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Fire Safety of Facades

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Abstract

Fire Safety of Façades

Façade fires do not occur often (in comparison to other major structure fires) but in recent years there have been a number of spectacular façade fires in high rise building such as the recent fire in Grenfell Tower, London.

Under-ventilated compartment fires may cause flames to spill out of window openings impinging the façade, thus devastating façade fires may start on one floor leap-frogging to adjacent floors. It is therefore necessary to limit or delay fire spread to higher floors. Requirements built on large scale fire testing may decrease the risk of these types of fires provided that the building is constructed according to the specifications provided by the manufacturer. Different countries have different regulations and tests for façades. New materials and façade systems are continuously introduced which might call for an update of these tests and regulations.

This report summarizes experimental and modelling efforts in characterizing the fire safety of façades using the Swedish SP Fire 105 and the British BS 8414 methods. Recent experimental results and modelling is presented exploring the variations in the fire exposure, fire load and the fuel used. The fire source and the heat exposure to the façade are characterized by additional temperatures measured by plate thermometers while some other aspects are only treated in the numerical study such as a change in fuel. It is found that the results from the BS 8414 are largely affected by wind and climate since the experimental test was performed outdoors, moreover fire spread on wooden façades is also briefly discussed.

In order to obtain a deeper understanding of the test methods and the results CFD (Computational Fluid Dynamics) Modelling in FDS was used. The models were based on measured input parameters including uncertainties and an assessment of the impact of said uncertainties. The models could often reproduce the experimentally found temperatures qualitatively and quantitatively. A detailed discussion on the regulations and the tests that lead to the SP Fire 105 test method is also presented. Summaries of the façade testing methods and conditions in other European countries are presented in the appendices.

Finally possible ways forward in updating the façade testing and regulations are discussed.

Key words: Façade, Fire, SP Fire 105, BS 8414, ISO 13785, FDS

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Preface

The Authors are grateful for the financial support from Swedish Fire Research Board (BRANDFORSK) which made this work possible. We have also benefitted from scientific input from an advisory group consisting of people with different background:

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1 Introduction

Façade fires do not occur often (in comparison to other major structure fires) but relatively recently a number of fairly high profile façade fires has occurred around the world that have had major consequences such as the fires in the United Arab Emirates (UAE) and Australia [1-4], China [3] and France [3]. These fires spread rapidly from floor to floor and there is a large risk that the whole building is engulfed in fire as became obvious in the very recent tragic fire in the Greenfell Tower in London in which several people died [5]. This shows the importance to limit or delay fire spread to higher floors.

This type of fires, i.e. fire spreading from floor to floor via external walls, is scarce (only 1.3 – 3 % of the total number of structure fires [1]) and is even scarcer in countries applying large-scale test methods for classification of the burning behaviour of façades. Requirements built on large scale fire testing may decrease the risk of these types of fires together with quality systems to ensure that the buildings are constructed according to the tested construction. However, the recent fires and the continuous introduction of new materials and façade systems might call for an update of these tests and regulations.

Different countries have different regulations and tests for façades and there is a large number of different tests used for verification and classification of façade systems, ranging from small scale tests to full scale tests [1]. A list of the different methods used in Europe is provided in Table 1 whereas a more complete description is provided in Appendix A and B. Since each country has their own building regulation there is a large spread in the requirements [1]. The differences in classification and test methods can also be a barrier to trade between countries.

Table 1 Test methods for façades in Europe [1, 6 - 7].

Test method	Scale	Countries using the test method
1. PN-B-02867:2013	Medium	Poland
BS 8414-1:2015 and BS 8414-2:2015	Full	UK, Republic of Ireland
DIN 4102-20	Medium	Switzerland, Germany
ÖNorm B 3800-5	Full	Switzerland, Austria
Prüfbestimmung für Aus-senwandbekleidungssysteme	Full	Switzerland
Technical regulation A 2.2.1.5	Full	Germany
Lepir 2	Full	France
MSZ 14800-6:2009	Full	Hungary
SP Fire 105	Full	Sweden, Norway, Denmark
Engineering guidance 16	Full	Finland
ISO 13785-2	Full	Slovakia

A major challenge is to find a way forward to a harmonized European methodology for testing and classification of façade systems. Testing and classification of the characteristics of construction products are under way to be harmonized within EU, including how properties are to be declared by the CE marking system. However, since CPR is mainly for single products it does not cover all fire safety aspects of façade systems as the whole façade system needs to be tested in order to classify the fire behaviour in a relevant way.

A harmonized test method needs to be able to assess all modes of vertical fire spread involving the façade. It is thus pertinent to discuss the mechanisms of vertical fire spread in actual fires in multi-storey buildings. There are a few frequently occurring modes of spreading (see also White and Delichatsios [1]):

- Flames from a broken window causing a window of the floor above to break allowing for spreading the fire;
- Inadequate fire stop in the gap between floor slab and exterior wall allowing for flames and hot gases into the next compartment;
- Deflection or distortion of metallic façade materials, e.g. aluminium, leading to deterioration of the fire safety allowing for fire spread inside the façade;
- Inadequate fire stopping around service penetrations, windows etc.

In Sweden a large scale method called SP Fire 105 is used to evaluate the façade system's fire behaviour [8-9] whereas other similar methods are used elsewhere such as Great Britain (BS 8414) [10] and the ISO 13785 [11] standard for assessment of façade systems.

This report discusses the Swedish assessment method in comparison to the British method and the ISO method. Moreover, the report presents results from experimental work conducted in Zagreb according to the BS 8414 standard and additional measurements performed during standardized testing at RISE in Sweden. The experimental work is accompanied with simulations to further asses the different test methods in order to understand them better and discuss the arguments for and against the methods where the experimental results are used as validation of the numerical models. The numerical models have then been used to assess small changes in the systems such as comparisons between thin and thick façade specimens, different soot different fuels etc. The focus of the work is the Swedish regulation and test method and possible improvements of this, but with an outlook to Europe and the rest of the world as harmonized test methods is underway in Europe.

2 The Swedish test method

The experimental setup described in the SP Fire 105 [6] is intended for determining the fire behaviour of external wall assemblies and façade claddings exposed to heat and flames from an apartment fire. The method has been presented internationally for different standardization committees [12-13].

The SP Fire 105 method evaluates a large scale façade fire where the test object is 4 x 6 m (width x height) and should resemble the real façade system as much as possible. The test set-up is provided in Figure 1. The fire exposure lasts around 15 – 20 minutes. The fire source is 60 litres of heptane burning in trays with attached flame suppressors. The purpose of the tests is to determine if the façade system itself contributes too much to the fire, e.g. not allowing it to spread above the second floor. The performance criteria of the façade system are maximum temperatures of the combustion gases at the eave and maximum heat flux to the specimen in the middle of the first fictitious window. No flame-spread above the second floor is allowed. Fire spread is assessed during and after the test and may not spread more than a given distance on either the inside or outside of the façade from the ignition source, the maximum spread is set to be below the second fictitious window as shown in Figure 1. After fire exposure the construction is cut into pieces to assess the internal fire spread in the core. During testing, falling down of parts and the occurrence of burning droplets is recorded and assessed.

An early Swedish test approach was developed in 1958 where a small scale laboratory method was shown to give approximately the same results as a large scale reference test setup [14 - 16]. The small scale method was in this case a one meter wide and a four and a half meter high test rig with a fire source of 20 kg burning wood. The validity of this old method was put into question in the eighties when the intensities of fires in more modern rooms were assessed to be larger relative to what was stated in the previous lab scale method. Further, the importance of including radiation from thicker flames with higher soot content present outside the fire room on the surface of the façade system was emphasized [15]. Therefore a larger study which included burning of 14 façades with a fully developed fire in a room as a heat source [15], was used to calibrate a façade test set-up mimicking the fire exposure from the large scale tests with a real room fire.

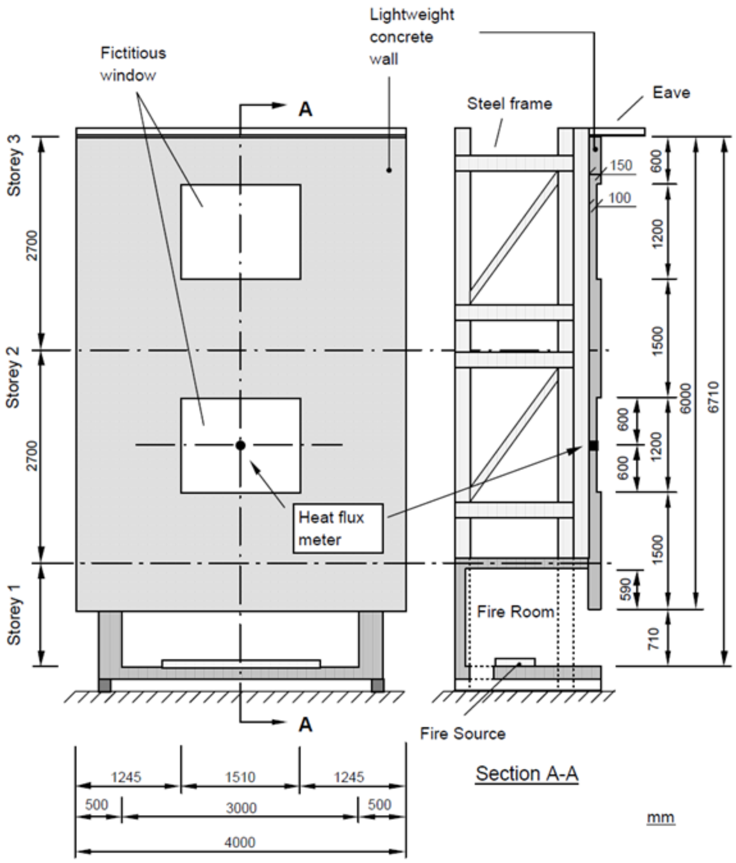


Figure 1. SP Fire 105 test rig.

Additional work and development were performed by Hermodsson and Månsson[12] which lead to the SP Fire 105 method. Fire hazards that were taken into account in [12] included:

- The surface spread of fire with combustion of the façade material;
- Fire spread within the façade system, here effects such as spread within air cavities or that of burning of insulation material withing the construction were considered;
- Spread through leap-frogging between vertically aligned windows;
- Diffusion of molten materials as a result of melting of the internal insulation.

The fire load density was 110 MJ/m^2 of total surface area of the enclosure. The enclosure dimensions were 4 x 2.2 x 2.6 m^3 (comparable to the dimensions in Figure 1) with the opening factor 0.06 m$^{1/2}$. During the tests approximately 50% of the fuel was burning outside the chamber. This excess fuel factor is dependent on the geometry of the enclosure as well as on fuel parameters such as composition and geometry. This testing procedure exposed the façade to a heat flux of approximately 140kW/m^2 at the first floor above the fire room and approximately 75 kW/m^2 at the second floor, as measured by a Schmidt-Boelter gauge. This fire load could be simulated using a trough with 60l of heptane as fuel.

To further investigate the variation stemming from different materials in the façade specimens a second series of tests were performed [15]. In this series of test three main types were tested; mineral wool insulation with wood studs and steel or aluminum sheet cladding;

mineral wool insulation with a thick layer of plaster and cellular plastic insulation with a thin layer of plaster.

In the large reference tests the façades were classified using the following three criteria:

- No collapse of major sections of the external insulation system;
- The surface spread of flame and the fire spread within the insulation should be limited below the window on the third floor. Fire spread that allows for igniting eaves are not permissible;
- No fire spread through windows on the second floor. This was determined by the heat flow towards the centre of the window to be less than 80 kW/m^2.

The result from the fourteen tests were that the construction of the façade system was more important than the reaction-to-fire properties of the individual materials [15] and thus a large-scale method for assessment of fire performance of relevant façade systems was needed. Note also that the SP Fire 105 method is very likely to produce conservative testing results due to the geometry of the opening of the fire compartment, with a short and wide opening. This type of opening configuaration is more likely to yield flames and a plume that is close to the façade, presumably causing a more severe heat load to the wall. The sample is intended to represent a fire scenario corresponding to an apartment fire with a broken window resulting in large flames that strikes out impinging on the façade.

The SP Fire method may also to some extent represent a burning trash container standing along a façade, although the placement of the fire source would change the flow dynamics and the heat transfer to the façade since the fire source is designed to have approximately 50 % of the fuel combusting outside of the fire room.

3 Swedish building regulations

In the Swedish building regulations (BBR [9]) requirements is found for external walls and façades. Regarding exterior walls, BBR specifies "Façade linings must only develop heat and smoke to a limited extent in case of fire." which means that it must provide satisfactory time for evacuation and firefighting.

All buildings are divided into different building classes, which mean that the requirements vary depending on the type of building and its use. The classes are:

- Br0: Buildings with more than 16 storeys, larger buildings including hospitals and prisons.
- Br1:The class includes buildings of more than two storeys, buildings with two storeys but intended for temporary accommodation and buildings used for sick and disabled or has meeting hall on the second floor.
- Br2: Includes buildings with two storeys with more than two apartments, or has a meeting hall on the ground floor or a building where one floor is a care facility.
- Br3: All other buildings.

For smaller buildings, and buildings with occupation providing for easier escape, it is indicated that the material used should meet the requirements of reaction-to-fire class D-s2, d2 (normal combustible material with limited smoke production however there is no restriction on burning droplets), which means that certain types of combustible insulation is acceptable (Typically of class Br2 or Br 3.). For larger buildings, with more complex business, the requirements are higher and more specific. The requirement for exterior walls in buildings of class Br1 is as follows:

1. The separation function is maintained between fire compartments
2. The spread of fire inside the wall is limited
3. The risk of fire spread along the façade surface is limited
4. The risk of injury due to parts falling from the exterior wall is limited

According to the BBR the provision above can be met under certain conditions, for point 2 the exterior walls containing only material of at least reaction-to-fire class A2-s1,d0 (A non-combustible material with no or hardly any smoke production or droplets.) or separated in such a way that a fire inside the wall is prevented from spreading past the separating structure. Furthermore, exterior walls designed in at least reaction-to-fire class A2-s1,d0 meet the provision's requirements in point 3.

One important aspect is falling parts; the exterior walls should be designed so that the requirement in point 4 is met to ensure the risk of falling structural elements, such as broken glass, small bits of plaster and the like, is limited. This is also relevant for a number of countries within EU, see Appendix B.

An alternative to meet point 2, 3 and 4 of the provision for a building up to eight storeys, is to test the façade system according to SP Fire 105 [8] where the following conditions are to be met [8];

a) no major parts of the façade fall down, for example, large pieces of plaster, panels or glass panes, which could cause danger to people evacuating or to rescue personnel,
b) fire spread on the surface finish and inside the wall is limited to the bottom edge of the window two floors above the fire room, and
c) no exterior flames occur which could ignite the eaves located above the window two floors above the fire room. As an equivalent criterion, the gas temperature just below the eaves must not exceed 500 °C for a continuous period longer than 2 minutes or 450 °C for longer than 10 minutes.

For exterior walls in buildings with more than eight storeys, in addition to criteria a–c in the test, the exterior wall must not increase the risk of fire spreading to another fire compartment in a floor above the fire room. As an equivalent criterion when testing according to SP FIRE 105, the total heat flow into the façade in the centre of the window in the storey above the fire room must not exceed 80 kW/m^2 [9], which was defined in Ondrus et. al. [15].

One may ask whether these requirements are reasonable, and how to verify that the requirements are met. The general advice in BBR is in some respects precise while some of them are ambiguous and can be interpreted in different ways. According to the general recommendation it is stated that the façade system meets the requirement if the exterior wall maintain its compartmentation ability. It is not clear what level of separating ability is reasonable, according to point 1 above. One interpretation could be that it should be the same level as the floor structure, i.e. EI 60 (It should hold the fire resistance functions, integrity and isolation when exposed to the normal testing curve in ISO 834). This would be the conservative interpretation since a 60 minute fire resistance test of the façade would be more severe than an SP Fire 105 test that lasts roughly 20 minutes and it can be questioned if this interpretation is reasonable. Windows are exempt from these requirements if the distance is at least 1.2 meters between the windows. However other details such as penetrations through the façade would in that case also have to satisfy these requirements.

The SP Fire 105 method can assess the extent of fire spread along the exterior of the façade surface and inside parts of the wall, and the extent of falling parts. The requirement accepts the spread of fire in the façade and on the façade surface up to two floors above the fire room to the level of lower edge of the window. This means that there may be a fire spread in the wall to a compartment for which there is a fire resistance requirement. Thus there is a risk that a fire subsequently spreads to an adjacent compartment.

Another uncertainty is the requirement point 4, “the risk of injury due to parts falling from the exterior wall is limited”. The general recommendation specifies that “Exterior walls should be designed so that the requirement in point 4 is met to ensure the risk of falling structural elements, such as broken glass, small bits of plaster and the like is limited.” The requirements, when tested according to the SP Fire 105 method, are that “no major parts of the façade fall down, for example, large pieces of plaster, panels or glass panes, which could cause danger to people evacuating or to rescue personnel”. What is now enforced, broken glass or large sheets of glass, small or large pieces of plaster? This naturally leads to that the interpretation of the recommendations can vary widely. As a remark, the test method is a national Swedish method, but the results can also be used in Denmark, Norway and to some extent in Finland to show that the design meets the requirements of the respective country's building regulations, although it is not presently a European standard. The Nordic countries have different limitations on the applicability of the method linked to the number of floors.

4 Experimental work

SP Fire 105 [8], BS 8414-1 [9] and ISO 13785-2 [10] are all based on the same principle of a flashover room fire where flames extend out of a broken window impinging on the façade above the window. All three methods are large scale test methods with approximately the same geometrical extensions however a return wall is missing in the SP Fire 105 method. Furthermore, the BS 8414-1 and ISO 13785-2 methods can be performed outdoors which is not allowed in the SP Fire 105 method. The fire source is different both in type of fuel and the total energy and heat release rate HRR, however all are in the same ballpark of simulating a typical room fire.

There are many factors that can influence the effective fire exposure in a test method, and in façade testing also the surrounding environment is sometimes of great importance. Experimental results show that the effective fire exposure to the façade may vary in the SP Fire 105, BS 8141-1 and ISO 13785-2 test methods depending on environmental and geometrical factors. All three methods define an amount of fuel to be used, e.g. in BS 8141-1 and ISO 13785-2 a volume of wood and in SP Fire 105 a volume of heptane and in addition all three define the geometry of the combustion chamber. It is thus not possible to actively control (regulate) the heat exposure to the façade surface during a test, and it may differ from test to test due to factors such as air movements around the combustion chamber and geometry of the test specimens, see Ref. [17 - 18]. In ISO 13785-2 it is specified that the ventilation conditions can be changed during the calibration test, however during testing this should be fixed and not altered. In the SP Fire 105 method, the influence from geometry of the test specimen is important if the boundary of the defined fire room is set as the lower front edge of the façade system since this can vary with e.g. the thickness of the façade specimen. In case of a boundary along the inner edge of the façade system the thickness of the façade is a natural effective parameter for changing the fire exposure of the vertical surface.

In order to investigate the impact of different variations in test set-up and validate numerical models to further analyse these variations, two different test series have been conducted, one with SP Fire 105 tests in Borås and one with BS 8141-1 tests in Zagreb

4.1 SP Fire 105 tests

Nine tests were conducted, four tests of combustible insulation with a protecting render, three different wood façade systems with wood impregnated with fire retardants, one test with combustible insulation protected with bricks and one directly exposed insulation of phenolic resin as presented in Table 2.

Table 2 Tests performed using the SP Fire 105 method.

Façade (mm)	Render etc (mm)	Insulation (mm)	Total Thickness (mm)
Render 200	Render 10	200 EPS	210
Render 212	Render 12	200 EPS	212
Render 222	Render 12	200 EPS + Paste 10 mm	222
Render 272	Render 22	PIR 250	
Brick 330	Bricks 117	Phenolic insul. 168 + Cavity 45 mm	330
Phenolic Insul. 174	-	Phenolic insul. 174	174
Wood 56 mm	Cedar shingles + Spruce plywood 28	Cavity 28	56
Wood 66 mm	Wood panel 21	Battens and cavity 45	66
Wood 67 mm	Spruce 22	Cavity + studs 45	67

The thermal exposure was measured 0.5 m from the combustion chamber using three additional plate thermometers not specified in the test method. The purpose of these measurements is to assess the variability and heat exposure from the fire source. The mean temperatures of these plate thermometers obtained in each test are presented in Figure 2. The temperature varies between the different tests. One parameter that affects the measured plate temperature is the thickness of the test specimen due to different heat transfer into the specimen and difference in length from the fire source.

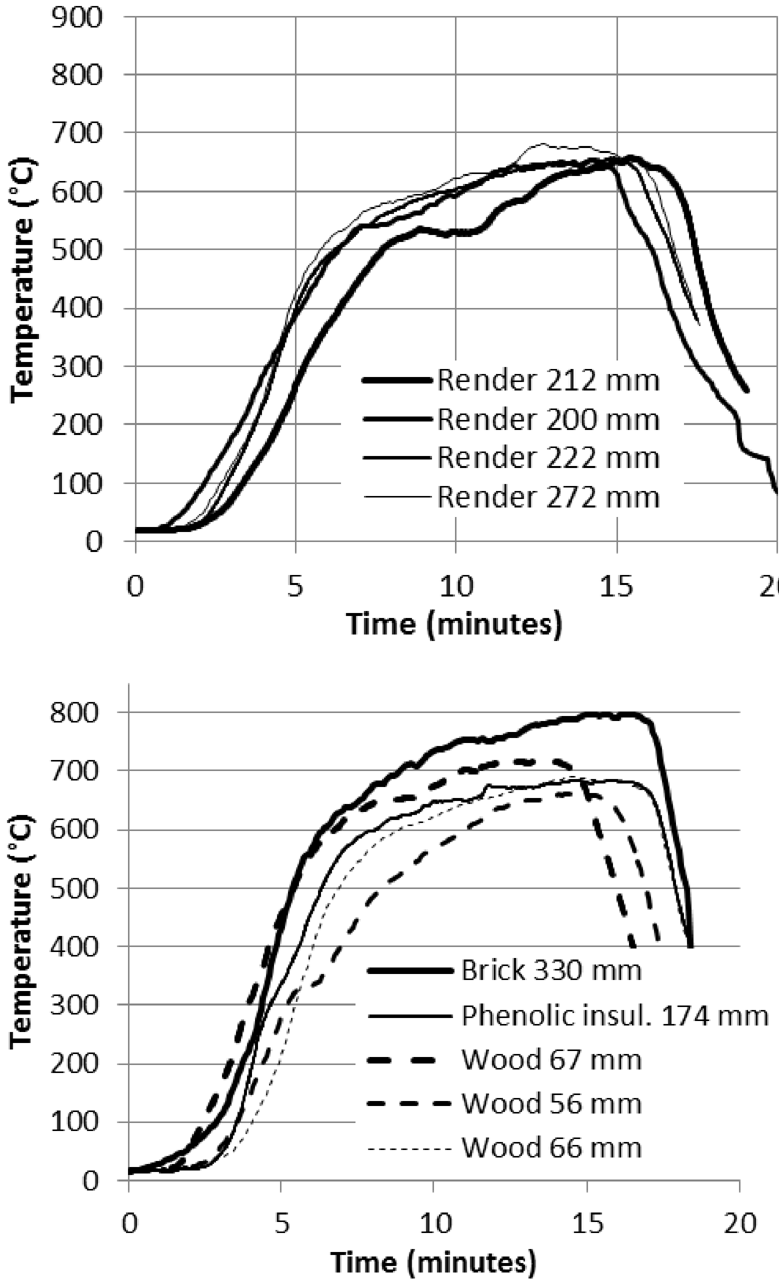


Figure 2. Mean temperature as a function of time at the horisontal centerline 0.5 m from the combustion chamber.

The temperature was also measured using a plate thermometer pointing outwards 2.1 m above the upper edge of the combustion chamber. The results are presented in Figure 3. Since the test specimen in some cases contribute to the heat production, the measured temperatures are not fully comparable since the total generated heat is different in the different tests. In the case with combustible insulation and rendering, the render have in some cases cracked open and thus combustible gases from the insulation will be released and add to the fire.

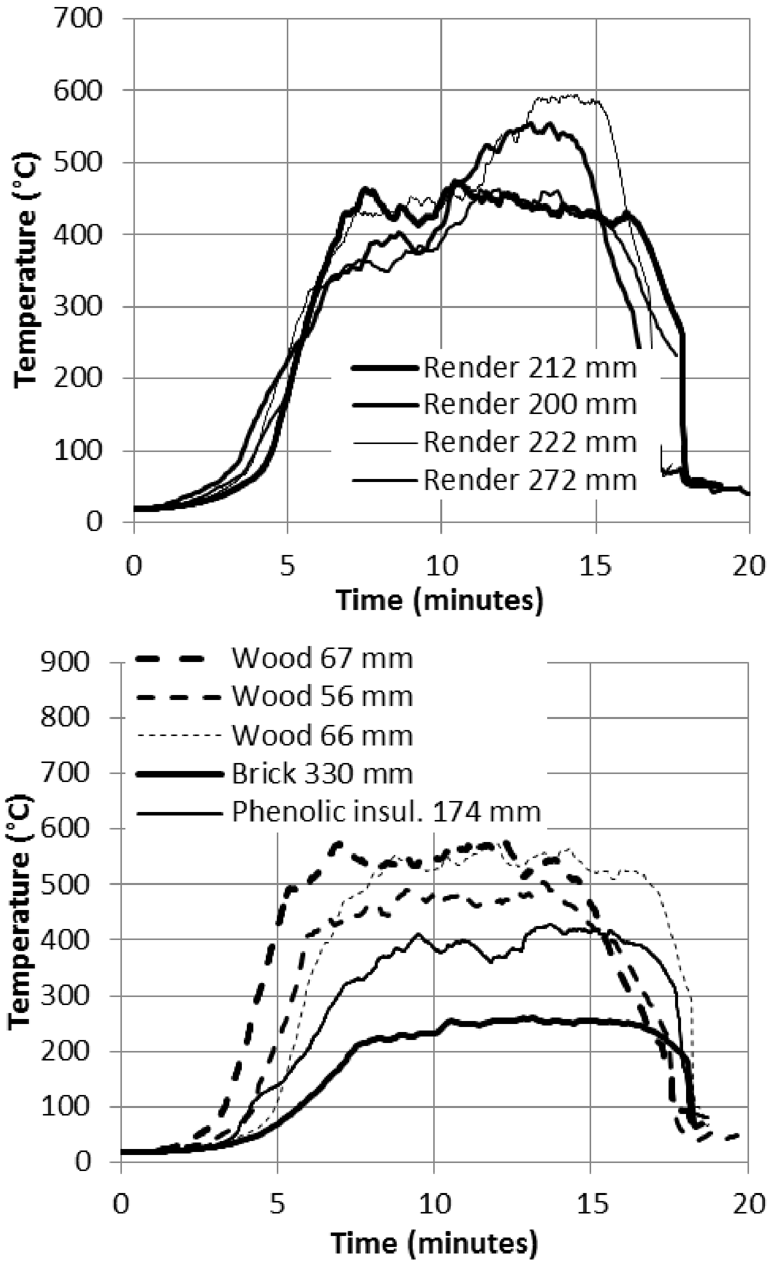


Figure 3. Plate temperature [◦C] as a function of time, measured at the centreline 2.1 m above the combustion chamber, where plate thermometer is pointing outwards.

One test differs from the other and that is the very thick façade with bricks. The measurements show that the plate thermometer temperature from the combustion chamber is higher than the other tests, and that the temperature 2.1 m above the combustion chamber is lower. This can to some extent be explained by the thickness of the façade system. The radiative heat depends on the thickness of flames. When the thickness of the façade increases, also the length for the flames to reach the façade surface increases, and thus the thickness of the flames seen by the plate thermometers is different compared to the regular façade system. This underlines the fact that plate thermometers measure a type of effective surface temperature on a small reference specimen. This effective temperature is a much more representative quantitative measure of the thermal exposure on flat objects than the gas temperature. The thickness of the façade system affects the heat exposure of the façade surface since some of the energy will be absorbed by the bottom edge of the test specimen, i.e. the edge facing downwards, and can be seen as an extension of the fuel chamber, as well as the floor. The thicker the specimen, the more energy will be absorbed by the bottom edge and the floor resulting in a lower temperature measured by the plate thermometer along the façade as seen in Figure 3.

4.2 Zagreb tests

Two series of tests were carried out outdoors in Zagreb, Croatia, one in March 2014 and one in May 2014 (See Figure 4 and 5.), partly presented in Anderson, Boström, Jansson and Milovanovic [17 - 18]. The tests were made in accordance with BS 8414-1:2002 as shown in Figure 4. In each test three façade rigs were used with different test specimens, i.e. three different façade systems. The three façades were prepared with different types of external thermal insulation composite systems (ETICS). The specimens were instrumented as defined in the standard where 8 thermocouples are placed at each of the two heights from the top of the combustion chamber, at 2.5 m and 5 m. The thermocouple is type K (Chromel/Alumel) mineral-insulated 1.5 mm (nominal) diameter thermocouples with insulated junctions. In addition to these measurements, temperatures were measured at different heights from the combustion chamber with different types of thermocouples. The test specimen extends 6 m above the combustion chamber and is 2.6 m wide with a return wall (wing) of similar height and 1.5 m wide. The fire exposure conditions represent an external fire source or a fully-developed fire in a room, venting through an opening such as a window aperture that exposes the cladding to the effects external flames. The square opening of the combustion chamber has a side length of 2 m and the fire source is a wood crib with a nominal total heat output of 4500 MJ over 30 minutes at a peak rate of 3±0.5 MW. Wall 1 consisted of noncombustible mineral wool insulation, Wall 2 of EPS insulation and fire stops at different heights of rock-wool insulation, and Wall 3 of EPS insulation. All three walls had a 5 mm rendering reinforced with glass fibre mesh and final organic (acrylic) render on the surface and classified for the reaction to fire as B-s2,d0 or better.

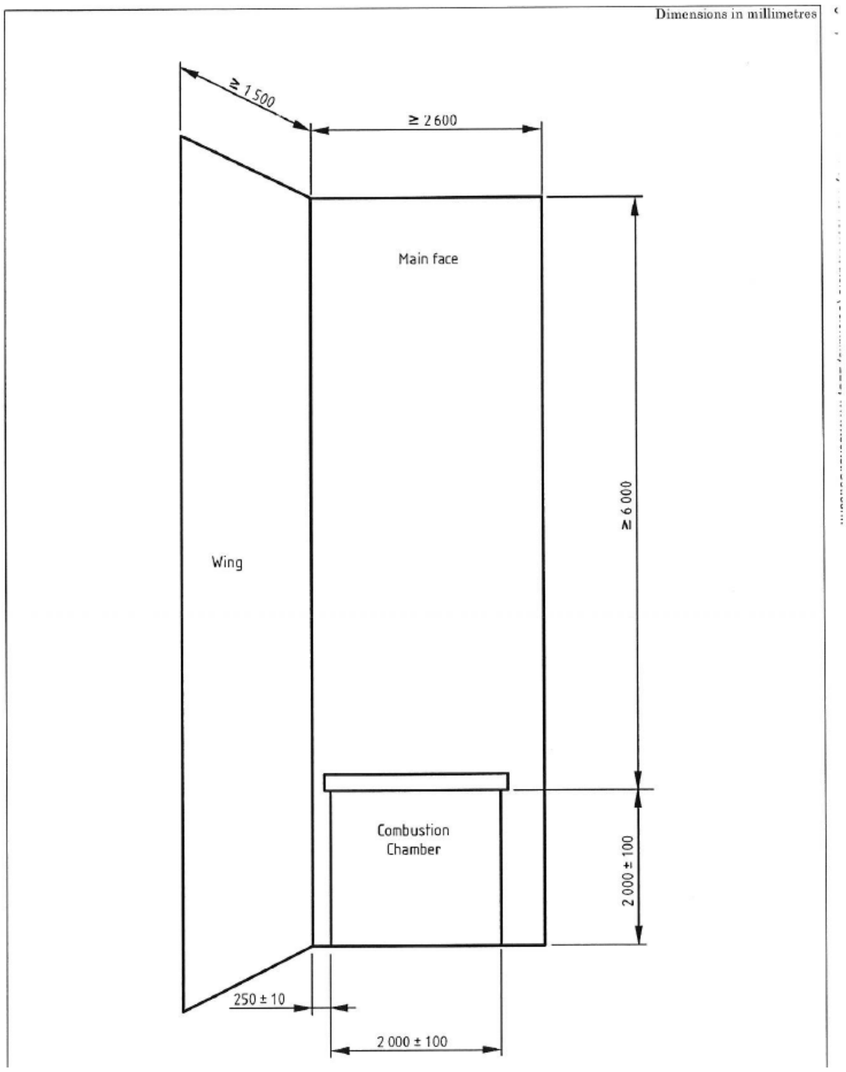


Figure 4. The geometry of the experimental method according to the standard BS8414 – 1 (above) [8] used as input information to the models.

Figure 5. The three façades tested during the Zagreb tests in March.

The two tests series were exactly the same, except the climate conditions since the tests were carried out outdoors. In the first test series, in March 2014, the temperature was around 15 °C and the wind speed varied between 2 and 5 m/s. In the second test series, in May 2014, the temperature was around 25 °C and the wind speed varied between 0 and 2 m/s. During the tests the weight of the fuel was measured by load cells. The initial weight of each wood crib is given in Table 3. It can be noted that the initial weight differ considerably since the standard only prescribe the volume of conditioned wood to be used and it does not fully consider the large difference of density of wood and that the total energy of the fire source can vary. The fuel consumption during the test is shown in Figure 6 is. The fuel consumption has been calculated as the time derivative of the fuel weight throughout the test. The data indicate that the fuel consumption was much faster during the test in March 2014 when the wind speed was higher.

Table 3. Weight of wood cribs in the tests.

Test	Wall 1	Wall 2	Wall 3
March 2014	363 kg	369 kg	357 kg
May 2014	395 kg	437 kg	445 kg

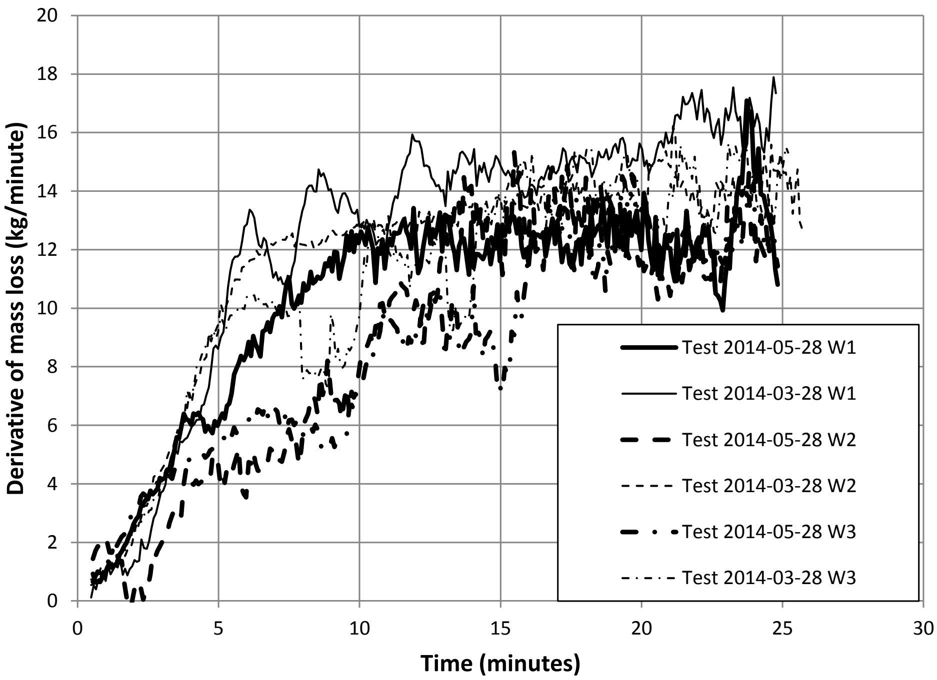


Figure 6. Fuel consumption per time unit [kg/min] as a function of time during the fire test where WX stands for Wall X.

Figure 7. Position of plate thermometers in front of the combustion chamber.

The heat exposure from the combustion chamber was measured by placing four additional plate thermometers in front of the chamber, three at a distance 0.5 m, and one 1.0 m from the fire source as seen in Figure 7. The plate thermometers were pointing towards the fire. The results from the measurements 0.5 m from the combustion chamber are presented in Figure 8 as the mean value of the three plate thermometers. These measurements correlate closely with the fuel consumption, i.e. in the tests with faster fuel consumption; the measured plate temperatures are higher.

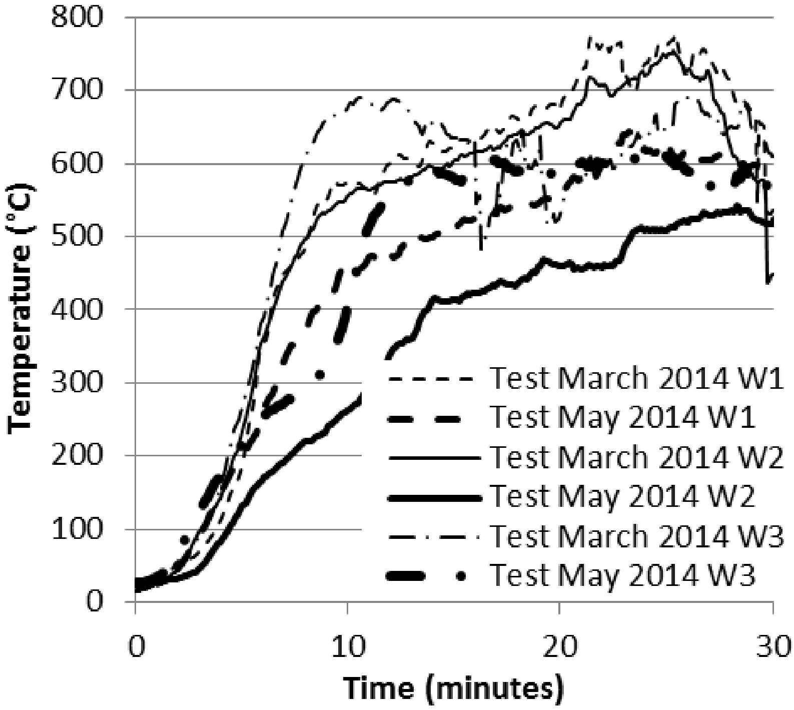
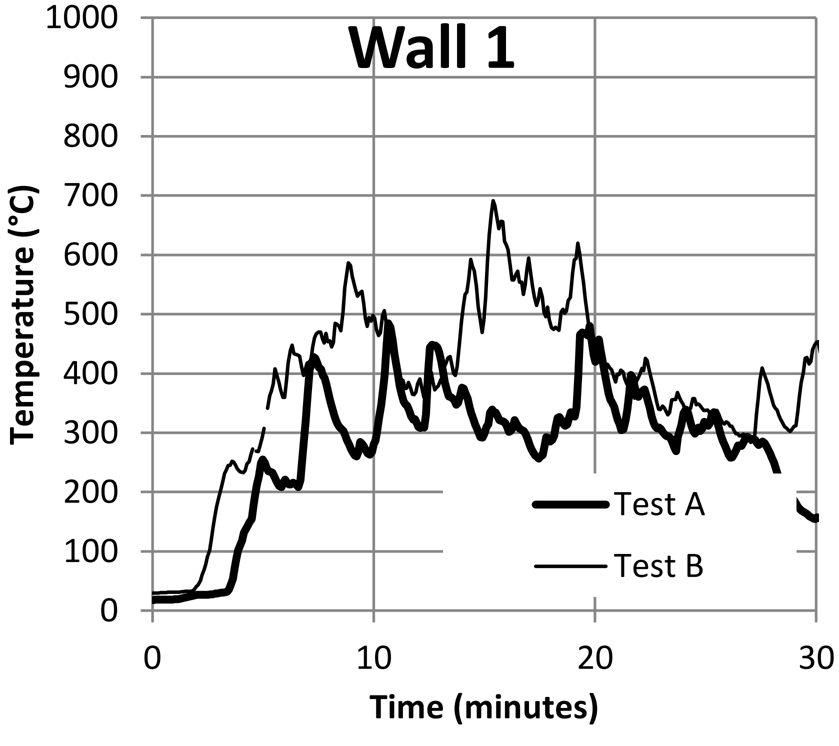


Figure 8. Mean plate thermometer temperature [◦C] 0.5 m from the combustion chamber where WX stands for Wall X.



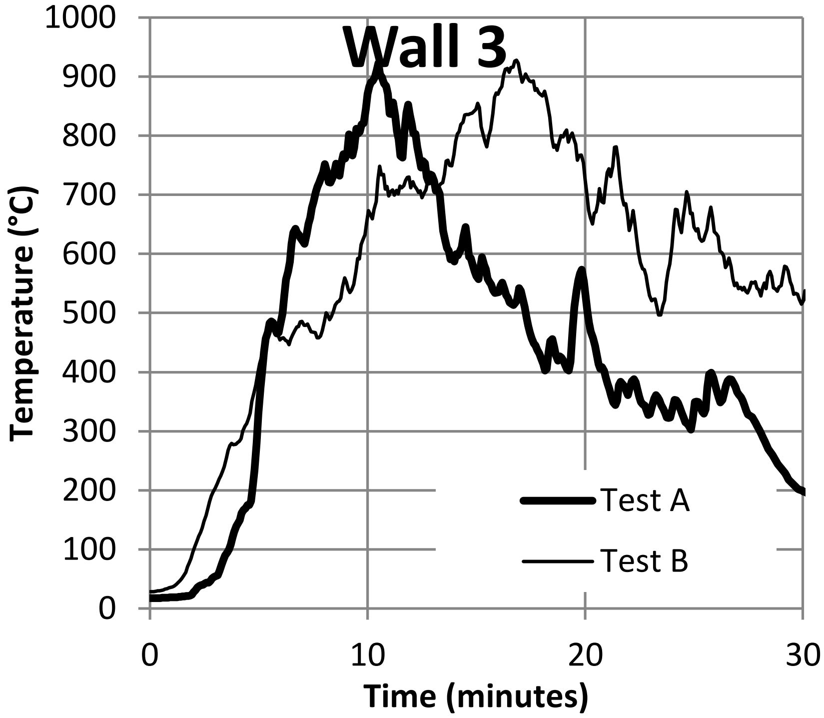


Figure 9. Plate thermometer temperature [◦C] as a function of time, 1.25 m above the combustion chamber, plate viewing outwards.

The temperature was also measured with a plate thermometer 1.25 m above the top edge of the fuel chamber in the middle of the main façade face, see Figure 9. This plate thermometer was placed 10 cm from the façade surface and pointing outwards, i.e. it measures the incident heat exposure to the façade. The measurements are generally unstable and thus the temperature fluctuates to a large degree. This is most probably due to the wind and for Wall 3 the extra heat produced by the combustion of the EPS insulation causing a difference between the three cases.

The results from the three different façade systems show that, although the systems are relatively similar, large deviations in the measured temperatures are found due to significant additional combustion occurring in one of the systems and the difference in climate on the two test occasions.

5 Modelling of façade fire tests

A large-scale façade test method is complex, and there are many different factors that can affect its repeatability and reproducibility. When wood cribs or liquid pool fires are used, an uncontrolled variability in the heat release rate is introduced. This variability can be introduced by e.g. wind effects. The thickness of the test specimen will affect the exposure since energy will be absorbed by the boundaries before the fire reaches the façade surface and the dynamical flow of hot gases may change and thus change the heat transfer to the façade. Air movements around the test set-up (the wind) may have a significant impact on the test. With the help of numerical modelling it is possible to make extensive parameter studies (varying within realistic intervals), and thus determine which parameters that have an important effect on robustness of the test method. The use of simulations may also reduce the amount of large scale development testing which is relatively costly.

Façade fires have been studied for a long time [19 - 27], starting with analytical estimates on prevention of fire spread caused by a hot upward current [19]. More recently numerical studies were introduced, in 2001 the SP Fire 105 test rig was modelled using the CFD code SOFIE [18]. The model was compared with the standard measurements conducted during a calibration fire test for a non-combustible façade. In the standard fire test two thermocouples are placed under an eave, six meters above the fire room and a heat flux meter is placed in a lower fictitious window 2.1 meter above the fire room. The results of the simulation show the response of the two thermocouples and the heat flux meter during 9 minutes of fire exposure. This corresponds to slightly more than half the time of exposure during a real test. The simulations corresponded fairly well with the measurements except in the vicinity of the fire source. A recommendation based on these numerical tests of the SP Fire 105 was to use more than 64 rays in the radiation model when modelling this type of scenario which represented state of the art in 2001. Recently there have been a few publications [23-27] where detailed comparisons between numerical data and experimental tests have been performed for façades.

In the present study, the default setting of 100 radiation angles in FDS is used. Further, the whole scenario during fire exposure is modelled and additional measurements conducted during an experimental fire test are used for comparison with the simulation. The previous numerical work was performed using Fire Dynamics Simulator (FDS) version 5.5.3 [28-29]. The Navier-Stokes equations in the limit of low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires are solved by the FDS software. Historically, in FDS 5.5.3 the algorithm used was an explicit predictor-corrector scheme that is second order accurate in space and time where turbulence was treated by means of Large Eddy Simulation (LES) in the Smagorinsky form which now has been changed to the Deardorff model in FDS 6. This is in contrast to most other CFD codes for fire safety engineering where Reynolds averaged Navier-Stokes models are used. The heat transfer by radiation is included in the model via the solution of the radiation transport equation for a gray gas. The equation is solved using a technique similar to finite volume methods for convective transport, thus the name given to it is the Finite Volume Method (FVM). When using 100 discrete angles, the finite volume solver requires about 20 % of the total CPU time of a calculation, a modest cost given the complexity of radiation heat transfer.

6 Numerical work

The numerical work was performed using FDS version 6.2.0. A number of numerical experiments have been conducted in order to make comparisons between ISO 13785-2, BS8414-1 and SP FIRE 105 methods. Although, there are no measurements for the ISO 13785-2 method it is of interest to compare the numerically generated results to assess differences in the methods. The comparisons are made with additional plate thermometers that have been implemented to be able to more precisely assess the exposure. In particular, one plate thermometer in front of the fire source and one along the façade is included in the numerical models and the performed tests, to assess the fire source and the exposure to the façade specimen are additional measuring points, respectively.

One important factor determining the exposure on the façade is the HRR of the fire source. Due to the complexity of the geometry, in particular the perforated steel sheet acting as a flame suppressor in SP 105, detailed modelling of evaporation of the fuel due to back radiation and subsequent burning is difficult to manage. An estimation of the HRR can be done by visual observation during the fire tests showing a clear highest level of fire intensity between 8 to 14 minutes and that the fuel is consumed after approximately 16 minutes. Based on these observations and that the total fire load is 60 litres of heptane with roughly a combustion efficiency of 0.8, a Heat Release Rate (HRR) curve can be defined. This can be compared with values previously measured by Babrauskas using the large scale calorimeter at RISE during four SP Fire 105 tests [13]. The average value from these four tests is included in Figure 10. The reason for variation in the HRR is that some of the tests had additional combustible materials and the burning of the tested insulation systems on the façades is included during a measurement with the large scale calorimeter at RISE. A rough estimation of the energy in the damaged areas reported by Babrauskas [13] shows approximately 5-10% extra energy from the burning of the insulation materials which corresponds fairly well with the difference in area under our estimation and area under the curve from the previous measurements.

In these three models the HRRs as presented in Figure 10 have been used. Note that the total energy used in the fire source in both BS8414-1 and ISO13785-2 is significantly higher than that contained in the 60 litres of heptane used in SP Fire 105.

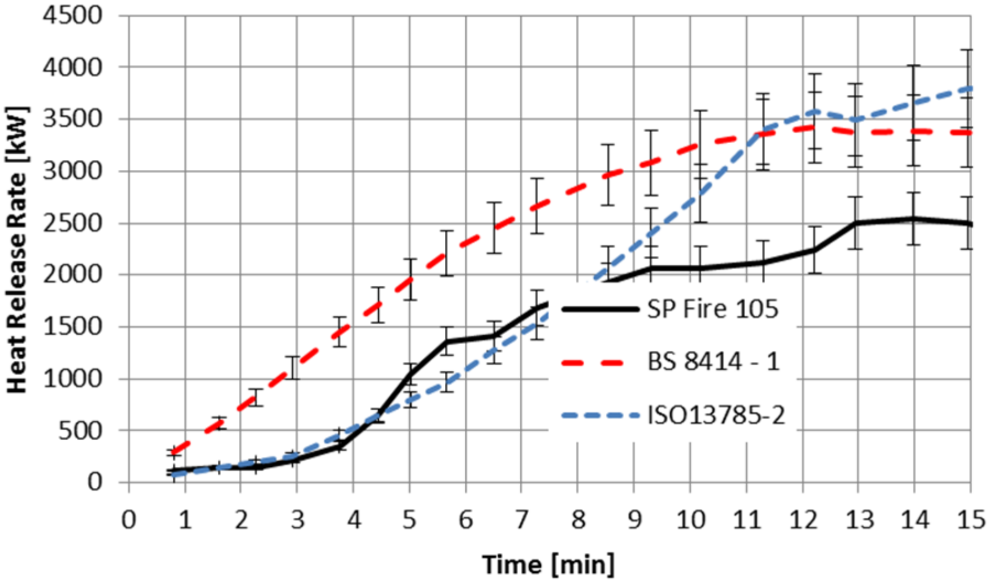


Figure 10. The HRR used in the simulations including the assumed uncertainty of ±10% to be used as a variation in the simulations. The HRR for SP Fire 105 is adopted from measurements Ref [13] and in the case of BS8414-1 from measurements presented in Refs. [17-18] The HRR used in ISO is calibrated using the information from the standard Ref. [11].

In order to be able to evaluate variations to the test method a model was set-up in FDS of the SP Fire 105 test rig with the simplifications that the complete back structure of the façade rig is made out of Siporex (lightweight concrete blocks) and that the façade material is constructed of one homogeneous block with the material data specified in Table 4. The purpose of the homogenized façade is to test whether a generalized model to evaluate the performance of the façade system. In order to evaluate the models, measuring stations corresponding to the measurements made in the experimental work was set-up. In particular for realistic comparisons with experimental results, a thermal model for plate thermometers [30 - 31] was included in the FDS model. The plate thermometer was originally developed for controlling the heat exposure in fire resistance furnaces and has also been proven to be a robust alternative to heat flux gauges during fire conditions. The plate thermometer is a physical object measuring an effective temperature that consists of a stainless steel plate (Inconel 600 of size 100 mm x 100 mm x 0.7 mm) with a 10 mm thick insulation pad on the back side. Due to its construction it will have a finite response time that also has to be taken into account in the modelling, i.e. a thermal model for the plate thermometer is needed. In the numerical model, a physical object with the same dimensions as the experimental counterpart representing the plate thermometer has been implemented. The thermal material data of the Inconel was taken from the manufacturer's data sheet while the insulation material was characterized by the transient plane source method at SP [32]. The emissivity of the steel plate was set to 0.8 which is based on absorptivity measurements. In order to validate the plate thermometer model in FDS a comparison of the step response time was made using a 35 kW/m^2 heat exposure in the cone calorimeter which yielded a very good agreement [23].

6.1 Estimating uncertainties in a CFD model

In general good agreement and qualitatively the same behaviour have been found when comparing simulation results with experimental data for plate thermocouples, thermometers and bi-directional probes at different locations in the model and test, see [17,18,23-27]. However there are lots of uncertainties accompanying the input data of simulations such as natural variations in input data or wind effects, variations that are not necessarily normal distributed. Thus, these uncertainties have to be taken into account in the models.

Here five parameters used in the models of the BS 8414-1 and ISO 13785-2 façade fire tests are varied and the results obtained are compared with previous simulations, corresponding results for SP Fire 105 have been presented earlier in Anderson et. al. [26 – 27]. Note that only uncertainties stemming from variations in the input data are discussed, and not uncertainties stemming from grid resolution although a preliminary sensitivity study was performed in Jansson and Anderson [23]. The parameters with assumed uncertainties are summarized in Table 4. Note that the magnitudes of all uncertainties in material data are based on assumptions, however they are estimated based on natural variations and experimental errors and are here used to investigate how the uncertainties propagate through the non-linear model (i.e. the FDS simulation).

The general problem of uncertainty quantification in CFD models is usually limited by long simulation times and thus only a few parameters are feasible to investigate. However, deterministic sampling allows for investigations of variations in significantly more parameters. Adequate uncertainty quantification with a low number of simulations is thus within reach. Here the variance in the output can be estimated with only six simulations where five parameters are to be modelled uncertain. Although, the assumed variations in the material parameters are larger than can be assumed from measurements and this variability is used to assess the dependence of different material properties of the façade on the computed results. The parameters in Table 4 are given with maximum deviation around the mean value. Note that the mean values of the material data is taken from typical values of fibre reinforced polymer material and the material of the back structure of the façade is Siporex with conductivity k = 0.15 W/(m K), density ρ = 500 k/m^3 and specific heat capacity c_p = 1000 J/(kg K) (The effect of variations in the Siporex material data is not investigated and the Siporex material data is considered constant for all models).

Table 4. The variations for the façade cladding used in the uncertainty quantification in all three models.

Parameter	Mean value	Variation
Thermal conductivity (k [W/(m K)])	0.242	±30%
Density (ρ [kg/m^3])	975	±30%

Specific heat capacity (c_p [J/(kg K)])	1000	±30%
Heat Release Rate ([kW])	See Figure 10	±10%
Wind (U_0 [m/s])	0.5	±0.5 m/s

In comparing the different test methods it is important to remember that the different methods have a significant difference in fire load and duration. Table 5 presents a short summary of the differences.

Table 5. Energy prescribed in simulations, analysis of Figure 10.

Test method	Total energy released during 15 minutes [MJ]	Total energy per meter width of opening [MJ/m]
BS 8414-1	2163	1082
ISO 13785-2	1715	858
SP Fire 105	1334	445

6.2 Deterministic sampling

Due to the lack of knowledge of the precise details of the numerical model or system, seemingly random behaviour can be governed by deterministic, though non-linear, models. Fire models are typically non-linear models. Thus, in such systems, small variations may have a significant impact on the outcome. Moreover, modelling is often performed in stages by different numerical or analytical tools where the uncertainties may propagate through the system [33-36]. It is usually a very difficult task to objectively establish the confidence levels in numerical predictions. Uncertainty Quantification (UQ) is the science of quantitative characterization and reduction of uncertainties in numerical studies and real world experimentation. UQ aims at determining how likely certain outcomes are if some aspects of the system are unknown. Deterministic Sampling (DS) [35, 37] is a relatively new method used for UQ, and is employed here to offer an efficient alternative to more expensive method such as random sampling methods. The method is based on the idea that a continuous probability density function can be replaced by an ensemble of discrete deterministic samples, provided that the two representations have the same statistical moments. This method is related to the fractional factorial design [37] method in that simulations using the maximum and minimum values of the variability are utilized in the simulations.

The theoretical background that is the basis for the explicit choices of ensembles used in this work is summarized though our case where five parameters are modelled uncertain. This ensemble of five parameters constitutes the needed input to the numerical model, although the model includes more parameters, it has been reduced to limit the computational time. In the absence of correlations, the ensemble of m samples is given by [35]:

$$\Sigma = \langle\theta\rangle \otimes 1^{1\times m} + \mathrm{diag}\left(\langle\theta\rangle \circ \mathrm{std}\left(\frac{\theta}{\langle\theta\rangle}\right)\right) \cdot \hat{V},$$

where $1^{1\times m}$ denotes a row vector of m 'ones', $\otimes$ outer product, $\circ$ element-wise multiplication, and $\mathrm{diag}(\mathrm{X})$ is the diagonal matrix with the vector X on its diagonal. Here std is the standard deviation, θ is a column vector with the uncertain parameters, <> denotes the mean values of the parameter and · is the vector multiplication. The excitation matrix $\hat{V}$ contains all variations; each column describes one normalized (using the mean value plus the variations according to the matrix $\hat{V}$) model sample variation from its mean. In Table 4 the variations in five of the main parameters are presented. There are thus, $n = 5$ parameters that need to be modelled uncertain. For instance the standard (STD) ensemble can be used where the model is evaluated using the maximum deviation for each parameter:

$$\hat{V}_{STD} = \sqrt{n} \cdot \left(I_{n\times n} \quad - I_{n\times n} \right) =$$
$$\begin{pmatrix} \sqrt{5} & 0 & 0 & 0 & 0 & -\sqrt{5} & 0 & 0 & 0 & 0 \\ 0 & \sqrt{5} & 0 & 0 & 0 & 0 & -\sqrt{5} & 0 & 0 & 0 \\ 0 & 0 & \sqrt{5} & 0 & 0 & 0 & 0 & -\sqrt{5} & 0 & 0 \\ 0 & 0 & 0 & \sqrt{5} & 0 & 0 & 0 & 0 & -\sqrt{5} & 0 \\ 0 & 0 & 0 & 0 & \sqrt{5} & 0 & 0 & 0 & 0 & -\sqrt{5} \end{pmatrix}$$

Each row in the above matrix is one evaluation of the model where the first row in the matrix describes the evaluation using the positive maximum deviation in the first variable, second row positive maximum deviation in the second variable and so forth. The most computationally efficient way of investigating the outcome of variations in certain parameters are however to vary all parameters at the same time. One such example is the binary (BIN) ensemble created by permutations of ±1,

$$\hat{V}_{BIN} = \begin{pmatrix} +1 & -1 & +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 & +1 & +1 \\ -1 & +1 & +1 & -1 & -1 & +1 \\ +1 & +1 & +1 & +1 & -1 & -1 \\ -1 & -1 & +1 & +1 & +1 & +1 \end{pmatrix}$$

It should be noted that the maximum variation of the standard ensemble is $\sqrt{5}$, while it is only 1 for the binary, moreover there is no need to run the model with all mean values since the mean value of the outcomes are found as mean value over the ensemble. By varying all parameters in all samples of the binary ensemble, its maximum variation is minimized. The risk of saturating or evaluating the model at a point in parameter space where the model diverges is quite significant in using the standard ensemble presented above, thus here only the BIN ensemble is employed. The standard ensemble is easily generalized, but the binary ensemble has a more complex construction. Calculating the model ensemble by evaluating the model H for every sample (column) of Σ, produce the row vector $H(\Sigma)$ of m results. The expected result is given by:

$$\langle H \rangle = \langle H(\Sigma) \rangle = H(\Sigma) \cdot (1/m)^{m\times 1}.$$

The results from the computational work $H(\langle \theta \rangle)$ are compared to experimental results. If the difference is large, non-linear effects are significant. If the difference is small it is likely, but not sure, that the model can be approximated to be linear.
The variance of the model result is given by:

$$\mathrm{var}(H) = \left\langle \left(H(\Sigma) - \langle H(\Sigma)\rangle\right)^2 \right\rangle = \left(H(\Sigma) - \langle H(\Sigma)\rangle \cdot 1^{1\times m}\right)^2 \cdot (1/m)^{m\times 1}.$$

Assuming a coverage factor $k = 2$) for also the result, the modelling uncertainty will be,

$\mathrm{unc}(\mathrm{H}) = 2\sqrt{\mathrm{var}(H)}$.

In summary, the confidence interval of the modelling result is given by:

$\left[\langle \mathrm{H}\rangle - 2\sqrt{\mathrm{var}(H)}, \langle \mathrm{H}\rangle + 2\sqrt{\mathrm{var}(H)}\right]$,

which is the interval determined by the mean value ± 2 times the standard deviation, where the coverage factor of 2 indicates a confidence level of 95 % for this interval.

6.3 Modelling of SP Fire 105

The results presented here are a reproduction of some of the results presented in [26 - 27] and are shown here to simplify the comparative work. Here the analysis and use of deterministic sampling is introduced but not all results are presented here. The thermal data for the material is taken as the mean values in Table 4 and the HRR as shown in Figure 10.

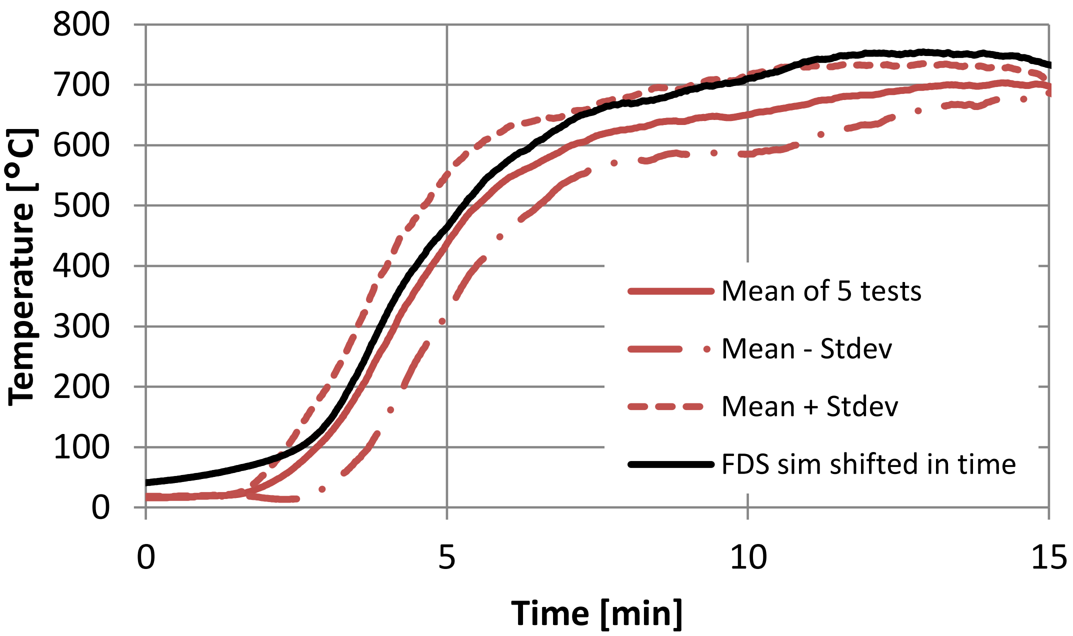


Figure 11. The resulting temperatures from the PT in front of the façade, 0.5 m from the fire room.

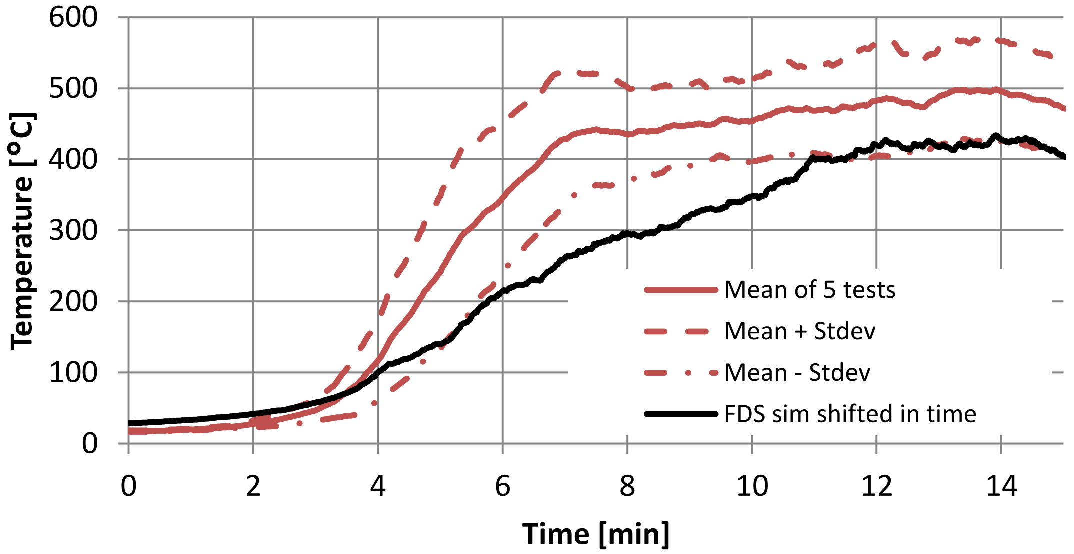


Figure 12. The resulting temperatures from the PT in the first fictitious window, 2.1 m above the fire room are shown. Here the brown lines are experimental measurements and the black is the simulation and the simulated results are shifted forward 30 s in time.

In Figure 11 and 12, the fire source impact is characterized by a PT 0.5 m from the fire room and one PT pointing outwards 2.1 m above the upper edge of the fire room (beside the heat flux meter in the fictitious window). The fictitious windows are just indentations in the façade specimen. These measurements are in addition to the standardized measurements specified in the method. The experimental data are taken from tests with three different wood materials with façade systems containing fire retardants, one brick wall with combustible insulation and one directly exposed insulation of phenolic resin. The data from the five tests are used to compute mean value and standard deviation and then compared to the results from the simulation with façade properties indicated in Table 4. The time shift (30 s) for the simulation is adjusted to roughly match the exposure in Figure 11, finding a quite good qualitative and quantitative agreement mostly within one standard deviation. We have approximately the same amount of uncertainty, around 3%, in the computed temperatures determined by evaluating the standard deviation of the time series, i.e. the measured temperatures are roughly within one standard deviation of the computed temperature.

In Figure 12, the exposure on the façade is estimated by a PT where it is found that the temperatures in the simulation is significantly lower than those in the test, however there is a significant contribution to the HRR from the wood and phenolic resin façade systems yielding increased measured temperatures. In the simulations this has been accounted for only as an increase in the total HRR released by the burner and thus additional combustion on the façade is neglected. Naturally the thickness of the test specimen will affect the exposure since energy will be lost to the surroundings and the underside of the façade system before the fire reaches the vertical façade surface when the fire load at the inner edge of the underside of the façade system is defined. Moreover, a specimen that significantly stretches out from the façade rig may change the flow pattern of hot gases out of the fire room and thus change the local fire dynamics and the heat transfer, see Figure 13.

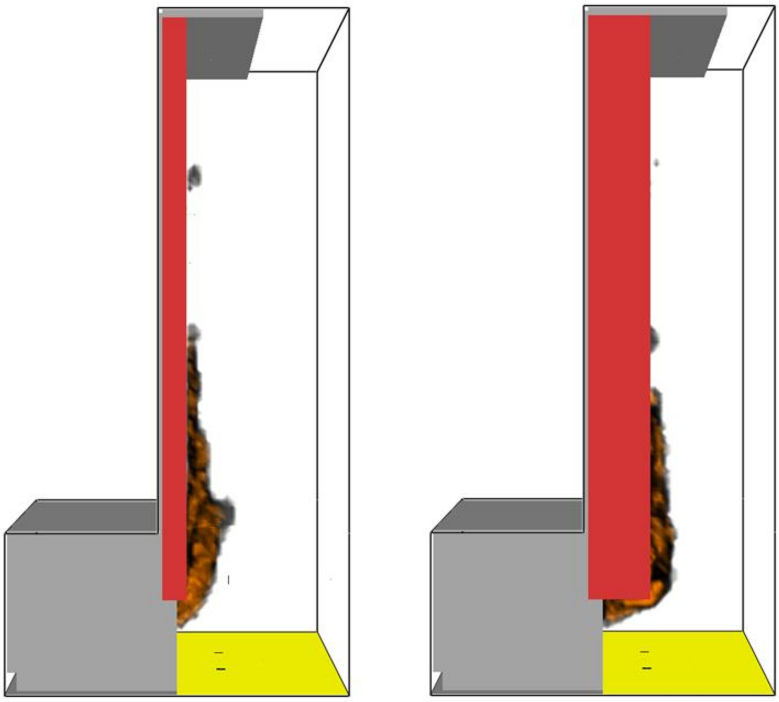


Figure 13. Geometrical factor of a thick façade specimen in test methods is illustrated in a FDS model.

In Figure 14 and 15 the simulated temperatures are shown for a regular façade (100 mm) and a thicker façade (330 mm) system. The computed temperatures are evaluated in front of the façade 0.5 m from the fire room and at the midpoint the length of the fire room opening (pointing towards the fire source) and 2.1 m above the opening of the fire room in the middle of the first fictitious window below the heat flux gauge included in the standard testing (pointing outwards towards the plume). The heat flux gauge is a common water-cooled Schmidt-Boelter device.

It is found that the temperature in front of the façade is increased with a thicker façade specimen protruding further out from the regular holding rig. Here it is interesting to note that the reverse behaviour is found for the temperature measured by the plate thermometers on the wall, as shown in Figure 14 and 15. This shows the same qualitative and quantitative behaviour as found in the experimental comparison performed by Ondrus and Pettersson [15] where an increased temperature in front of the façade, and a decreased temperature on the façade 2.1 m above the fire room, is observed. The dynamics of the plume and the heat transfer into the façade specimen changes due to the thicker specimen, seemingly leading to this difference. Due to the extension of the façade, the flows direct the hot gases slightly more away from the fire room closer to the PT in front of the façade and at the same time limit the exposure to the main wall occupied by the specimen. This leads to an increased temperature in front of the façade.

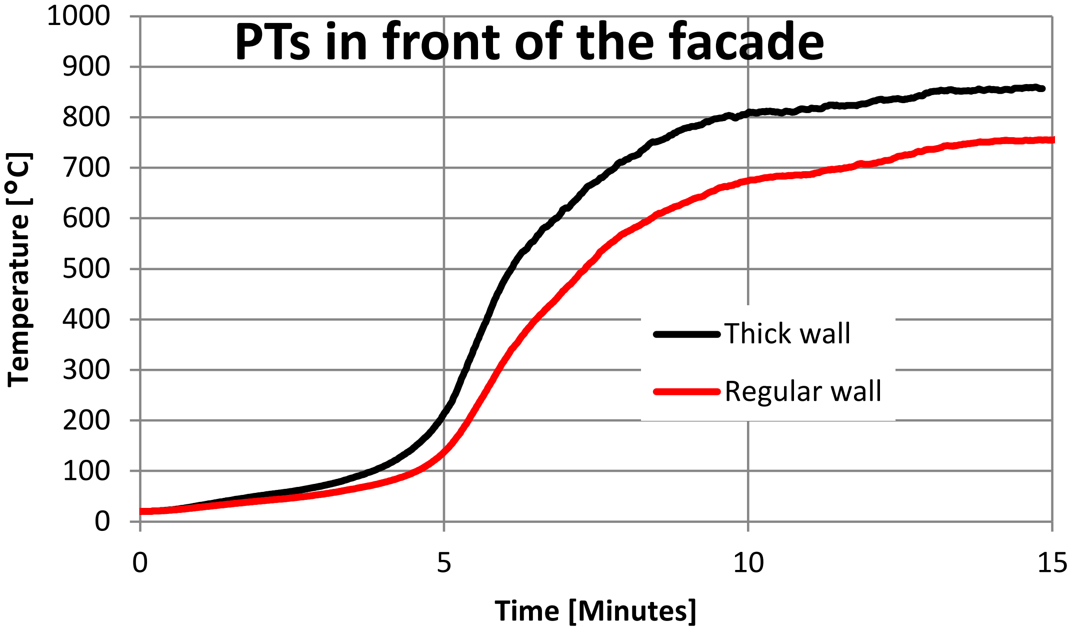


Figure 14. Temperature [◦C] computed by the plate thermometer model in front of the fire room 2.1 m above the upper edge of the fire room in SP Fire 105.

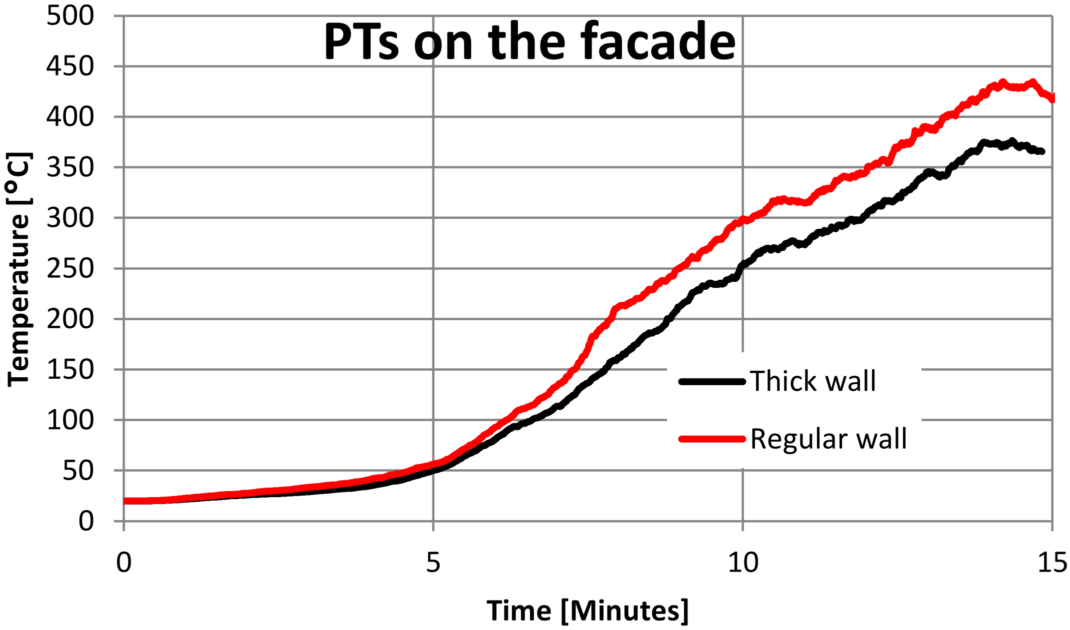


Figure 15. Temperature [◦C] computed by the plate thermometer model on the façade in SP Fire 105, as shown in Figure 1.

6.4 Modelling of BS 8414 - 1

The model used for the SP Fire 105 test method was modified to accommodate for the geometry in BS 8414 – 1 (See Figure 4 for dimensions.) and the fire source was exchanged to represent burning of wood. A slice file displaying the gas temperature distribution at a constant time of the simulation result of the BS 8414 and the ISO 13785 models are shown in Figure 16. The temperature plots show significant mixing of colder air and hotter gases from the fire. Simulations have been performed according to the deterministic sampling scheme using the variations from Table 4 and the HRR presented in Figure 10. The temperature obtained by a plate thermometer in front of the fire source is shown in Figure 17. The temperature was also measured with a plate thermometer located 1.25 m above the top edge of the fuel chamber as displayed in Figure 18. This plate thermometer was placed 10 cm from the façade surface and pointing outwards, i.e. it measures the incident heat exposure to the façade. Note that the placement of the measurements is approximately at the same location as in the SP Fire 105 considering the height above ground, however only results for the thin façade specimen are shown. The red dashed lines represent the mean value ± one standard deviation.

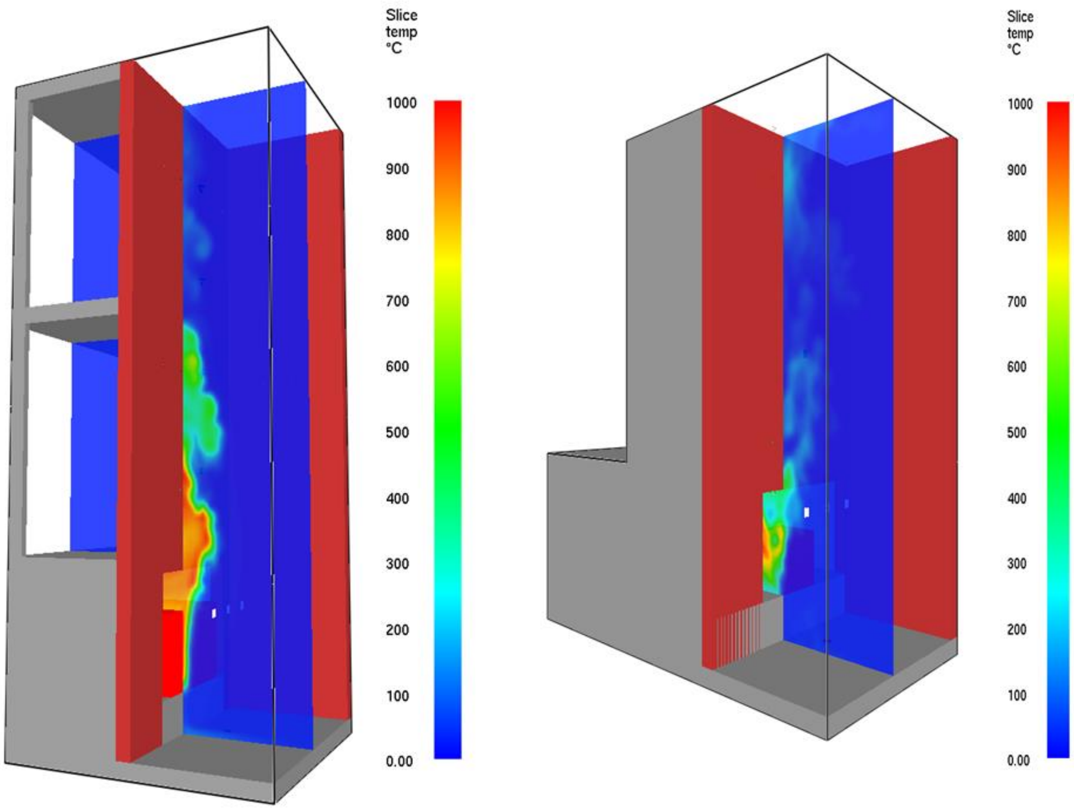


Figure 16. Representation of the simulation models in FDS of the BS 8414 – 1 (left) and as a comparison the ISO 13785 – 1 (right) fire testing methods. The time slices of the temperatures are taken at 600 s into the simulation.

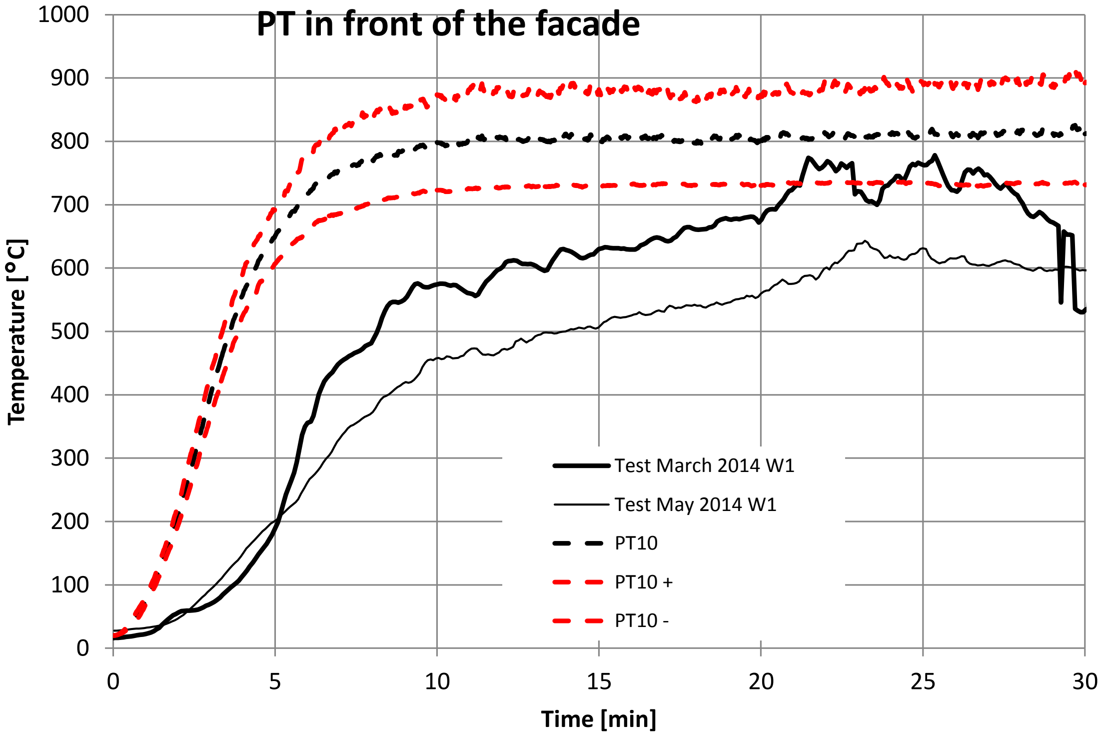


Figure 17. Temperature computed by the plate thermometer model in front of the BS 8414 - 1 façade, as indicated in Figure 7. Here PT 10± refers to ± one standard deviation.

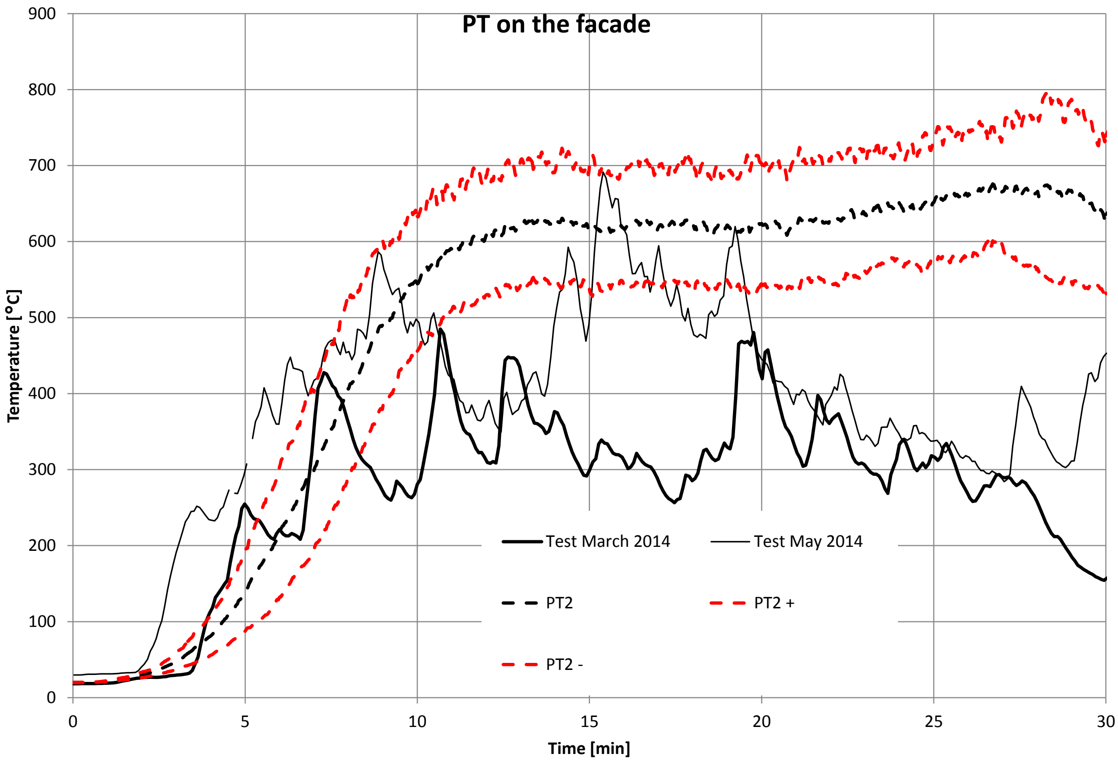


Figure 18. Temperature [◦C] computed by the plate thermometer model on the BS 8414 - 1 façade. Here PT 2± refers to ± one standard deviation.

In a previous study [23], good agreement was found between simulations and experiments, however in that comparison the wind effect was neglected and thus a variability that existed in the experimental result was lacking [17 - 18]. In this work variations in input data is included and thus a variation indicated by a mean value ± a standard deviation is shown in Figures 17 and 18. A constant wind of 0.5 ± 0.5 m/s is utilized and is thus implemented in the simulation as 0 m/s and 1 m/s respectively, however in the experimental situation the wind varied quite a lot. The resulting temperatures in Figures 17 and 18 follow the evolution of the HRR and it is evident that the variation in the wind introduces a significant deviation in the temperatures both in front of the fire source and on the façade. The artificial wind in the model move the plume to the side thus the hot gases are further from the PT in front of the façade as well as the PT on the façade leading to reduced temperatures.

6.5 Modelling of ISO 13785-2

A computational model of the ISO 13785 – 2 test method was constructed and analysed using the same measuring points for evaluation. Note that there is however no experimental data discussed for the ISO 13785 – 2 method, furthermore only results for the thin façade specimen are shown. The HRR presented in Figure 10 was used, which is numerically calibrated by the information given in the standard [11] unlike the other two cases where the HRR was adopted from measurements.

One detailed attempt to model the ISO test set-up has been done previously with varying results in comparing with the corresponding experimental test, mainly because of insufficient information of test conditions [38]. Note that, during full fire exposure in the calibration test the front face of the façade shall be subjected to a total heat flux of 55 ± 5 kW/m^2 measured by the three heat flux meters placed directly above and along a line parallel to the horizontal centreline of the fire room opening. The total heat flux at 1.6 m above the window opening shall be 35 ± 5 kW/m^2 however it seems difficult to fulfil both requirements of heat flux. In the simulation, the heat flux at the top heat flux gauges was calibrated to be just below 40 kW/m^2, on the other hand this gives a total heat flux at the lower level of almost 80 kW/m^2. If, on the other hand, we calibrate the heat flux at the lower level we find that the measurement at 1.6 m above the window is significantly lower than 30 kW/m^2.

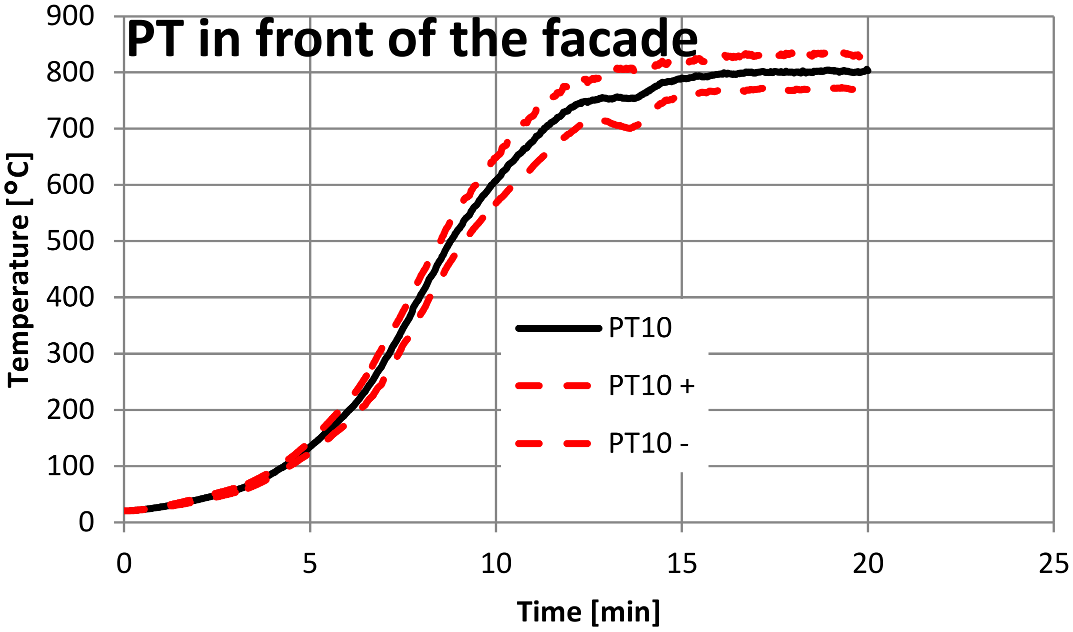


Figure 19. Temperature computed by the plate thermometer model in front of the ISO13785 - 2 façade. Here PT 10± refers to ± one standard deviation.

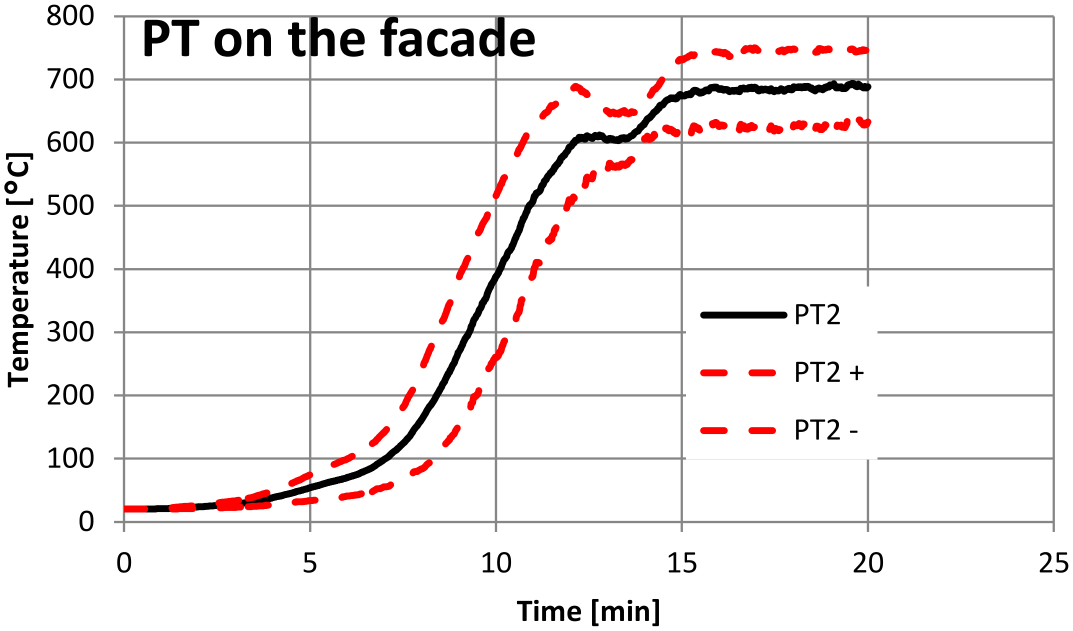


Figure 20. Temperature computed by the plate thermometer model on the ISO13785 -2 façade. Here PT 2± refers to ± one standard deviation.

In order to have a conservative case, the HRR giving the higher heat flux values was used, as given by the HRR in Figure 10. Note that the peak plateau of the HRR is rather similar to that of the BS 8414 – 1 case, thus rather similar results in terms of computed temperatures are expected, since all other conditions are otherwise similar. Note that there is a small plateau in the temperature in Figure 19, corresponding to the small dip in HRR in Figure 10. In Figure 19 and 20, the corresponding temperatures measured by plate thermometers in front of the façade and on the façade at 3.25 m above ground are shown, respectively. The red dashed lines represent the mean value ± one standard deviation of the variations found using the deterministic sampling method. Although, not explicitly shown here it has been found that rather modest changes in the HRR used may have significant effect on the plate temperatures.

6.6 Comparison

Comparing the simulated temperatures found in the BS 8414 – 1 and ISO 13785 – 2 models it is anticipated that they are quantitatively the same at the plateau where the fire intensity is at maximum. However due to a slightly faster fire growth in BS 8414 – 1 model, this maximum is reached earlier in this case. Note that the statistical variation as measured by the standard deviation is smaller for the ISO 13875 – 2 model compared to the BS 8414 – 1 model although the same variation in the input parameters are employed. Furthermore, the variation is only around 0.03 (StDev/mean) for SP Fire 105 for the plate thermometer data as seen in Table 6 [18] whereas it is 0.09 and 0.04 for BS 8414 and ISO 13785, respectively. It is important to note here that the spatial extension of the material in the burning chamber is kept constant throughout the simulations.

In Table 6 and 7, a summary of the simulations results in terms of mean value and standard deviation averaged over one minute at maximum fire intensity between 14 and 15 minutes are presented. In particular it is noted, that the standard deviation for BS 8414 – 2 is much larger than for the other two methods. One of the reasons here is the difference in flow dynamics since the fire room is very small in comparison to the fire load which seems to give different dynamics of the flows along the façade. In SP Fire 105 an air intake behind the heptane pool is present providing a steady flow of fresh air into the fire room whereas in the BS 8414 method the fire room is closed giving a slightly more pulsating dynamics which causes slightly larger variations in the flows along the façade.

Table 6. Summary of the results in front of the façade in mean values and standard deviations contrasted at the maximum temperature averaged over one minute between 14-15 minutes.

Simulation	Mean (Max. fire temperature) [°C]	StD (Max. fire temperature) [°C]	StD/Mean
SP Fire 105	744	23	0.031
BS 8414 – 1	806	76	0.094
ISO 13785 – 2	779	35	0.044

Table 7. Summary of the results on the façade in mean values and standard deviations contrasted at the maximum temperature averaged over one minute between 14-15 minutes.

Simulation	Mean (Max. fire temperature) [°C]	StD (Max. fire temperature) [°C]	StD/Mean
SP Fire 105	421	15	0.035
BS 8414 – 1	624	79	0.127
ISO 13785 – 2	658	43	0.065

Using numerical modelling, within the Fire Dynamics Simulator v 6 [28-29] paradigm, the same trends as found in the experiments were observed. In general a good agreement between the experimental data and the numerical model was observed when measured heat release rate (HRR) was used as an input in the simulations. The same agreement was however not found close to the burning chamber where the numerical models gave substantially higher temperatures. Reasons for this are unclear. However, for SP Fire 105 the differences in computed and measured temperatures are possibly a consequence of the shape of the flame suppressing lattice in the fire tray that lead to a burner like behaviour of the heptane pool. The lattice causes different local combustion effects compared to that of a liquid surface in a pool fire, effects which are not properly reproduced or resolved good enough in the numerical simulation by using a prescribed heat release rate and the current mesh resolution. It is also noted that there is a consistent time lag between the simulated and the measured temperatures. For the wood cribs in BS8414 – 1 and ISO13875 – 2 possibly similar effects and limitations in the modelling could be expected as a specified HRR is used.

The resulting numerical models can be used for assessing small variations in the test methods such as effects of different fuels, effect of return wall, and placement of measurements and climate conditions during testing.

7 Observations

There are a wealth of different tests and simulations using the SP Fire 105 method available and here a few observations are presented.

7.1 Fire spread

In SP Fire 105 fire spread is determined by visual inspection. In order to implement measurements replacing the visual inspection, testing has been conducted using plywood as specimen by Boström, Skarin, Duny and Jansson McNamee [40]. It was concluded, by combining the visual observations made after the tests (figures 89 and 90 in Ref. [40]) with the temperature measurements in the area where charring was observed (figures 91 and 92 in Ref. [39]), that burning of the plywood surface takes place when the temperature reaches 300 – 400 °C. Subsequent measurements in Single Burning Item (SBI) setup [39] confirmed that a surface temperature around 300 °C indicated combustion of the tested plywood. It should, however, be noted that all these tests have been performed on one material only. In order to establish a more general temperature criterion for surface combustion of other materials, more tests have to be performed. The Boström et. al. study [40] showed that it may be possible to conduct these studies using small scale tests, such as SBI. Although in the end, it is important to verify the results with large scale façade tests.

Large scale tests were also performed in the project as reported by Boström et. al [40] using the SP Fire 105 rig. By visual means it was concluded that charring was present above the lower edge of the second window and thus the façade would not have been approved using the SP Fire 105 method. In the British classification of façades, the temperature measured in the air 50 mm from the façade surface is used with the failure criterion that the temperature may not increase more than 600 K for a time longer than 30 seconds. However, if this criterion is applied in the assessment of the results presented in the Boström et al study [40] the plywood façade wood pass the test based on the British classification. Thus, indicating that if surface temperature measurement is used as a failure criterion a lower threshold is needed.

7.2 Effect of soot

One important parameter that may affect the heat exposure on the façade is the amount of soot produced as discussed by Anderson e. al. [24]. A comparison between heptane and propane fuels was conducted through numerical simulations to investigate this. The fire source in SP Fire 105 is a heptane fuel pool with a fire suppressing grid made of pipes. In the propane case the same heat release rate was employed using a diffusion burner with propane as fuel. The soot production rate was set to 0.037 g/g for heptane and 0.01 g/g for propane. The simulation indicates that it would not be a significant difference in results, see Figure 21 and 22, with a change in fuel when considering the Plate thermometers. However, since the soot may change the surface properties and the emissivity, the radiation – convection balance may change if the fuel is changed and the visibility of the façade is significantly reduced using heptane as a fuel as displayed in Figure 23.

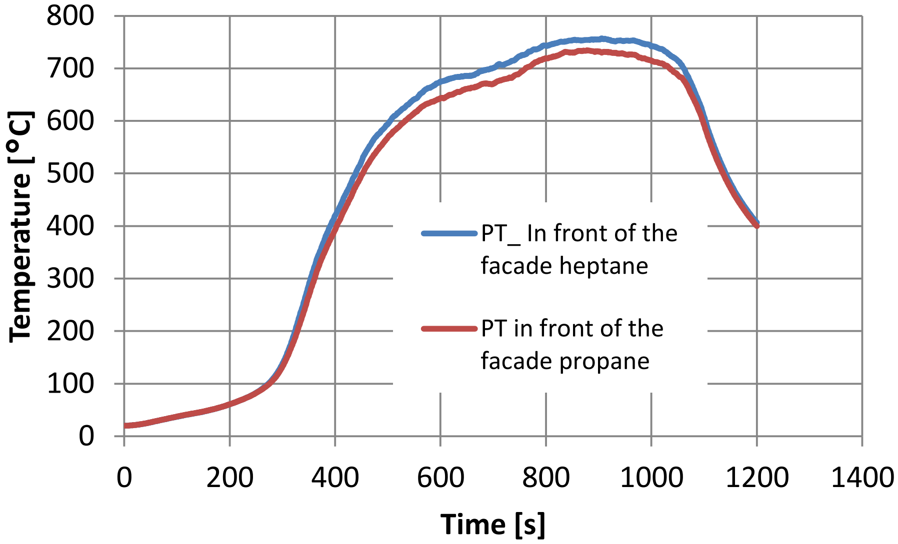


Figure 21. The temperature [°C] as a function of time measured by a plate thermometer placed 0.5 m from the fire source at the horizontal centreline.

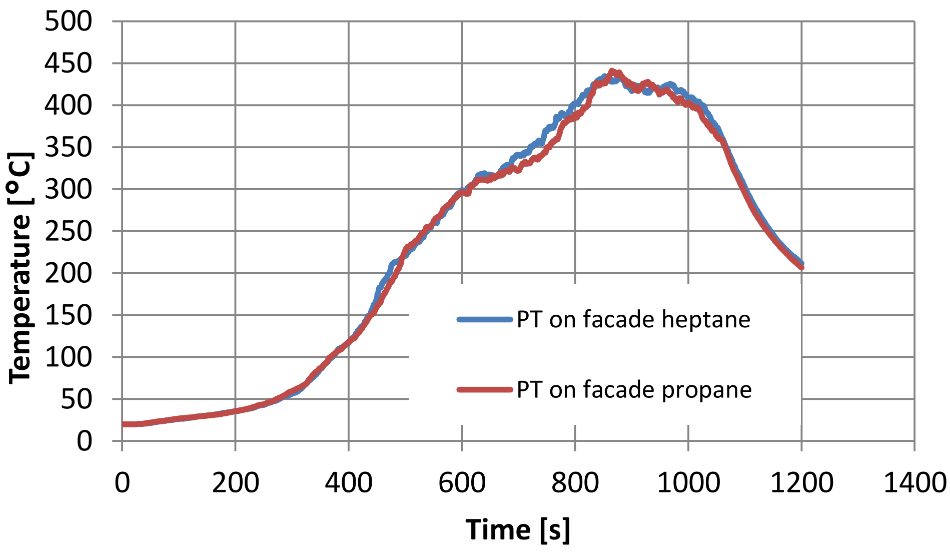


Figure 22. The temperature [◦C] as a function of time measured by a plate thermometer placed beside the heat flux meter in the first fictitious window on the façade.

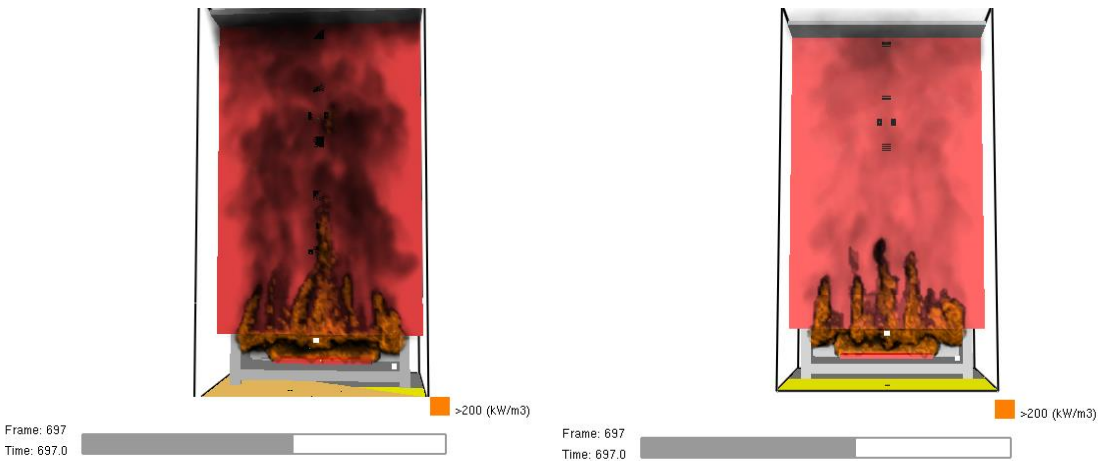


Figure 23. A qualitative comparison of smoke production between the heptane (left) and propane (right) in the FDS simulation at 697 s into the simulation using the same colour scheme.

7.3 Heat exposure to the façade

7.3.1 Temperatures in front of the fire room

In quantifying the fire exposure, the fire source is assessed with a standard plate thermometer measuring the temperature at the centreline in front of the façade 0.5 m from the fire room. The results of these measurements are presented in figure 24 for eight standard tests with eight different, but typical, façade systems as discussed in Section 4, Table 2. For clarity the data is presented in two separate graphs. The mean value and one standard deviation is over-plotted on the test data.

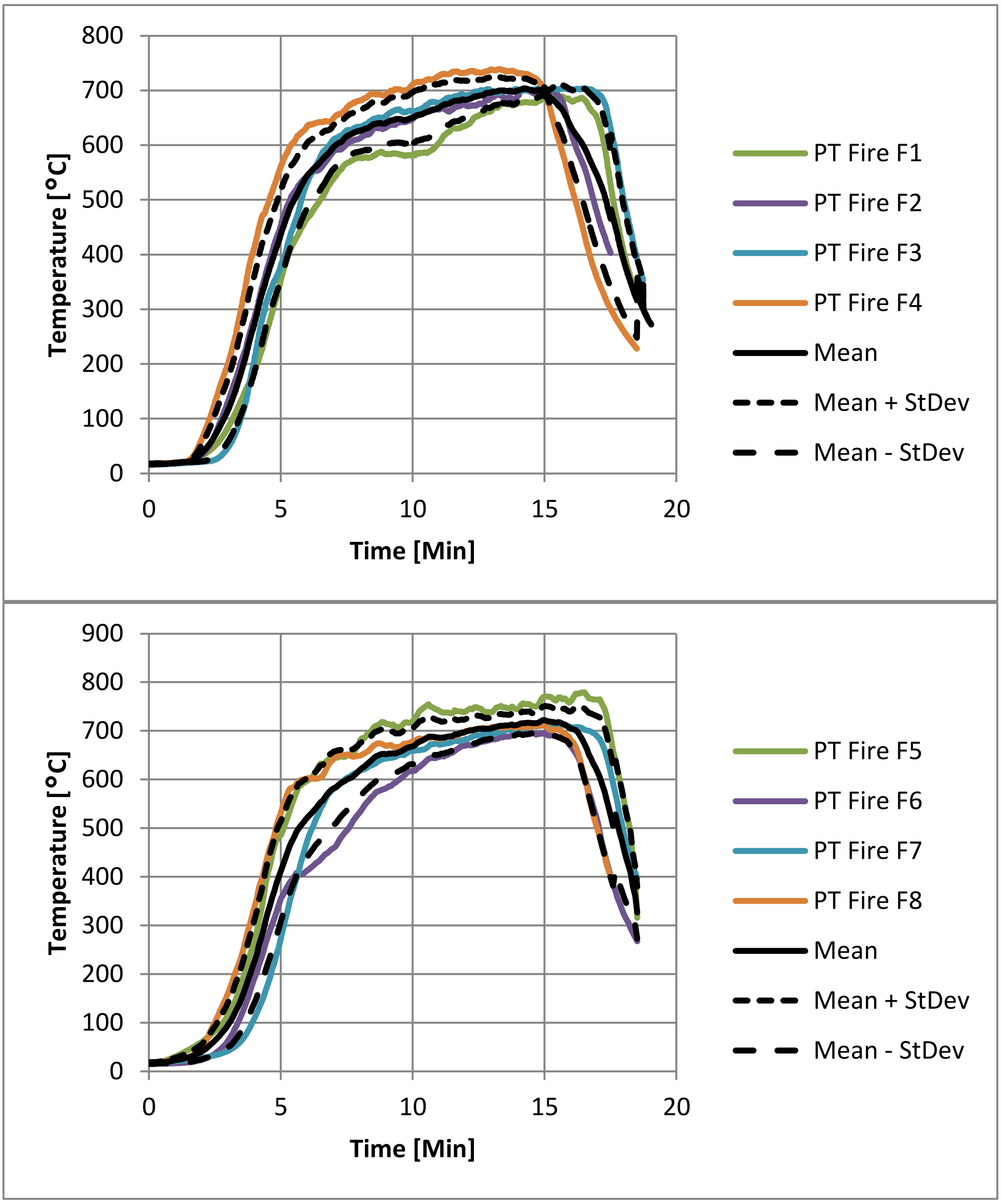


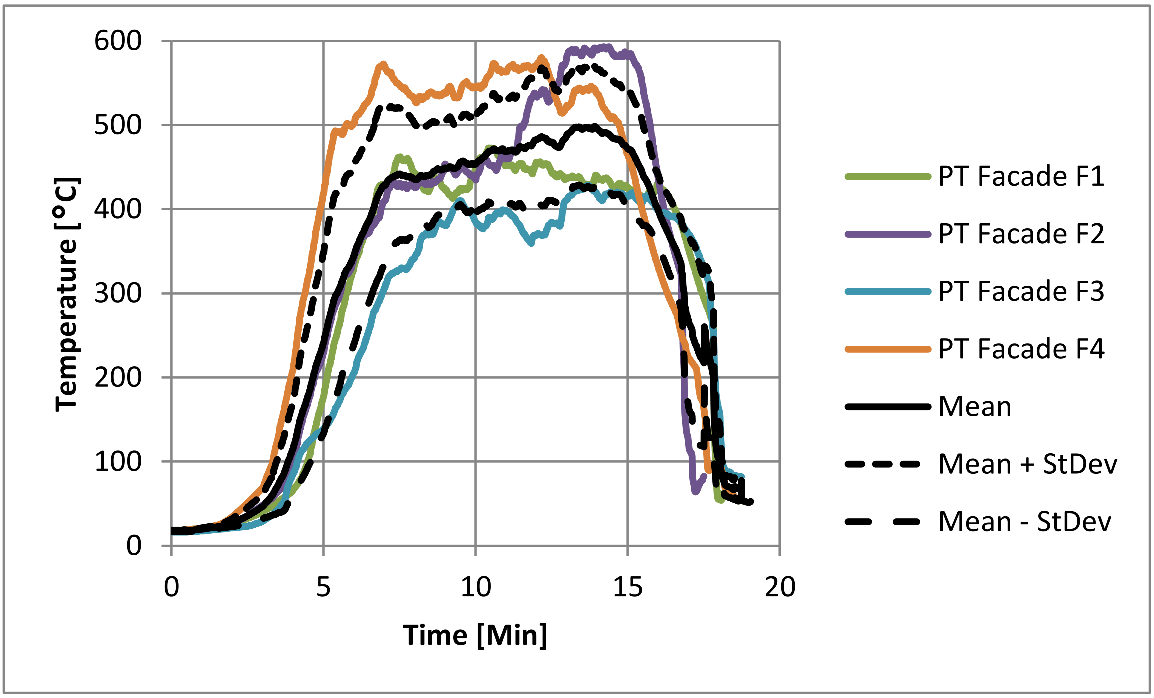
Figure 24. The experimental temperature [◦C] as a function of time measured by a plate thermometer placed in front of the fire room at the horizontal centreline and at a distance 0.5 m.

Figure 24 shows that there is some variation in the fire source which comes from natural variations. However, it is also indirectly dependent on factors such as the geometry of the façade specimen creating a different flow out from the fire room and thus the impact on measurements by the plate thermometer in front of the façade is dependent on e.g. the thickness of the façade specimen, thus in a comparative setting there are some variations.

7.3.2 Temperatures on the façade at the first fictitious window

The plate thermometer temperature measured next to the heat flux gauge on the façade is displayed in Figure 25. The mean value and one standard deviation is over-plotted on the test data.

The thermal attack on the first fictitious window is assessed by the temperature measured by a plate thermometer which closely follows the time evolution of the HRR. It can be observed that after 10 minutes of fire the temperature is above 400 ◦C indicating that the window would break at some point during the test.



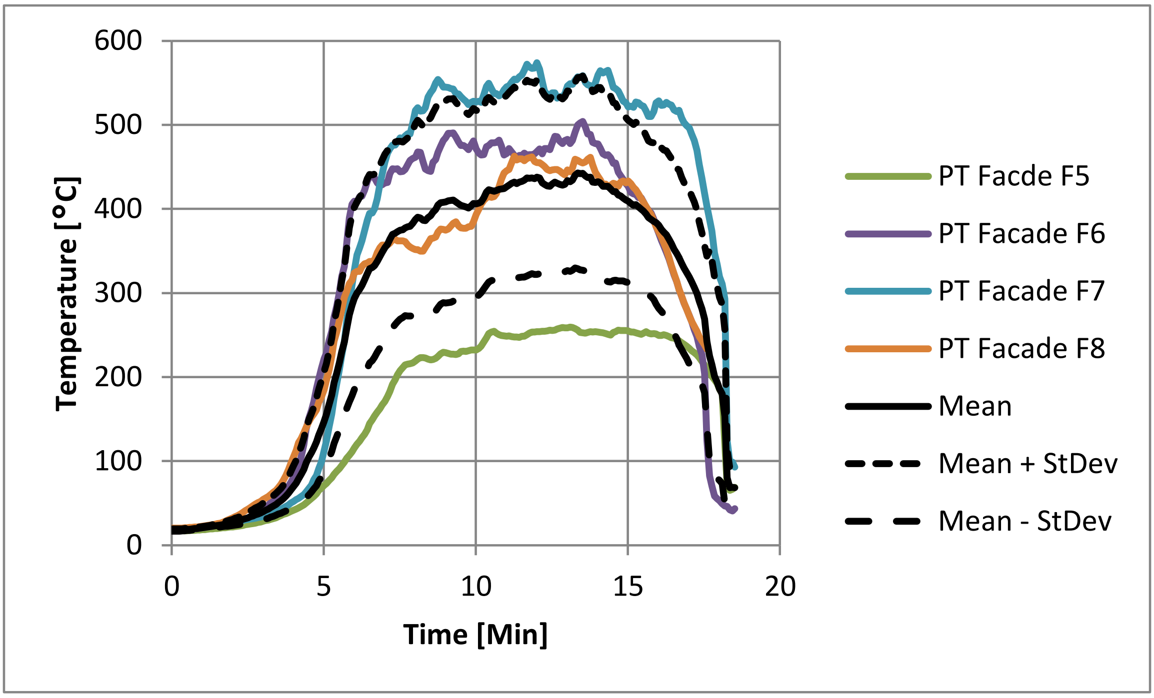


Figure 25. Temperatures [◦C] measured by plate thermometers placed flush on the façade beside the heat flux gauge in the first fictitious window for eight different façade specimen.

7.4 Heat flux values for reference

One of the measurements included in the SP Fire 105 standard [7] is the heat flux [kW/m^2] measured by a heat flux gauge at the fictitious window where the maximum allowable heat flux is 80 kW/m^2 [9]. However, heat flux measurements usually suffers from large variations and uncertainties if performed in the fire plume and therefore, although a heat flux measurement gauge is included in SP Fire 105, it would be preferable to replace this with a measurement with a plate thermometer. Measurements from a plate thermometer can also easily be used for numerical purposes.

In Figure 26, the heat flux is displayed averaged over 10 seconds. In order to assess the spread in the measurement data, the mean value and one standard deviation is over-plotted on the test data. A large variation in the measured heat flux is observed, in particular in comparison to the temperatures measured by the plate thermometer placed on the façade face thus, preferably, comparative measurements are performed using plate thermometers.

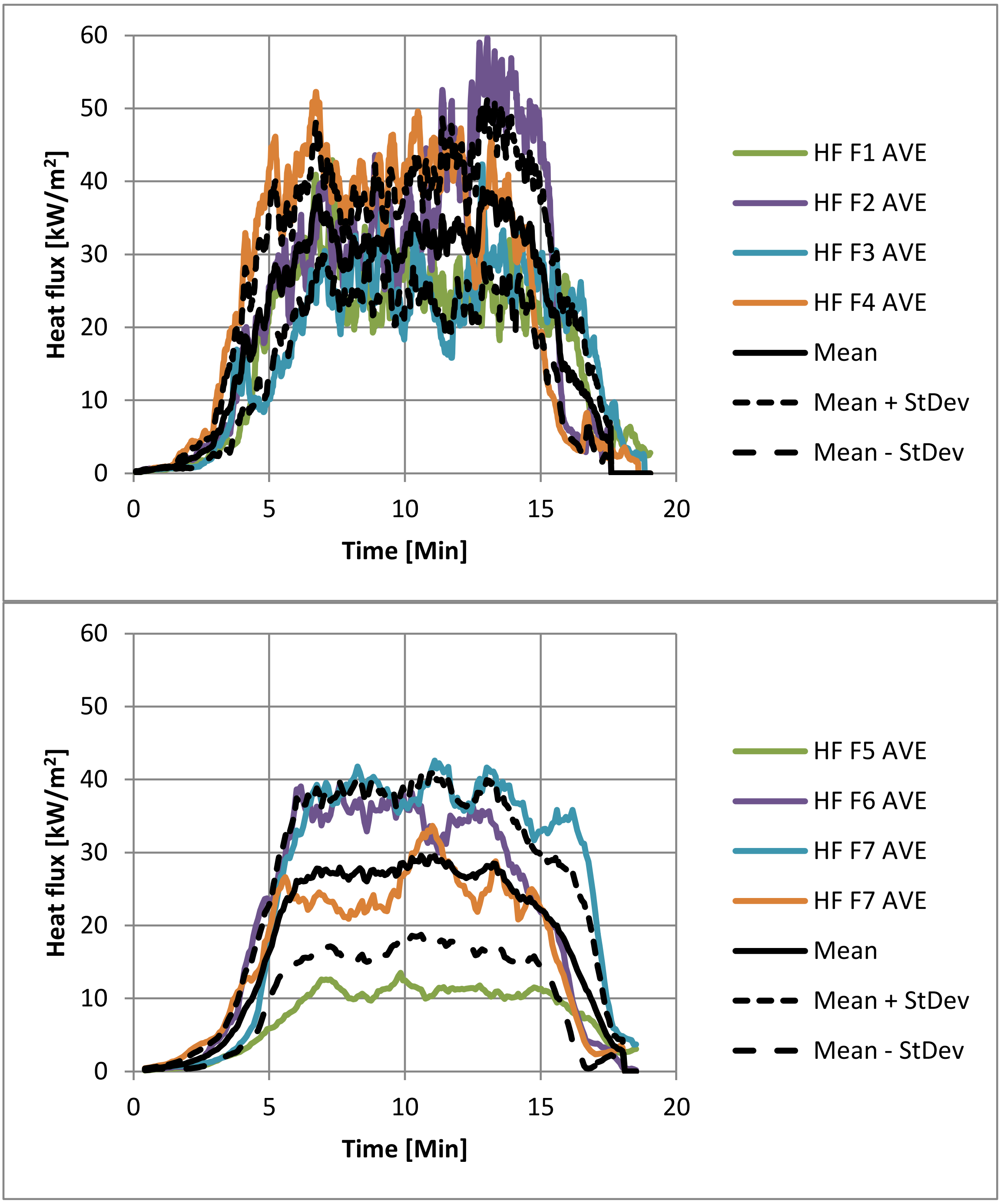


Figure 26. Heat flux [kW/m^2] as a function of time measured in the middle of the first fictitious window for eight different façade specimen.

8 Discussion

Investigations of fire spreading from floor to floor via external walls have been carried out for a long time [1, 7, 21] and a number of test methods have been proposed and implemented in order to evaluate different wall claddings, insulations and geometrical considerations [6, 7].

The use of rules and testing methods are very different in different parts of the world. In part, this can explain some recent incidents. It is noteworthy that there were no reaction-to-fire requirements at all for surface material for façade systems for buildings in the UAE before 2012 [3-4,22], while today there are requirements for allowable materials with a certain fire class. There are supposedly hundreds of skyscrapers in the UAE that are built with the old regulations, and thus there is a great risk that additional façade fires can occur [22].

Analysis of the façade fire in Australia 2014 shows that the surface material and façade system met the requirements [2]. The regulatory framework allows analytical design and the façade was constructed according to that. The Australian fire safety engineering methods takes into account the number of floors, fire risk and the use of the building. However, combustible materials on the balconies including especially air conditioners changed these conditions and a disastrous fire was a fact. Personal injury was in this particular case minimized by an efficient sprinkler system inside the building.

In this report, the three methods SP Fire 105, BS 8414-1 and ISO 13785-2 have primarily been discussed and it can be concluded that there are a few specific differences between the methods including that ISO 13785-2 and BS 8414 can be used outdoors and a return wall is included for these two methods, but not for SP Fire 105. Another difference is the fuel used. BS 8141-1 uses wood while SP Fire 105 used 60l heptane. It has been recognized that the wind may have a significant effect on the test, influencing the fire source and mass loss rates as well as specific results on measurements due to movement of flames with respect to the measuring points that may affect the outcome of the test.

In order to assess the methods and possible minor variations of those methods numerical tools have been developed and validated against experiments. The report summarizes these tests and simulation efforts. One of the main issues that have been identified in comparing simulation results with experimental measurements are uncertainties stemming from natural variations in parameters used in the modelling or stemming from measurement uncertainties or effect of ambient conditions

In the experimental work, measurements characterizing the fire source and the heat exposure to the façade with plate thermometers in addition to those as prescribed in the standards have been introduced, in order to be able to compare with numerical simulations. It is found that, in most cases that the models can represent the experimental data rather well taking into account the variation in experimental data and simulations, except very close to the fire source see reference [23] for a more detailed discussion on this topic.

Although the variation in the input parameters of the modelling are the same for all numerical models it seems that the BS 8414 – 1 is more prone to variations, i.e. a larger standard deviation is found for this method, see Table 6.

The models are now used to produce background information and assessments in the harmonization work that is performed within EU.

9 Recommendations and future direction

For a long time there was ongoing work within the organization EOTA (European Organisation for Technical Assessment) which aimed to develop a harmonized methodology for assessing the fire characteristics of façade systems, however no agreement could be reached between the member organizations. Furthermore, this work became obsolete when the new Construction Products Regulation (CPR) was introduced on July 1, 2013.

Presently discussions are ongoing within EGOLF (European Group of Organisations for fire Testing, Inspection and Certification) to assist in the development of a common European methodology for evaluation of the fire safety of façades. An obstacle in this work is that the testing methods and regulations currently used at national level in the member countries greatly differ from each other. One interesting example is that, in Sweden it is acceptable to use normal, non-fire classed, windows which means that the risk of fire spread from the outside of the façade into the second compartment is significantly higher compared to e.g. Germany, however the façade testing method in Sweden is significantly more severe than the German method.

Fire spread along and inside façades have been the subject of many studies that have tried to sort out what the critical conditions are but there is still no accepted definition. An example of this is a recent study that shows that the regulatory framework in the Nordic countries shows significant differences in levels even though the building traditions of the countries are similar [41].

It is important to avoid or minimize any arbitrariness in the assessment of test results. In order to achieve this, the harmonized method to be developed must clearly specify measurements and clear requirements on e.g. fire source, falloff and combustion inside the façade system.

It is very uncertain when a European method can be available. However, there is now a large collaboration project ongoing including several fire laboratories to support this. RISE is coordinating this project, funded by the European Commission, to propose a new classification system and test method. This work is of great importance to ensure that fire safety of façade systems are handled in a realistic way. In the current proposal a combination of the British method BS 8414-1 and the German method DIN4102-20 is to be used. The method BS 8414-1 is not much different from the ISO 13785 method and it could mean that there will be a common EN-ISO method.

Work is underway to develop underpinning technical data that shows the strengths and weaknesses of the different methods. This work is necessary to assess the methods and what requirements are appropriate. It is found that the results from fire tests may vary greatly with the test environment (e.g. the weather in case it is allowed to be performed outdoors, which is the case for BS 8414-1) and the geometry of the object being tested and these are facts that must be taken into account when the new methodology is developed.

The experimental results in this work showed that the fire exposure on the façade varies in both BS 8141-1 and in SP Fire 105. In these two methods, the amount of fuel to be used is specified, in BS 8141-1 a certain volume of wood and SP 105 Fire a certain volume of heptane, instead of, as in many other test methods (not necessarily façade testing), a certain fuel consumption rate or incident radiation. In addition, the geometry of the combustion chamber is specified. This means that it is not possible to control the fire exposure on the façade surface, and it may differ from test to test due to factors such as air movement around the combustion chamber and the geometry of the façade system.

It was also found that the thickness of the test object affects the exposure on the façade surface because the convective heat transfer change and energy will be absorbed by the underside of the façade before the fire reaches the façade surface. It has also been shown in other studies that the air movements that are around the test set (wind, etc.) can have a significant impact on the test. Even in a controlled environment indoors the fire exposure is somewhat uncontrollable, however to a much smaller degree.

In the way forward it is essential to ensure that the harmonized (within the EU) method for façades is robust, well repeatable and reproducible. However, in order to succeed there are several issues to be resolved. The fire exposure to the façade can for example be measured with plate thermometers (a sensor that represents an object and measures in specific direction) similarly as in traditional fire resistance tests and flame spread can be measured in the object with sensors instead of visual inspection. Another possible way forward is to define a time-temperature curve of the sample and use controllable gas burners or varying ventilation conditions, instead of defining a given amount of fuel. If other solid fuels are to be used, the pre-testing done to define the amount of fuel that should be used has to be complemented by regular calibration tests and detailed specifications how to arrange the source in the combustion chamber. It is also possible to control the fire with adjustable ventilation. However, the seemingly easiest way is to define a classification system where all countries specific regulations can be fulfilled with minimum change to the methods. This can e.g. be done by defining a classification system where size of the fire is specified, if windows are included or falling parts are recorded, work in this direction is under way. In order to have a harmonized method, a number of compromises between countries and methods are needed before any consensus can be reached. However, also consensus in analysis and what factors should be assessed and evaluated is needed.

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Appendix A

Test methods in Europe and their scope and field of application.

Country	Test method	Scope of test method	Field of application	Scale	Configuration
Poland	1. PN-B-02867:2013	Determination of fire behavior of façades without window. The test philosophy is to determine the heat and flames influence contribution of the façade's combustion on the effect of exposure of standard fire source.	All façade systems	Medium scale	Single vertical wall without openings
UK Republic of Ireland	BS 8414-1:2015 and BS 8414-2:2015	Part 1 - Fire performance of external cladding systems. Test method for non-load-bearing external cladding systems applied to the masonry face of a building. Part 2 - Fire performance of external cladding systems. Test method for non-load-bearing external cladding systems fixed to and supported by a structural steel frame.	Applicable to the system as tested.	Full scale	Right angle, return wall
Switzerland	Prüfbestimmung für Aussenwandbekleidungssysteme	The test method is used for the evaluation and proof of the fire behavior of external wall covering systems on the original scale, when exposed to fire from a simulated apartment fire with flames emerging out through a window opening.	The test method is applicable to linings and surface coatings (paints, plasters, etc.) used on exterior walls. Included are elements with limited application area, such as decorative elements, cornices and balcony railing garments.	Full scale	Single vertical wall, no wing
Germany Switzerland	E DIN 4102-20	Complementary test of the cladding systems (each part of the system has to be low flammable	Complementary test of the cladding systems (each part of the system has	Medium scale	Two wings (i.e. corner) configuration

Country	Test method	Scope of test method	Field of application	Scale	Configuratio n
		according to DIN 4102-1 or DIN EN 13501-1) for classification as low flammable as a system.	to be low flammable according to DIN 4102-1 or EN 13501-1) for classification as low flammable as a system.		
Germany	Technical regulation A 2.2.1.5	Test for ETICS with EPS insulation, shows fire performance of the system when a fire outside the building occurs. A burning waste container is represented by a 200 kg wood crib.	Test for ETICS with EPS insulation, shows fire performance of the system when a fire outside the building occurs. A burning waste container is represented by a 200 kg wood crib.	Full scale	Two wings (i.e. corner) configuration
France	LEPIR 2	Determination of fire behavior of façades of building with windows, test method and classification criteria	All façade systems including windows	Full scale	Single vertical wall
Hungary	MSZ 14800-6:2009 Fire resistance tests. Part 6: Fire propagation test for building façades	1. Combustible and ventilated façade solutions applied on non-combustible basis wall 2. Special façade solutions, where the vertical distance between the openings are smaller than a certain value (usually 1,3m) (For example between French windows) 3. Other façade structures with openings - solutions without non-combustible basis wall - solutions including a fire barrier - other innovative solutions	There are no provisions for extending the test results.	Full scale	Single vertical wall with two openings.
Austria Switzerland	ÖNORM B 3800-5	This method simulates a fire from a window	The test method described is app-	Full scale	Vertical wall and a right

Country	Test method	Scope of test method	Field of application	Scale	Configuratio n
		burnout of an apartment. The test simulates the flame height in the second floor over the fire floor (the test concept based on Kotthoff-theories). The behavior of the construction and material and the fire spread (flame spread) in the wall/cladding can be studied.	licable to: -ventilated façades -non ventilated façades -ETICS -(as well as for curtain walling according to Austrian building-regulations; from our point of view not possible for products according to EN 13830)		angle wing
Sweden Norway Denmark	SP Fire 105	This SP method specifies a procedure to determine the reaction to fire of materials and construction of external wall assemblies or façade claddings, when exposed to fire from a simulated apartment fire with flames emerging out through a window opening. The behavior of the construction and material and the fire spread (flame spread) in the wall/cladding can be studied.	The test method described is applicable to: -external wall assemblies -and façade claddings added to an existing external wall. The test method is only applicable to vertical constructions. The method is not applicable for determination of the structural strength of an external wall assembly or façade cladding construction when exposed to fire.	Full scale	Single vertical wall
Finland	Tekniikka opastaa 16 (Engineering guidance 16)	Test method, which determines the fire safety of the façade when insulation material is inflammable. The flame effect (flame spread and fire spread) on the surface of the wall and within the wall structure is examined.	Use of inflammable insulation material and render in 3-8 story buildings in reconstruction. Note: In practice the test method has been used for timber façades as well.	Full scale	Single vertical wall
Slovakia	ISO 13785-2			Full scale	Right angle, return wall

Appendix B

Requirements for falling off within European countries.

Country	Requirement	Method
Austria	No more than 5 kg or more than 0.4 m^2)	ÖNORM B 3800-5
Denmark, Norway, Sweden	There may not be any large pieces falling down from the façade	SP Fire 105
Finland	No pieces of the specimen (parts of wall) in excess of 0.1 m^2 shall fall down	Engineering guidance 16
Germany	Falling parts recorded	DIN 4102-20
Great Britain, Republic of Ireland	Spalling, delamination or flaming debris is recorded and should be considered as part of the overall risk assessment when specifying the system. Burning debris and pool fire.	BS 8414
Hungary	Heavier falling part than 5 kg	MSZ 14800-6:2009
Poland	Falling flaming parts	1. PN-B-02867:2013
Switzerland	Falling parts recorded	DIN 4102-20 / ÖNorm B 3800-5

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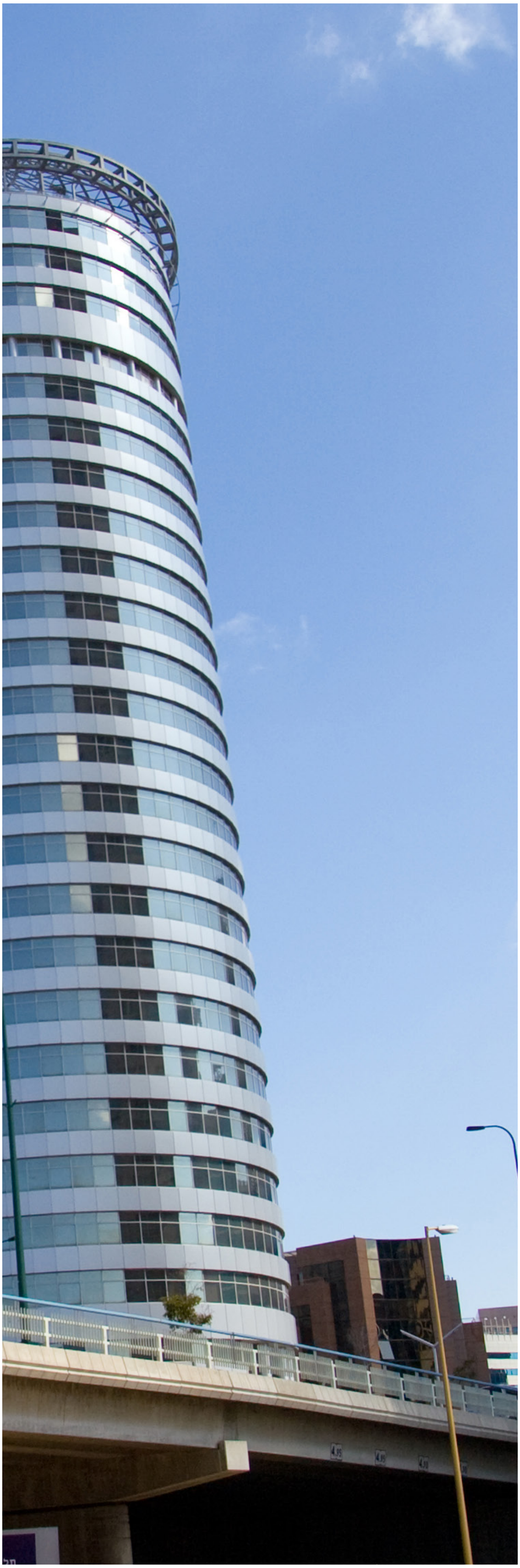

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