mesh resolutions (5 cm and 10 cm).

Appendix C: FDS Input for Horizontal Projection (100 cm)

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      FUEL='N-HEPTANE',
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      SOOT_YIELD=0.037,
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    DENSITY=2300.0,
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    MATL_MASS_FRACTION(1,1)=1.0,
    THICKNESS(1)=0.1/
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```

```

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&BNDF QUANTITY='NET HEAT FLUX'/
&BNDF QUANTITY='RADIATIVE HEAT FLUX'/
&BNDF QUANTITY='WALL TEMPERATURE'/

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&TAIL /

```

Appendix D: Python Code Used for Flame Shape Analysis

```
import cv2
import numpy as np
import matplotlib.pyplot as plt
video_path = 'flame_video.mp4'
wall_width_m = 7.0
min_area = 10
lower_pink = np.array([140, 50, 50])
upper_pink = np.array([170, 255, 255])
cap = cv2.VideoCapture(video_path)
if not cap.isOpened():
    print("Error: Could not open video.")
    exit()
ret, sample_frame = cap.read()
if not ret:
    print("Error: Could not read a frame.")
    cap.release()
    exit()
frame_height, frame_width = sample_frame.shape[:2]
scale_x = wall_width_m / frame_width
fps = 7.7
cap.set(cv2.CAP_PROP_POS_FRAMES, 0)
extensions = []
while True:
    ret, frame = cap.read()
    if not ret:
        break
    hsv = cv2.cvtColor(frame, cv2.COLOR_BGR2HSV)
    mask = cv2.inRange(hsv, lower_pink, upper_pink)
    mask = cv2.medianBlur(mask, 5)
    contours, _ = cv2.findContours(mask, cv2.RETR_EXTERNAL, cv2.CHAIN_APPROX_SIMPLE)
    flame_contours = [cnt for cnt in contours if cv2.contourArea(cnt) > min_area]
    xs = [pt[0][0] for cnt in flame_contours for pt in cnt]
    if xs:
        min_x, max_x = min(xs), max(xs)
        flame_width_px = max_x - min_x
        flame_width_m = flame_width_px * scale_x
        extensions.append(flame_width_m)
cap.release()
if extensions:
    mean_ext = np.mean(extensions)
    start_time = 50
    times = np.arange(len(extensions)) / fps + start_time
    print(f"Mean Flame Extension: {mean_ext:.2f} meters")
    plt.figure(figsize=(10, 5))
    plt.plot(times, extensions, 'k--', linewidth=1, label='Transient flame
extension')
    plt.plot(times, extensions, 'ko', markersize=4)
    plt.axhline(mean_ext, color='red', linestyle='-', linewidth=2, label=f'Mean =
{mean_ext:.2f} m')
    plt.xlabel('Time $t$ (s)', fontsize=14)
    plt.ylabel('Flame extension $f_e$ (m)', fontsize=14)
    plt.title('Flame Extension Over Time', fontsize=16)
    plt.grid(True, linestyle='--', alpha=0.4)
    plt.legend()
    plt.tight_layout()
    plt.show()
else:
    print("No flame detected in any frame.")
```

Appendix E: Flame Shape Analysis (Python Results)

Flame Height:

- Temperature Isosurface of 550 °C

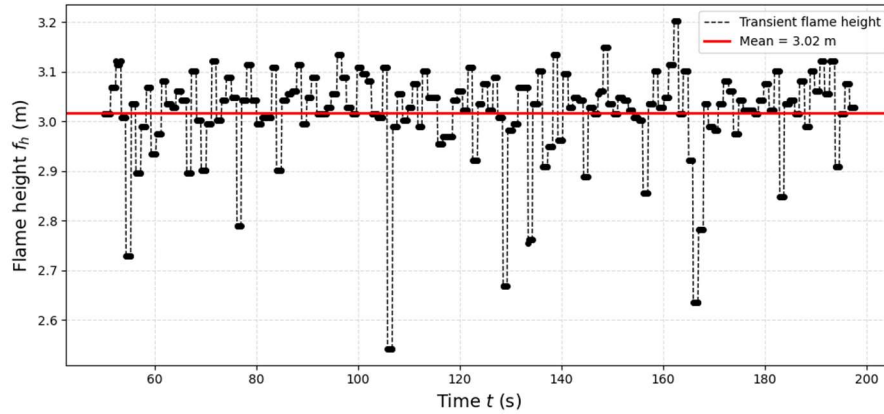


Figure 66 - Flame height over time and average flame height for free façade (no projection) using temperature isosurface of 550 °C under 2.4 MW fire scenario.

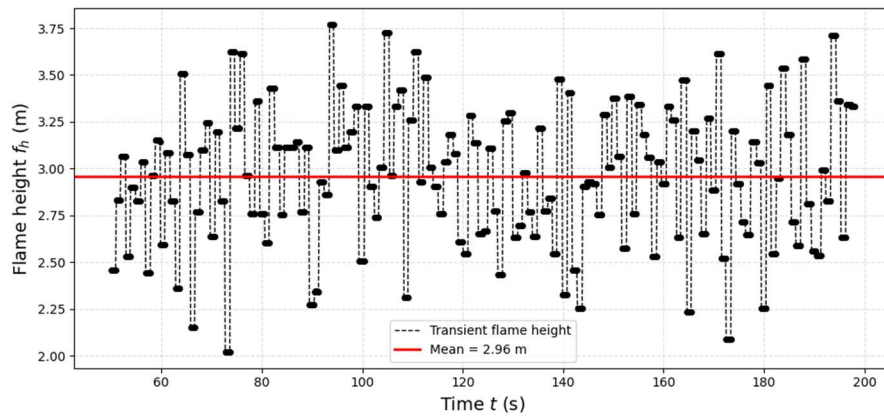


Figure 67 - Flame height over time and average flame height for facade with 30 cm horizontal projection using temperature isosurface of 550 °C under 2.4 MW fire scenario.

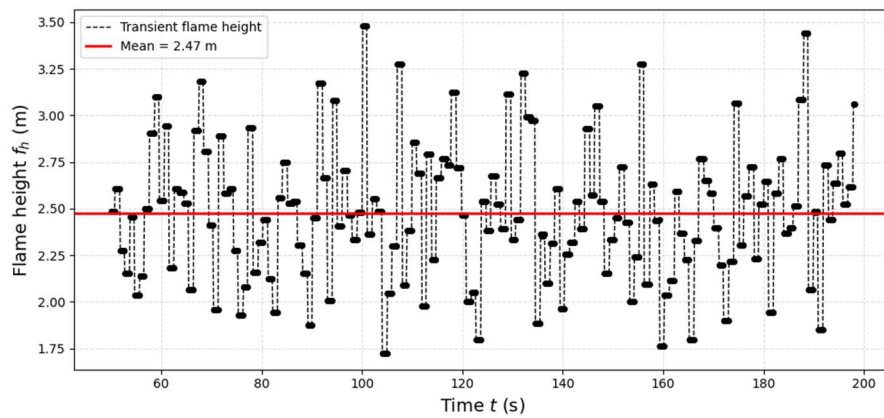


Figure 68 - Flame height over time and average flame height for facade with 60 cm horizontal projection using temperature isosurface of 550 °C under 2.4 MW fire scenario.

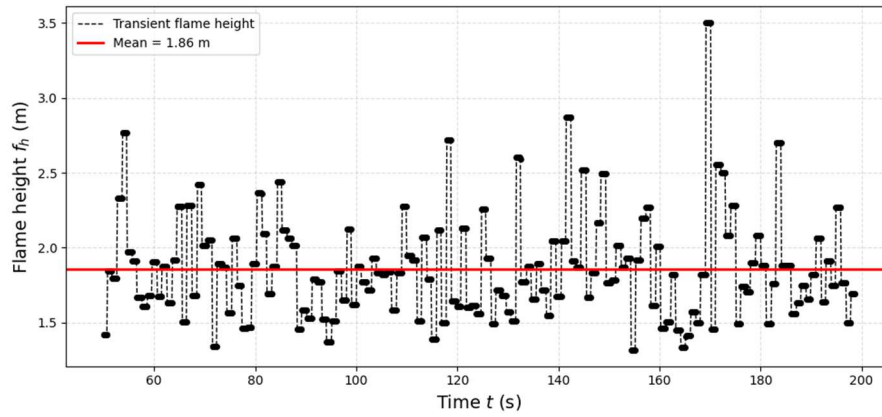


Figure 69 - Flame height over time and average flame height for facade with 100 cm horizontal projection using temperature isosurface of 550 °C under 2.4 MW fire scenario.

- HRRPUV Isosurface of 500 kW/m³

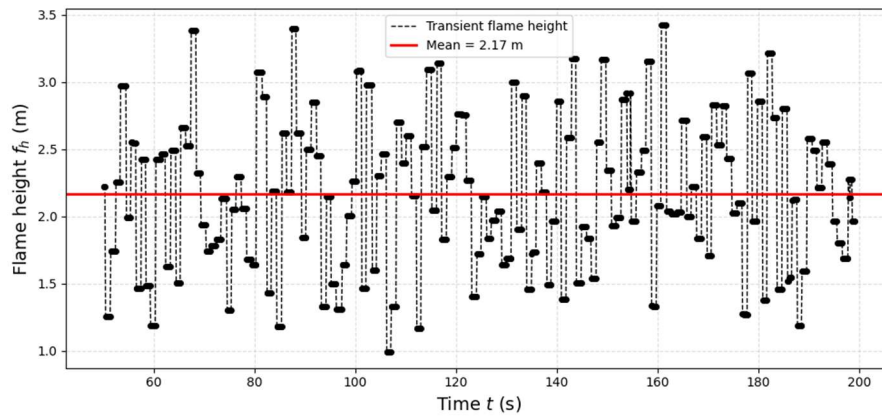


Figure 70 - Flame height over time and average flame height for free façade (no projection) using HRRPUV isosurface of 500 kW/m³ under 2.4 MW fire scenario.

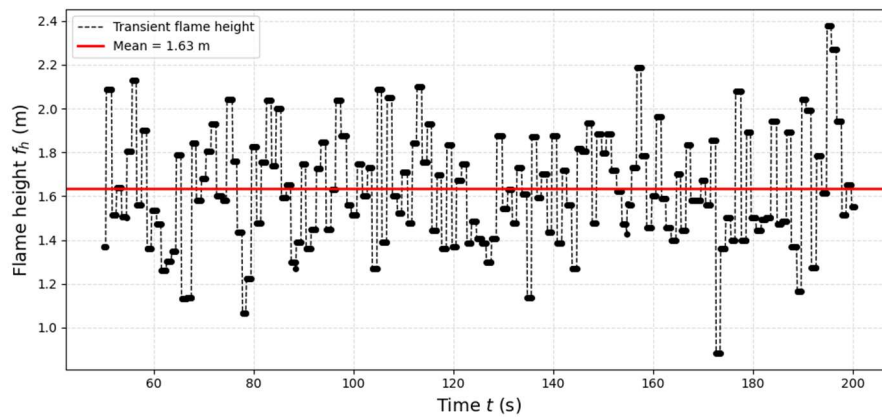


Figure 71 - Flame height over time and average flame height for facade with 30 cm horizontal projection using HRRPUV isosurface of 500 kW/m³ under 2.4 MW fire scenario.

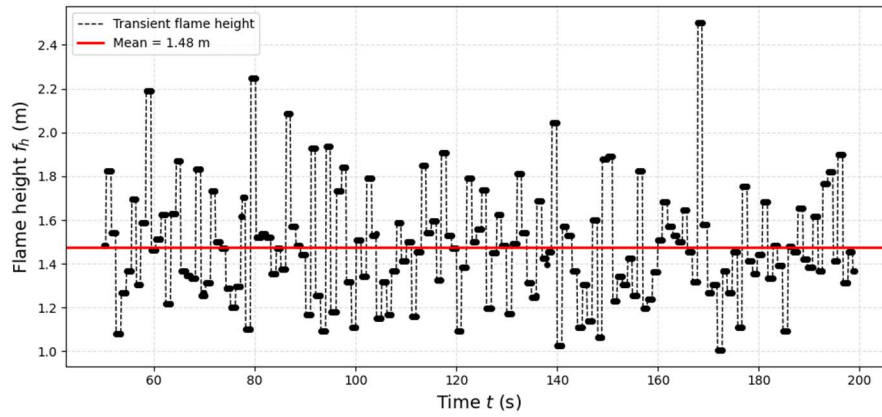


Figure 72 - Flame height over time and average flame height for facade with 60 cm horizontal projection using HRRPUV isosurface of 500 kW/m^3 under 2.4 MW fire scenario.

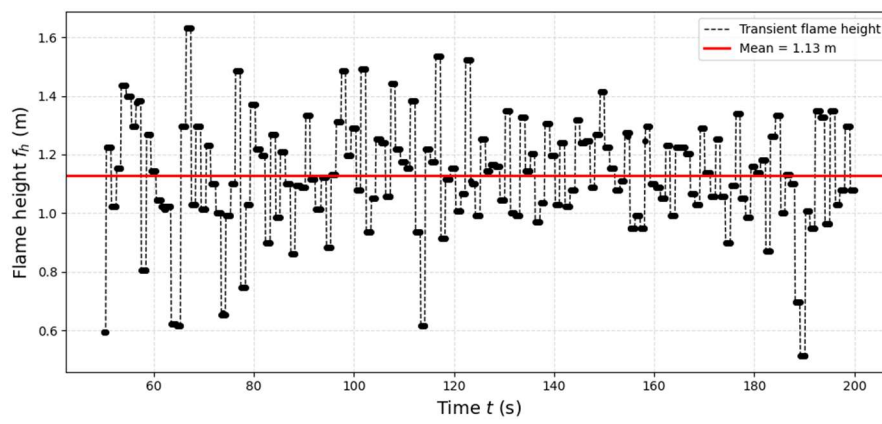


Figure 73 - Flame height over time and average flame height for facade with 100 cm horizontal projection using HRRPUV isosurface of 500 kW/m^3 under 2.4 MW fire scenario.

Flame Horizontal Extension:

▪ Temperature Isosurface of 550°C

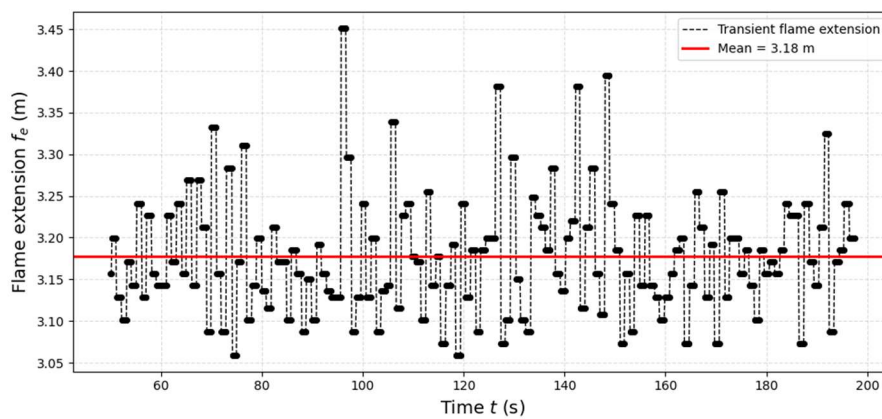


Figure 74 – Flame extension over time and average flame extension for free façade (no projection) using temperature isosurface of 550°C under 2.4 MW fire scenario.

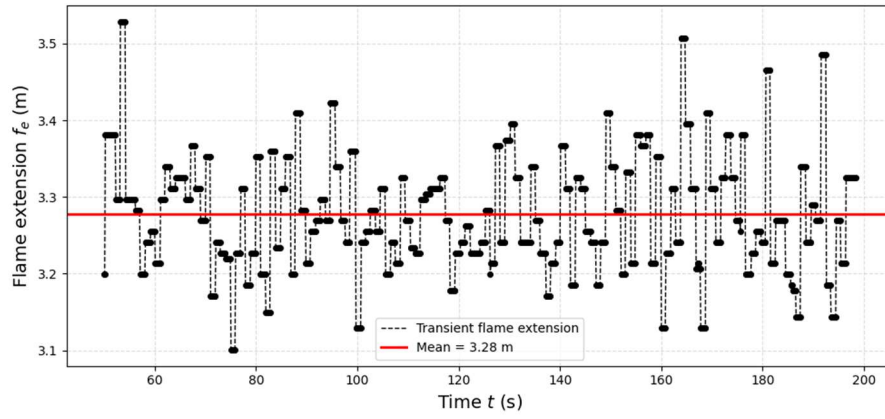


Figure 75 - Flame extension over time and average flame extension for facade with 30 cm horizontal projection using temperature isosurface of 550 °C under 2.4 MW fire scenario.

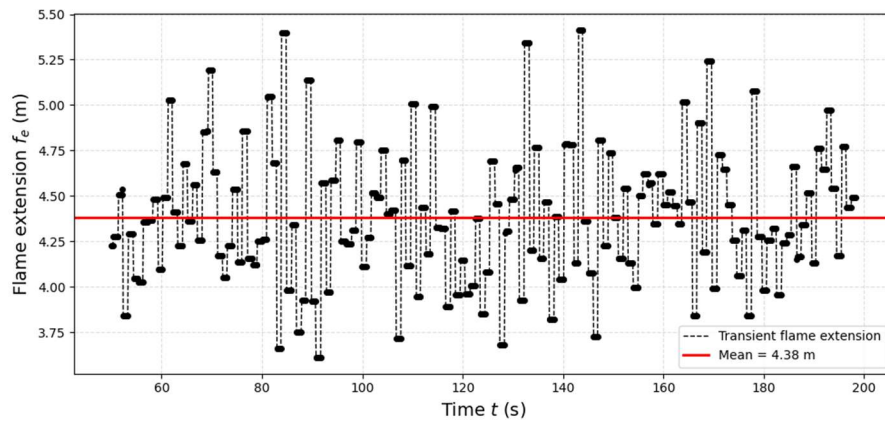


Figure 76 - Flame extension over time and average flame extension for facade with 60 cm horizontal projection using temperature isosurface of 550 °C under 2.4 MW fire scenario.

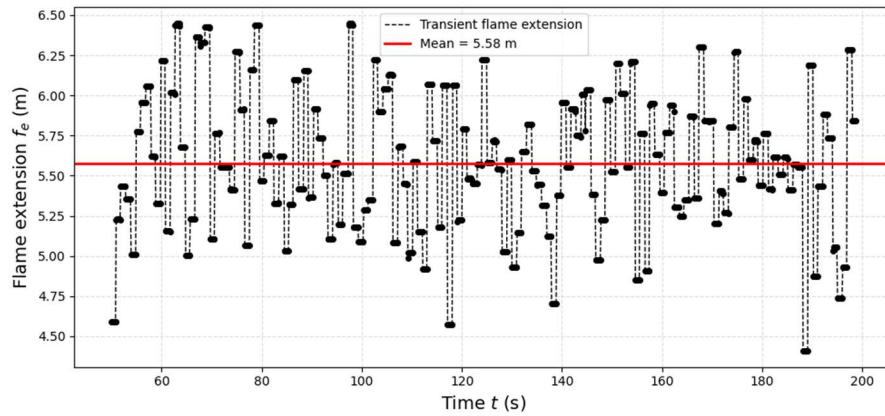


Figure 77 - Flame extension over time and average flame extension for facade with 100 cm horizontal projection using temperature isosurface of 550 °C under 2.4 MW fire scenario.

■ HRRPUV Isosurface of 500 kW/m³

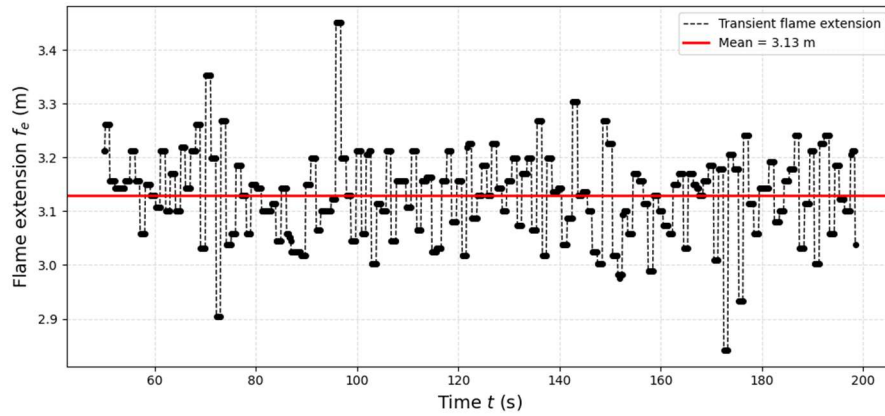


Figure 78 - Flame extension over time and average flame extension for free façade (no projection) using HRRPUV isosurface of 500 kW/m³ under 2.4 MW fire scenario.

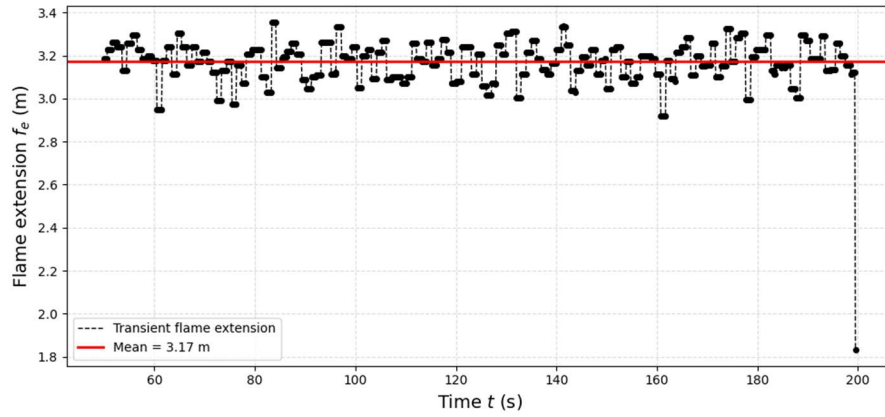


Figure 79 - Flame extension over time and average flame extension for facade with 30 cm horizontal projection using HRRPUV isosurface of 500 kW/m³ under 2.4 MW fire scenario.

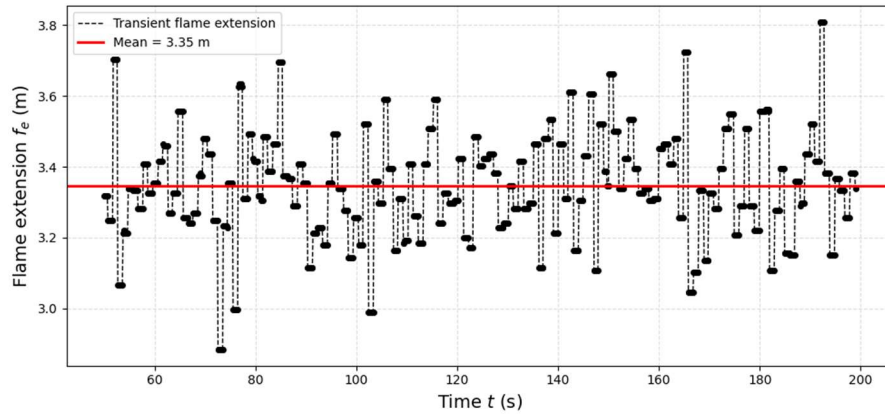


Figure 80 - Flame extension over time and average flame extension for facade with 60 cm horizontal projection using HRRPUV isosurface of 500 kW/m³ under 2.4 MW fire scenario.

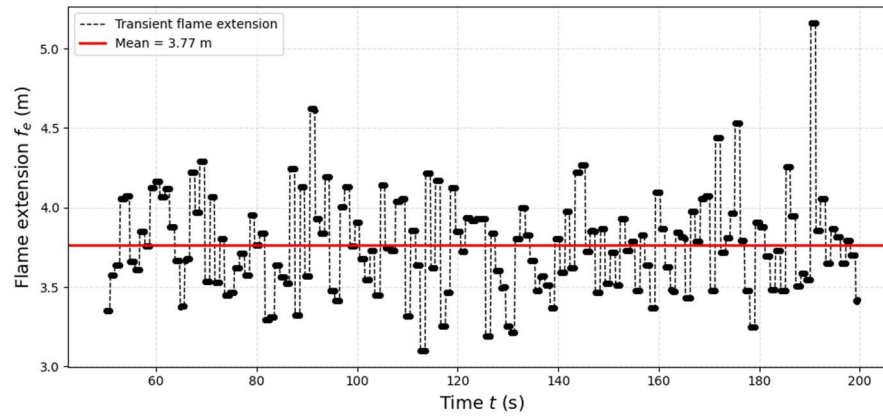


Figure 81 - Flame extension over time and average flame extension for facade with 100 cm horizontal projection using HRRPUV isosurface of 500 kW/m^3 under 2.4 MW fire scenario.