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Design Fires for Enclosures II -Field Model Based Design Fires

Brandforsk project 323-021

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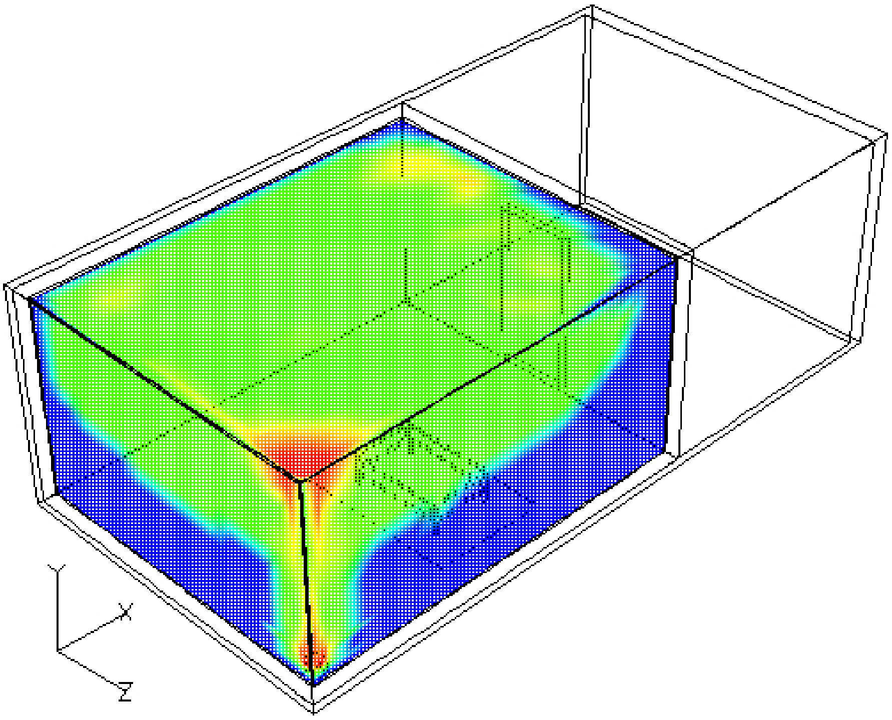

Abstract

One of the most important aspects to ensure safe evacuation of a building is to have an accurate tool for prediction of the fire development. This tool must be able to interpret and use information about the geometry of a building, surface linings and possible ignition hazards to create a proper design fire. Traditionally design fires are created using simple quadratic functions with a guessed growth rate. Recently, attempts were made using zone models to simulate the flame spread and better predict design fires in buildings. This work goes one step further using small-scale data to simulate two different large-scale fire tests in the CFD code SOFIE. The results were compared with experiment and earlier simulations done with a zone-model and the ConeTools model. Good predictions were achieved for most materials with the exception of some exotic materials. The procedure can be used for determining design fires for complex scenarios where the geometry does not allow zone models to be used.

Key words: flame spread, design fire, full-scale tests, simulations, CFD, SOFIE

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Preface

This work was sponsored by the Swedish Board for Fire Research, BRANDFORSK, as BRANDFORSK project 323-021. We would especially like to thank Cecile Cohe of the University of Valenciennes, France, for her big effort and large contributions to the simulation work.

Sammanfattning

Nyligen genomfördes ett projekt som undersökte möjligheten att använda zonmodeller för att skapa dimensionerande bränder. Utgångspunkten var att man använder data från småskaliga brandprovningar (konkalorimeter) på ytskikten och sedan kör en simulering av en rumsbrand med flamspridning i zonmodellen. Med zonmodeller är man dock begränsad i vilken geometri som går att simulera och även i vilken information man kan få ut från beräkningen. Detta projekt tar ett steg vidare och använder en CFD-kod med en enklare flamspridningsmodell. Också här utnyttjas data från liten skala för att förutsäga hur branden utvecklar sig. Som exempel har två olika fullskaliga rumsscenarier simulerats med CFD och resultaten har jämförts både med experimentella data och med simuleringar med de enklare verktygen som användes i förra projektet. Scenarierna som simulerats är Room/Corner test med gasbrännare som antändningskälla och ett större rum med en brinnande fåtölj och en gasbrännare som antändningskällor. I båda fallen simulerades flera olika material för att representera olika brandbeteende och olika Euroklasser, totalt 17 olika byggnadsmaterial. De experimentella resultaten är hämtade från tidigare projekt. Simuleringarna med CFD gav god överensstämmelse med experimenten med undantag för några produkter och det visas att man kan skapa en dimensionerande brand med CFD.

1 Background

Performance-based fire safety engineering (FSE) is an important tool for creating fire safe environments. However, much of the necessary information for using the FSE tool efficiently is today either lacking or poorly understood. An important part of FSE is the assumed fire growth for the environment in question. Many uncertainties in FSE are related to how close to a real situation the model fire can get. This model fire is frequently called the “design fire”. The choice of design fire will in the end have a big influence on how escape routes etc is dimensioned.

Earlier, the design fires used have been based on some very general, heuristic concept of fires and fire environments, e.g. ‘fast fire, slow fire’ and ‘official buildings, private buildings’, see for example [1]. The models describing the fire evolution were based on a simple quadratic time-function that provided a fire HRR (Heat Release Rate) $\dot{Q}$, e.g. :

$$\dot{Q} = \alpha t^2$$

The parameter α is chosen based on the type of building and/or material studied. It should be obvious that such a simple model cannot describe the complexity of real fire scenarios. It is used, however, in order to provide some kind of rough estimate of the fire evolution. As the physical models and the software and hardware becomes more evolved, the possibility of doing better simulations that corresponds more accurately to the real fire than the previous simple models increases. Such models and tools were demonstrated in a previous work [2] and the technique will be further elaborated in this report through the usage of a field model.

2 Differentiated simulation method

In an earlier SP report [2] it was shown a general methodology for creating design fires utilizing empirical data from the small scale ISO 5660 [3], Cone Calorimeter test. Two models were used in the study. One was a semi-empirical model called ConeTools [4] that simulates the intermediate-scale EN 13823 SBI-test [8] and the ISO 9705 full-scale Room/Corner Test [9]. The other was a 2-Zone model called BRANZfire [5,6] that incorporates the capability of flame spread modelling into a traditional 2-Zone model.

In the previous SP Report it was shown that the impact of enclosure size and ventilation, as well as the impact of various initial fires, e.g. a burning piece of upholstered furniture or a chair, could be incorporated into existing simulation tools with relative ease. It was also demonstrated that 'typified' materials could be defined and used in the method. An example of this approach, was the 'creation' of input data to the models through averaging of experimental Cone Calorimeter data for various materials, classified according to the Euroclass standard for surface linings [7]. It was shown that the method made it possible to 'recreate' expected experimental results for different classes in the SBI and Room/Corner scenario respectively. This was accomplished through the following procedure:

1. The SBI test-method (or Room/Corner ISO 9705) provided information on which Euroclass a certain material belonged to
2. Cone calorimeter data for materials belonging to a particular class were averaged
3. The data was used as input to a model in order to simulate an SBI experiment
4. The simulated results were found to be in accordance with what was to be expected from this particular class of surface linings, i.e. the system was 'closed'.

According to the SBI-criteria [7] for the Euroclass system, different classes are defined by a certain critical FIGRA[1] value. These Euroclass FIGRA-values and the values obtained from the simulations are represented in the table below.

Euroclass	**A2+B**	**C**	**D**	**E+F**
Classification criteria	$FIGRA \leq 120\ W/s$	$FIGRA \leq 250\ W/s$	$FIGRA \leq 750\ W/s$	$FIGRA \leq 750\ W/s$
Simulation	$FIGRA = 38\ W/s$	$FIGRA = 120\ W/s$	$FIGRA = 475\ W/s$	$FIGRA = 692\ W/s$

Table 1. Comparison between Euroclass FIGRA and simulated results from averaged Cone calorimeter data

As can be seen, the obtained values clearly demonstrate that the simulations based on averaged Cone calorimeter data provided correct FIGRA, except for the E+F Euroclasses where the obtained value was somewhat low but still close to the limit.

Obviously any kind of Cone Calorimeter data averaging is possible (wood based products, polymer materials, ...) or one could imagine using a worst/best case scenario for a particular group of materials to estimate a 'span' in fire behaviour. The only thing that is needed is sufficient amount of the small scale Cone Calorimeter data.

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[1] defined by max_(HRR(t)/t)

3 Field model

It was demonstrated in the earlier report that the simulation tools chosen managed very well to simulate the intermediate scale scenario (SBI [8]) and also the full scale scenario (ISO 9705 [9]) and it was further demonstrated that the models could simulate quite well fire evolution in even larger enclosures, based on the small scale data. This was confirmed through comparison with several real scale experiments.

The models used in the earlier work has many advantages in the sense that they are fast (a few minutes of simulation time), simple to use, and the results are easily interpreted by someone having just basic knowledge in enclosure fire and general fire dynamics.

However, the simplicity of the models used also has its drawbacks. Mainly this is related to a lack in degree of freedom to define enclosures with more complex geometries, or enclosures where the basic assumptions underlying the simple models are violated, e.g. where the enclosure volume is very large compared to the fire so that a 2-Zone model is invalid.

In case of a complex fire scenario, sometimes the only possible mean to simulate the events is through a CFD-based ‘field’ model (CFD = Computational Fluid Dynamics). This model uses first principles to simulate mass, heat and momentum variations within the computational domain. However, the CFD code also needs to be complemented with combustion and flame spread models in order to be able to simulate fires. By using the same type of flame spread model that was used in the simple models mentioned above, i.e. a flame spread model based on empirical data from the ISO 5660, Cone calorimeter test, we obtain a continuous overlap between the simple and the complex models. This also makes it possible to test and compare the results from the different tools as they are comparable in the sense that differences in result are due to the model itself and not to variations in input data.

In this report is shown the results from using the field model SOFIE that utilizes several flame spread models, among which one based on using input data from the Cone calorimeter.

The disadvantage of the field model is that it requires more experience and skill from the user, compared to the simpler models, in order to make the actual simulation but also in order to understand and interpret the output data. Further it requires much more computational powers. A complex, large-scale fire simulation can take several days up to weeks to complete.

3.1 SOFIE

The numerical simulations were carried out using the CFD code SOFIE (Simulation of Fires in Enclosures), which is specifically designed for prediction of fires within enclosures [10]. The code has been developed at Cranfield University (UK) within the framework of a European consortium, including SP Swedish National Research and Testing Institute. The SOFIE code is based on a finite volume algorithm using a non-orthogonal coordinate system with co-located velocities and a SIMPLEC type pressure correction scheme.

For the simulations reported in this work the dependent variable interpolation was achieved using a first order hybrid scheme and a TDMA solver. The turbulent model used was the standard κ-ε model with additional buoyancy correction incorporated. Combustion was simulated using an eddy break-up model [11] with different fuels depending on the materials. Soot was introduced into the computational domain through conversion of a constant fuel mass fraction into soot at the fuel source. A conversion factor of 2 % was used in this work, as this has previously been reported to be a reasonable approximation [12].

Further, the thermal radiation was simulated using the discrete transfer radiation model with gaseous optical properties described by a weighted sum of grey gases model [10].

3.1.1 Flame spread model in SOFIE

When simulating the fire spread in an enclosure the quality and robustness of the flame spread model is very important. The flame spread model used for the simulation is the Cone Calorimeter model in SOFIE [13]. This model demands as input heat release data from Cone Calorimeter tests at three different heat flux levels. The prediction of ignition is based on the critical heat load absorbed by the material and can be expressed by

$$\int_0^{t_{ign}} \frac{1}{2}\dot{q}(t)\, t^{1/2} dt = constant$$

where $\dot{q}$ is the heat flux towards the surface, calculated by the CFD code. Once the criterion is fulfilled the material ignites and the local pyrolysis rate (or heat release) follows a curve described by the cone calorimeter data. The actual heat flux towards the surface at ignition decides which cone curve to follow. Since we only have input curves for three heat fluxes, interpolation by splines is used to define exactly what curve to follow.

Required input to the model, apart from the three cone curves, is the threshold flux and the minimum heat flux. The minimum heat flux prevents ignition to occur at too low heat fluxes, even if the limiting threshold flux is reached (accumulated).

The advantage of a field model when predicting flame spread is the access to thermal data, such as temperature, heat fluxes, convection, etc, at all times and at every point along all surfaces. This allows the model to calculate the ignition and flame spread also in complex geometries. Figure 30 in Annex 1 shows flames spread on the surfaces of a room at different times.

4 Experiments

Simulations made in SOFIE, BRANZfire and ConeTools were compared to experimental data from two previous investigations, the EUREFIC Project [14, 15] and the SBI Research Program [16]. The data shown in this report from these two investigations are all related to the ISO 9705 Room/Corner scenario. These data were complemented with a third more recent experiment series made in relation to the production of a video for educational purposes on the early stages of a fire and the importance of surface lining in the development of a fire in a furnished room [17]. The experimental set-ups of the above tests are briefly described in the following chapters.

4.1 Room/Corner test

The ISO 9705 Room/Corner test was used as a reference full-scale scenario in both the EUREFIC project and the SBI project.

The EUREFIC research programme was initiated to improve the technology of fire testing of wall and ceiling materials. 11 different products were selected and tested both in the Cone Calorimeter and in the Room/Corner test. Data is available from both scales. All 11 materials tested were simulated in this project. Details of the materials are shown in Table 2.

Table 2. Description of the EUREFIC materials used in the simulations.

Material no	**Product**	**Density (kg/m^3)**	**Thickness (mm)**
EUREFIC 01	Painted Gypsum paper plasterboard	800	12
EUREFIC 02	Ordinary Birch Plywood	600	12
EUREFIC 03	Textile wall covering on gypsum paper plasterboard	800	1 + 12
EUREFIC 04	Melamine faced high density non-combustible board	1055*	12.5
EUREFIC 05	Plastic faced steel sheet on mineral wool	640*	0.15 + 0.7 + 23
EUREFIC 06	FR (Flame Retarded) particle board type B1	630	16
EUREFIC 07	Combustible faced mineral wool	87*	30
EUREFIC 08	FR particle board	750	12
EUREFIC 09	Polyurethane foam covered with steel sheets	170*	81 + 1
EUREFIC 10	PVC wall carpet on gypsum paper plasterboard	800	0.9 + 12
EUREFIC 11	FR polystyrene foam	37	25

* Surface plus substrate

The SBI research programme was aimed at developing a fire testing system for wall and ceiling linings, which would be the base for the Euroclass system. The main test is the intermediate scale SBI and the Room/Corner test was used as the reference scenario. In the programme 30 materials were tested in the Room/Corner test and many of them also in the cone calorimeter. For the simulations in this project, 6 materials were chosen. The choice was made to represent a wide range of fire behaviour including all Euroclasses.

Table 3. Description of the SBI materials used in the simulations.

Material no	**Product**	**Density (kg/m^3)**	**Thickness (mm)**
SBI M05	Varnished mass timbre, pine	380	10
SBI M09	Paper wall covering on plasterboard	700	13
SBI M10	PVC wall carpet on plasterboard	700	13
SBI M22	Ordinary particle board	700	12
SBI M26	Low density fibre board	250	12
SBI M29	Textile wall paper on calcium silicate board	875	10

The Room/Corner test, ISO 9705, consists of a concrete room with a door opening. The inner dimensions are 2.4 x 3.6 x 2.4 m and the walls and ceiling are covered with the lining to be tested, see Figure 1. In one of the inner corners is placed a square propane diffusion burner. During a test the burner follows a heat release programme starting at

100 kW during the first ten minutes and then increased to 300 kW during the next ten minutes, making a total test time of 20 minutes. All smoke gases coming from the doorway are collected in an exhaust hood and led to a measurement section where Heat Release Rate and Smoke Production Rate are measured. If the fire reaches a certain size (around 600 - 800 kW) there will occur a flashover. A flashover is a phenomenon where the fire suddenly gets uncontrolled and all materials ignite and massive flames come out of the doorway. After the flashover, the fire is restrained by the amount of air that can come in through the doorway, the fire is said to be ventilation controlled.

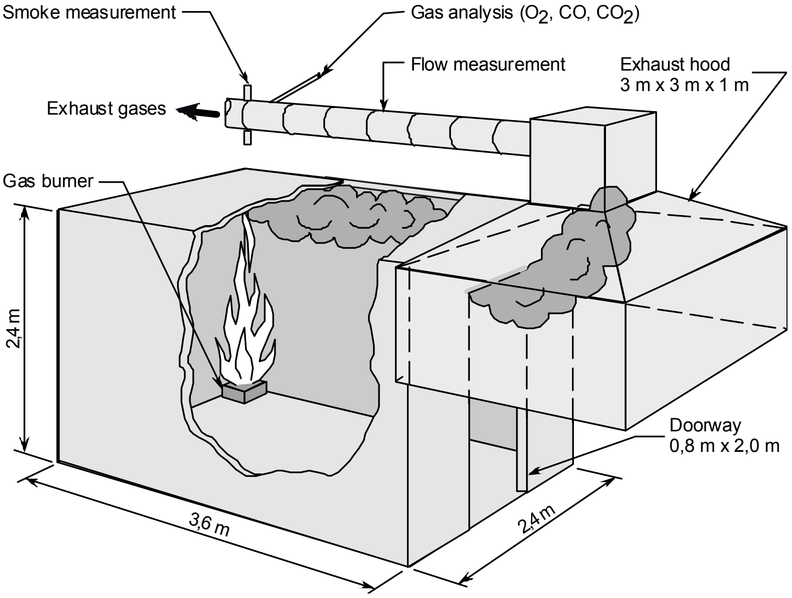


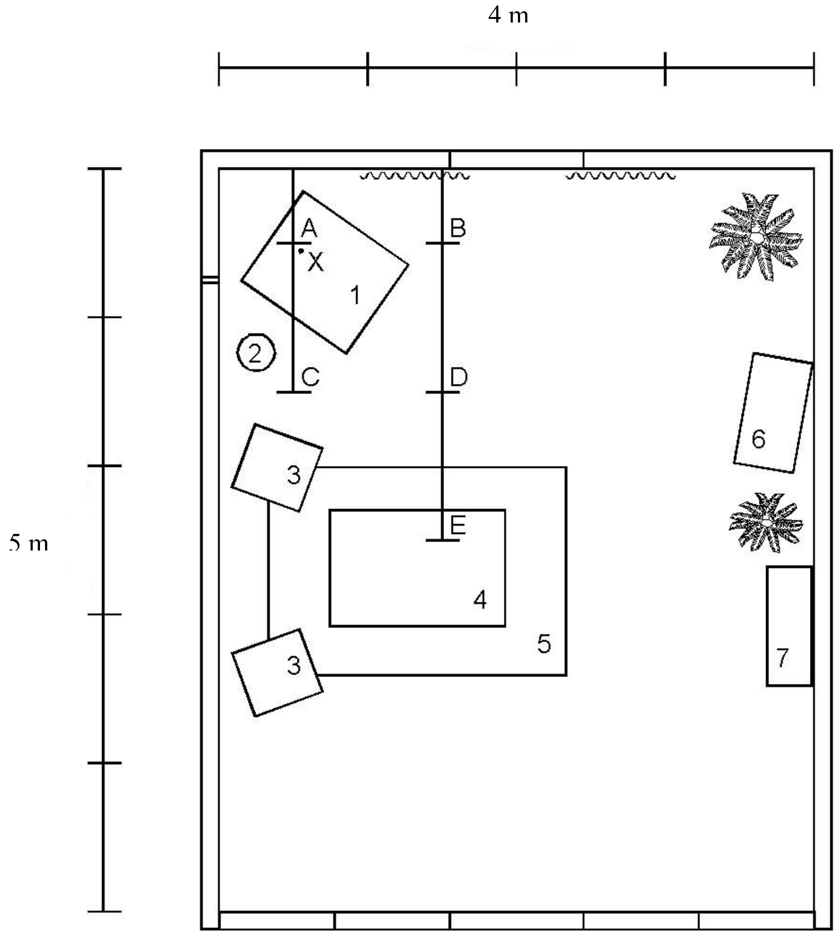
Figure 1. The ISO 9705 Room/Corner test, schematic view.

4.2 Furnished room

A number of full-scale experiments in a furnished room have been run at SP within a project aiming at creating an educational movie about fire in rooms. The movie is called “600 °C” [17] or “The Room Fire”. Data from the experiments were available and the scenario is well suited for the work with design fires and it was therefore decided to simulate the tests with SOFIE and Branzfire. A top view of the experimental set-up is shown in Figure 2. Two sets of experiments were conducted, one with a 30 kW gas diffusion burner as ignition source and one with an upholstered chair as ignition source. In both sets the ignition source was placed in the inner left corner. For both ignition sources, two different sets of linings were tested:

- In the first case, the walls and the ceiling were both covered with Euroclass B materials surface linings. The material used was 12 mm plasterboard.
- In the second case, the walls were covered with 12 mm high-density particleboard material and the ceiling with a 20 mm hardboard material. Both materials belong to Euroclass D.

The inner dimensions of the room were 4 x 5 x 2.5 m (width-length-height). There was a 2 x 0.9 m door opening in the front wall (bottom in Figure 2).



The objects are:

1- Chair, upholstered
2- Floor light
3- Seat
4- Table
5- Carpet
6- TV
7- Cupboard space

Thermocouples were placed just under the ceiling at the position from A to E and X.

Figure 2. Top view of the furnished room showing the experimental set-up.

5 Simulations set-up

5.1 Room Corner

In the SOFIE simulations the test room was represented without simplifications according to Figure 3. The large domain outside the room is included to minimize the influence of boundaries on the fire development in the room. The top boundary is set to atmospheric pressure. Any suction effect from the hood (see Figure 1) is neglected since this is considered not to affect the flame spread in the room.

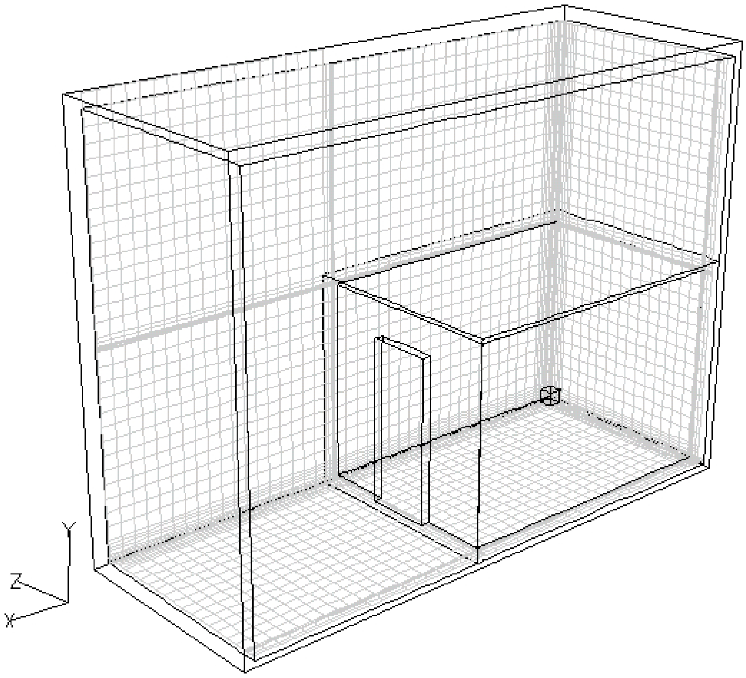


Figure 3. Geometry used for the simulation of the Room/Corner Test

The flame spread model requires input of two scalar parameters, the threshold flux and the minimum heat flux. These parameters were compiled from the cone calorimeter data.

All EUREFIC materials were also simulated with BRANZFIRE and data from these simulations are taken from the previous design fire report [2] where also further details about the zone model can be found.

5.2 Furnished room

In the SOFIE simulation, the geometry was simplified by defining only the upholstered chair or the gas burner, the carpet and the table, see Figure 5 - Figure 6. The other objects in Figure 2, e.g. flowers and lamps, were omitted for simplicity and not considered to contribute significantly to the fire development before flashover. In the chair scenario the chair could not be placed at an angle to the corner but was placed according to Figure 6. This restriction is due to the fact that the CFD code SOFIE uses a Cartesian coordinate system. The calculation domain was extended outside the room in front of the doorway in order to minimise the influence of boundaries.

In the case of the chair as ignition source the heat release was known from experiments with an identical chair tested under a heat release measurement hood. The resulting heat release rate used in the simulation is shown in Figure 4. Note that although the peak heat release is much higher than the 30 kW burner the fire development is very slow in the beginning. Also the fire in the chair starts in the seat and subsequently spreads, which means that the flames are not in contact with the linings until the fire involves the whole back of the chair. These events were modelled in SOFIE by using several fuel surfaces on the chair object that was activated at different times. It also means that the 30 kW scenario results in faster fire development in the room, see Figure 21 - Figure 22.

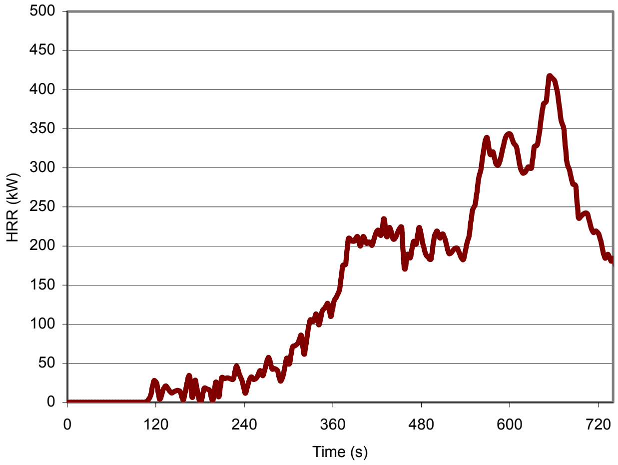


Figure 4. Heat release rate from the upholstered chair.

In the Euroclass B experiments both walls and ceiling were lined with plasterboard and this was easily defined in the CFD simulation. In the Euroclass D experiments however, the materials on the walls and ceiling were not identical, although quite similar both being wood materials. At this state SOFIE accepts only one type of surface material for flame spread simulation and the solution was to create an "average material" using cone data files from both materials. The input parameters threshold flux and minimum heat flux were also averaged.

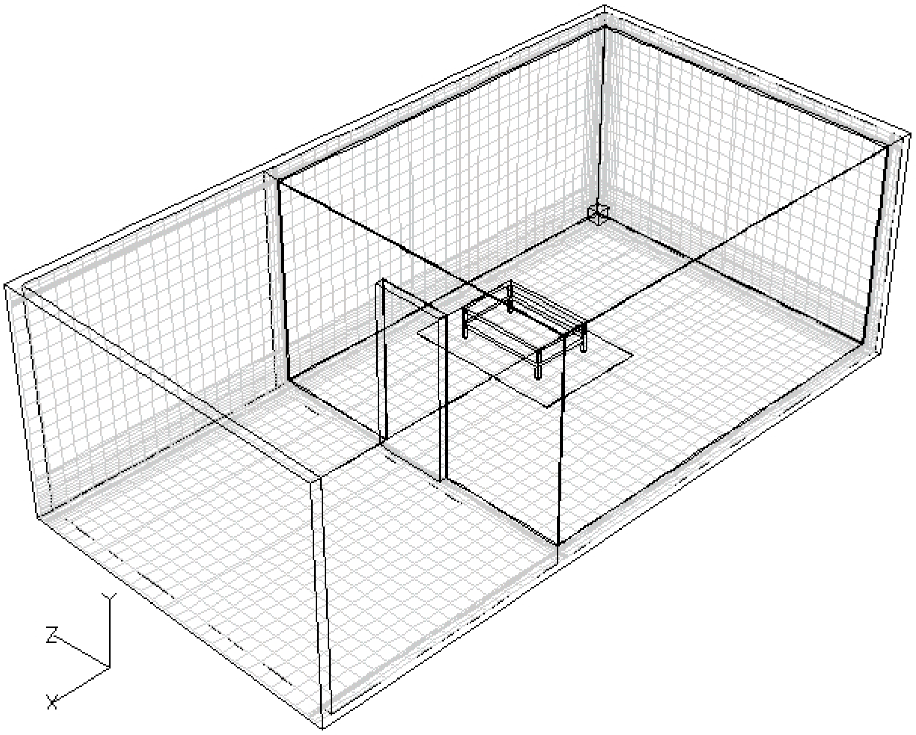


Figure 5. Geometry used for the simulation of the furnished room, gas burner scenario. The gas burner ignition source is placed in the left corner.

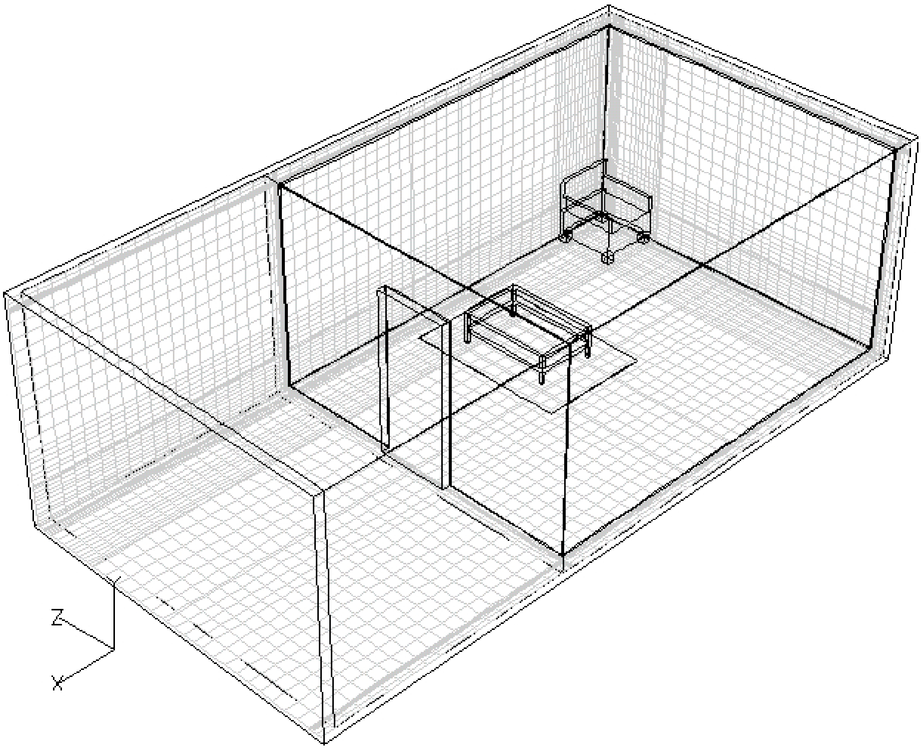


Figure 6. Geometry used for the simulation of the furnished room, upholstered chair scenario. The chair ignition source is placed in the left corner.

The chosen materials were also simulated in ConeTools and data was taken from [2]. It was however not possible to run the zone model BRANZFIRE on the SBI materials due to lack of cone data on several heat flux levels.

6 Simulation results

In the earlier report [2] it was found that the simulation tools produced results that were quite close to the experimental values. This is not very surprising since the instruments chosen for the simulation have both been tested and in a sense, optimised, with regards to the transformation of small-scale Cone Calorimeter data into Room/Corner or SBI behaviour. There is therefore no real reason to believe that the complex CFD tool would provide a more ‘correct’ picture of the events as long as the fire and enclosure are simple enough to be described by the more simple simulation tools. The experiments used in this and the previous report for comparison to the simulations, are almost all possible to simulate using BRANZfire and ConeTools. At least those that are based on Room/Corner or SBI experiments. For the larger enclosures and more complicated ignition sources, such as in the 600°C series of experiments [17] the limits for the simpler instruments are approached.

6.1 EUREFIC and SBI

Simulations of full-scale experiments in the Room/Corner test are compared with experimental data. For the EUREFIC materials a comparison is made between simulations in SOFIE, simulations in BRANZFIRE and data from experiments, for the SBI materials comparison is made between simulations in SOFIE, simulation in ConeTools and experiments. Note that the burner effect in the tests is 100 kW during the first ten minutes and 300 kW during the last 10 minutes.

Figure 7 shows an example comparison of experimental data and simulations of the Room/Corner test for EUREFIC material 01, which is painted plasterboard belonging to Euroclass B. The green line in the figure is data from experiment and it is clear that the material does not contribute much to the fire. Comparison with simulations in SOFIE and BRANZfire shows good agreement, although BRANZfire predicts a peak early in the test.

Another example is shown in Figure 8 for material M10 from the SBI project, PVC covering on plasterboard, belonging to Euroclass D. In the experiment the material reached flashover when the burner was increased to 300 kW (after 10 min). Both SOFIE and ConeTools are able to predict this behaviour. The complete set of graphs for all materials analysed can be found in Annex 1.

In general the agreement between SOFIE simulations and experimental data is good but for some cases SOFIE under predicts or over predicts the fire spread, see for example Figure 16 and Figure 21.

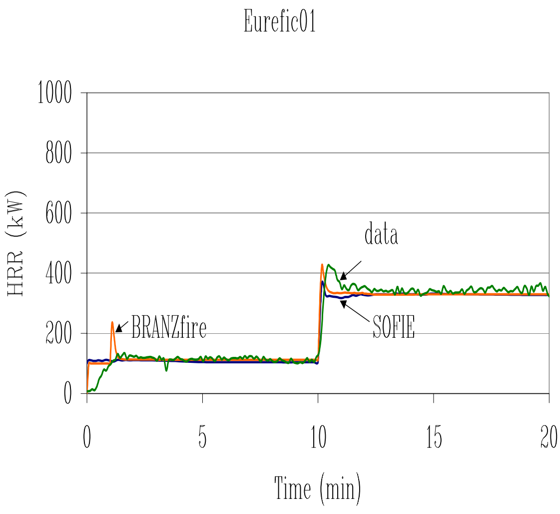


Figure 7. Painted plasterboard

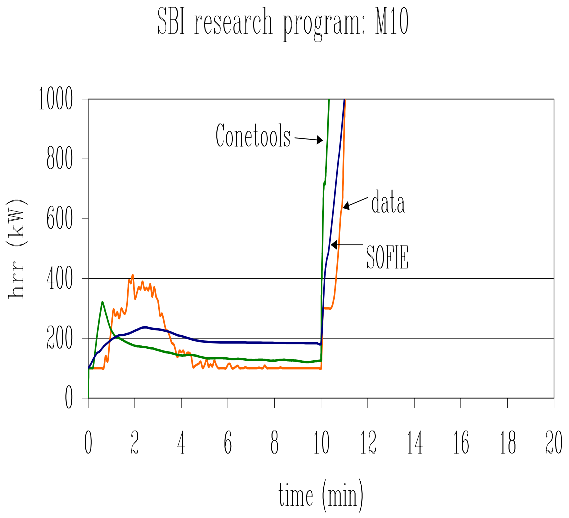
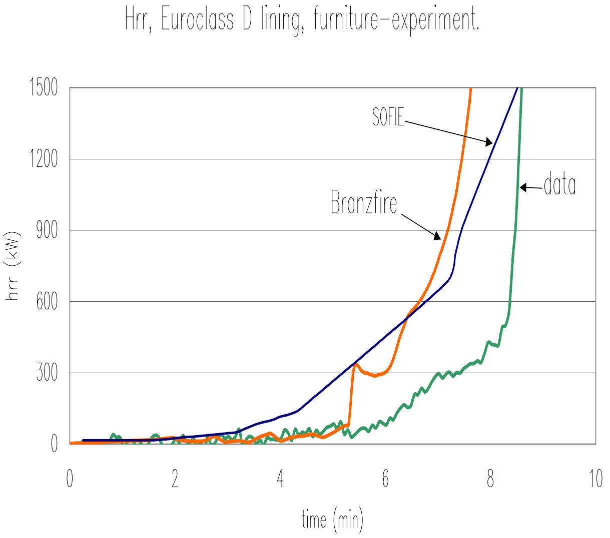


Figure 8. PVC on plasterboard

6.2 Furnished room (600 °C)

Here simulations are compared with experiments in the large room conducted during the recording of the movie “600 °C” [17]. The room was lined with different materials and Figure 9 shows a comparison of data and simulations from the case with Euroclass D linings (i.e materials that would reach a flashover in the Room/Corner test between 0-10 minutes during the 100 kW period) together with an upholstered chair as ignition source, see 4.2. Both in the experiments and the simulations the fire reaches flashover at approximately 8 minutes. This is demonstrated in the figures below.

The simulated temperatures were also compared in the furnished room test, see Figure 10. It is evident that SOFIE overestimated the temperature in the beginning of the test but at flashover the agreement is good. Temperatures after about 9 minutes are not relevant because the fire was extinguished.



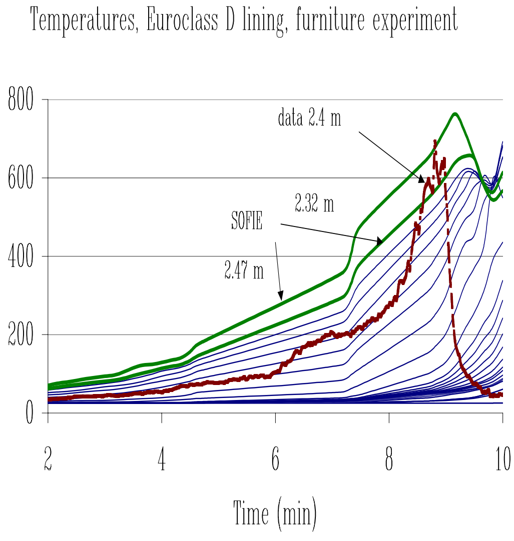


Figure 9. Euroclass D linings (hardboard and particle board).

Figure 10. Furnished room test with Euroclass D linings (hardboard and particle board).

7 Conclusions

Experiments from two different large-scale test set-ups are simulated with a CFD code and compared with simulations from the two simpler tools BRANZfire and ConeTools. Tests with several different materials with diverse fire behaviour are simulated. The results show good agreement between the CFD simulations and the experiments except for a few materials. The comparison with the simpler tools shows that for an uncomplicated scenario such as Room/Corner the simpler tools are usually as good as the CFD simulation. Sometimes even better. Therefore if the focus is to obtain the design fire or time to flashover for an uncomplicated scenario it is often sufficient to use a simple tool. If, on the other hand, the geometry does not allow a zone model to be used or if the interest lies in finding more detailed fire and enclosure data, such as a temperature or gas profile (species concentrations, etc), or to track detailed smoke movements in a building, the information can only be obtained from the CFD instrument.

This work has shown that CFD with simple flame spread models can be used to create design fires provided that small-scale data exists for the surface material. Future work is needed mainly to improve the flame-spread models in the CFD code.

Annex 1 Simulation results

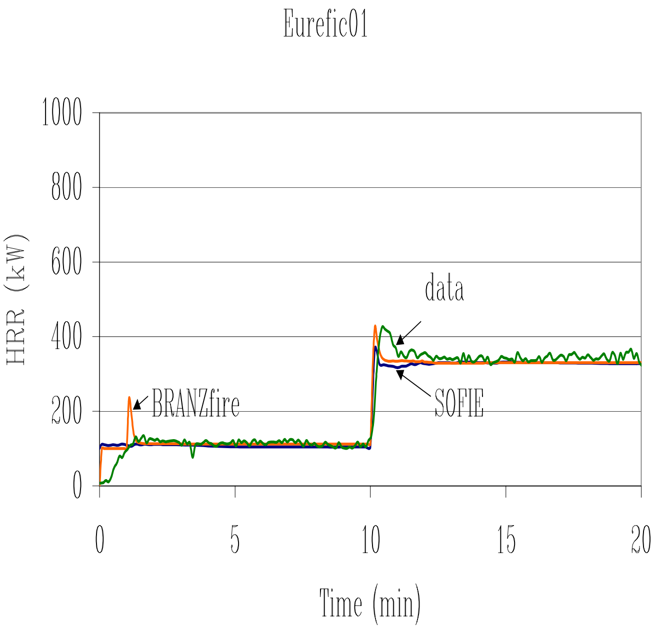


Figure 11. Painted gypsum plaster board

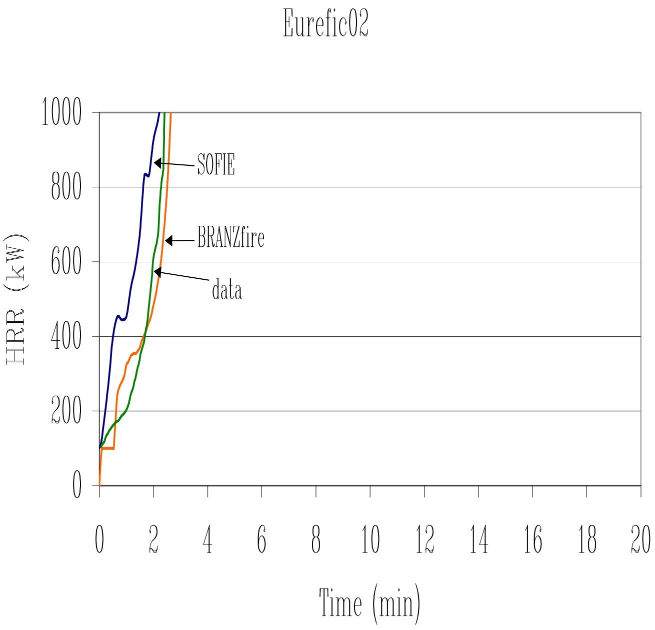


Figure 12. Ordinary Birch Plywood

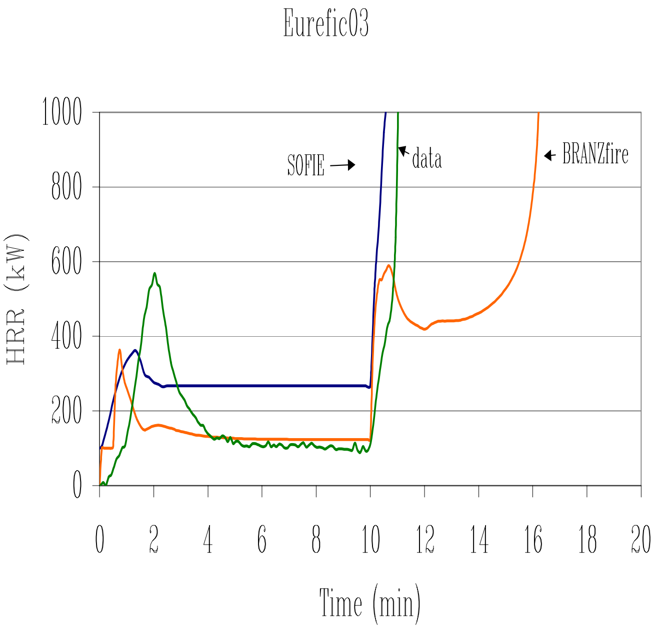


Figure 13. Textile on gypsum paper plaster board

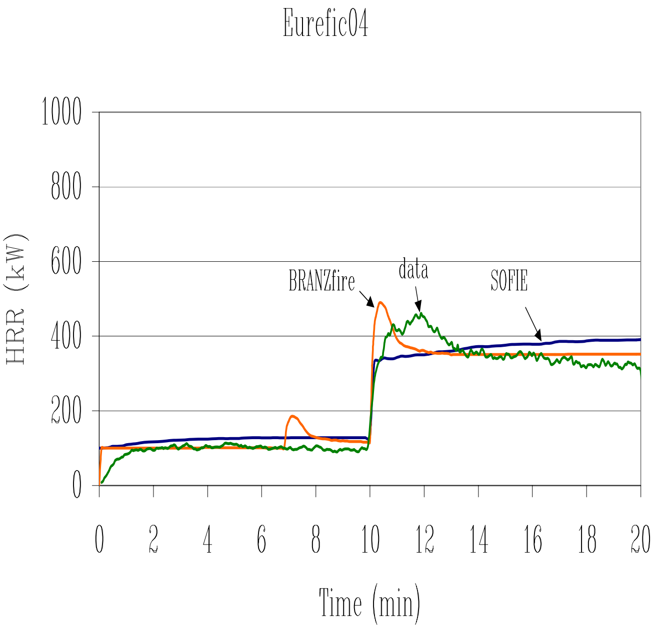


Figure 14. Melamine faced high-density non-comb. board

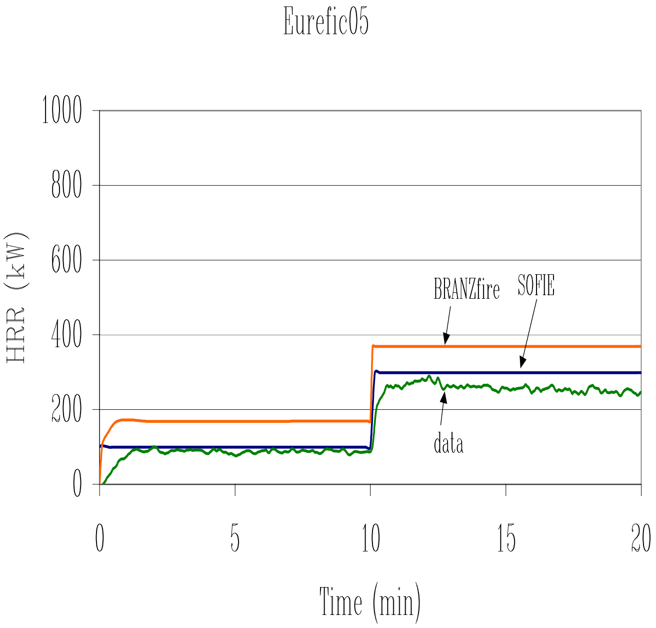


Figure 15. Plastic faced steel sheet on mineral wool

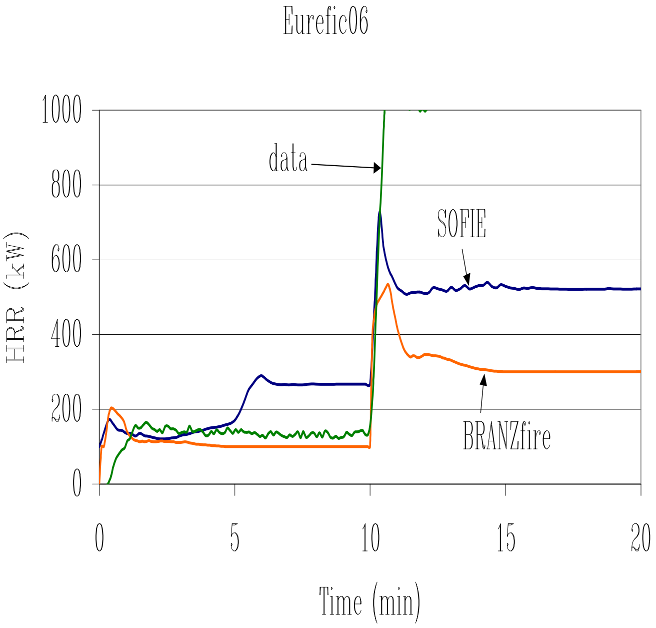


Figure 16. FR particle board type B1

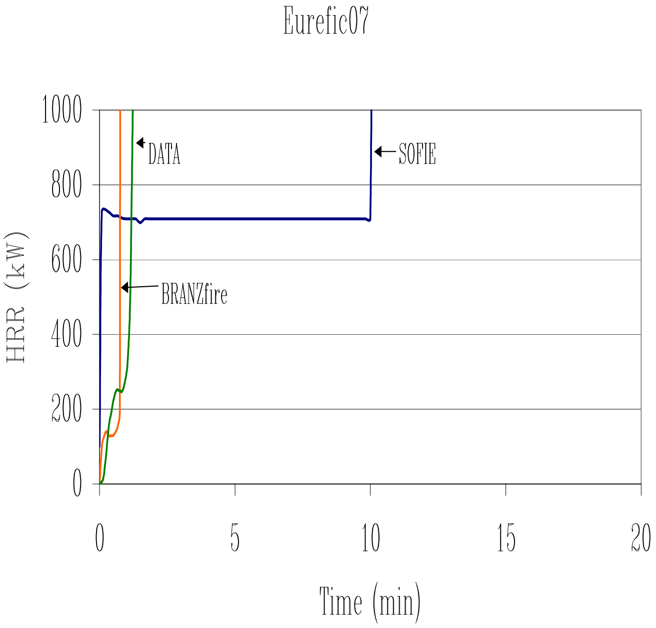


Figure 17. Combustible faced mineral wool

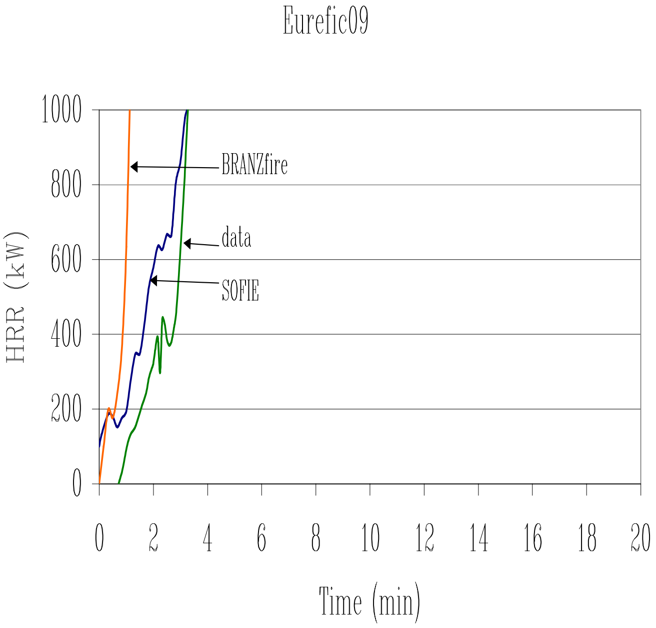


Figure 18. PUR foam covered with steel sheets

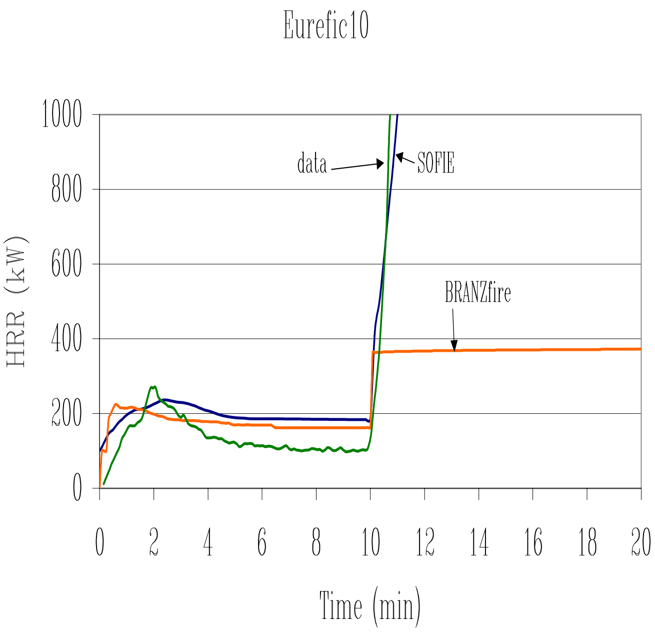


Figure 19. PVC on gypsum plaster board

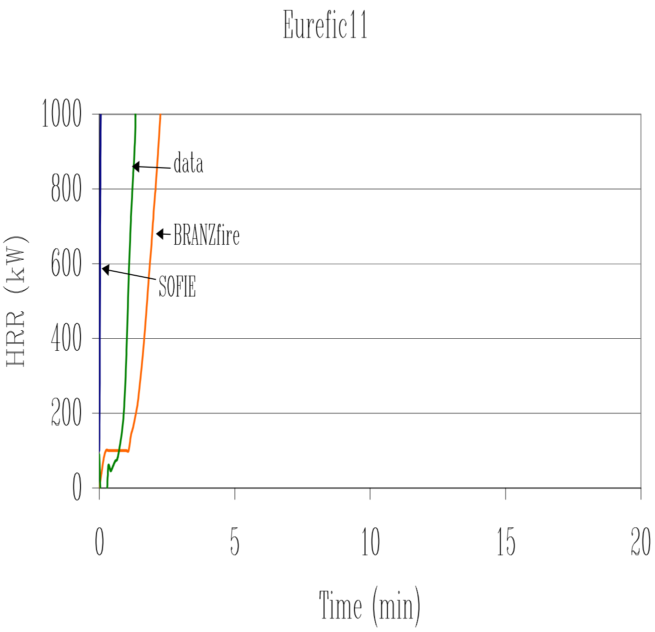


Figure 20. FR polystyrene foam

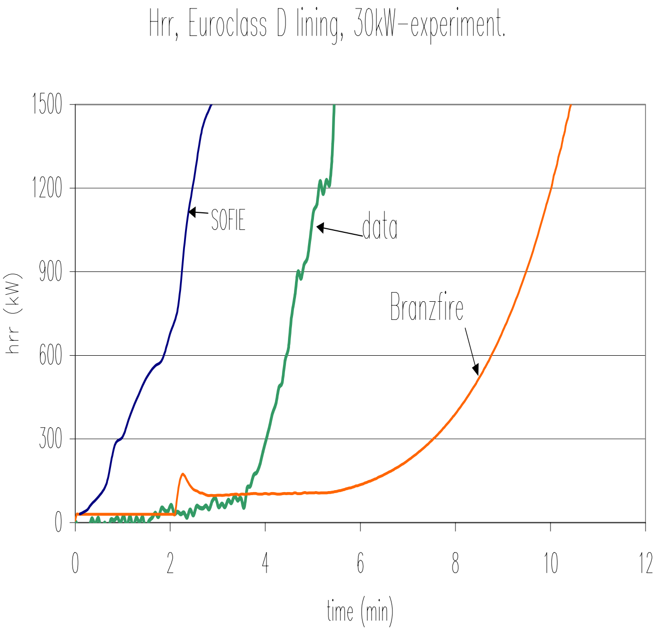


Figure 21. 600°C experimental data + simulations

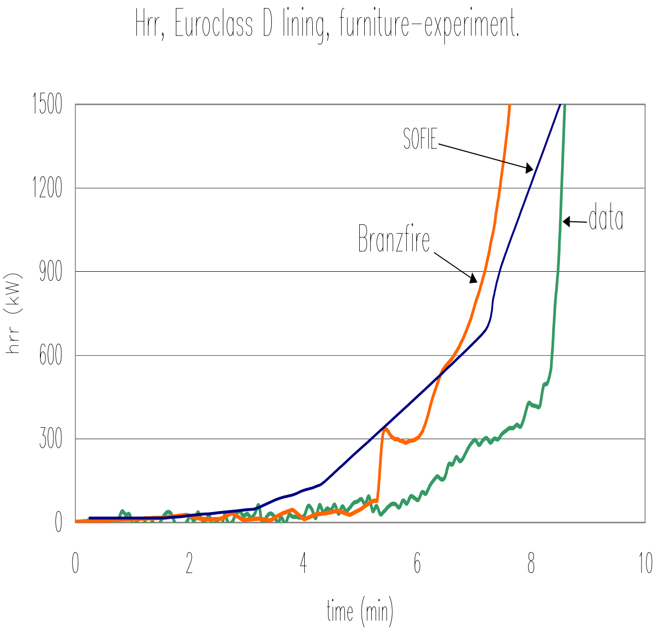


Figure 22. 600°C experimental data + simulations

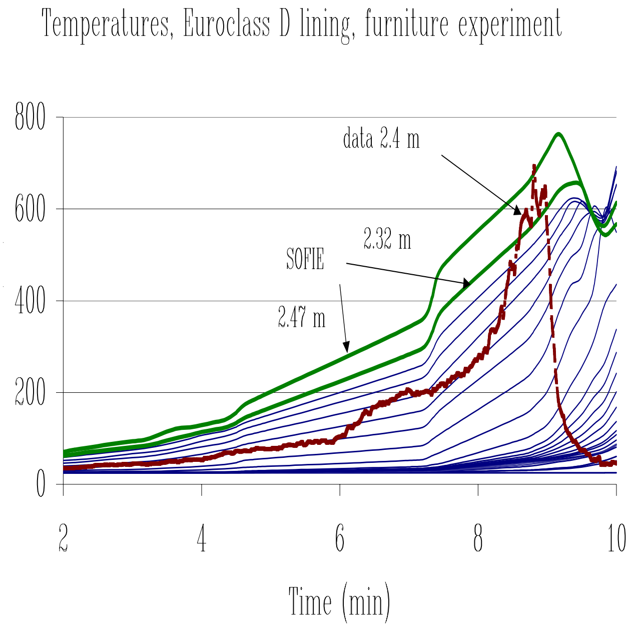


Figure 23. 600°C experimental data + simulations

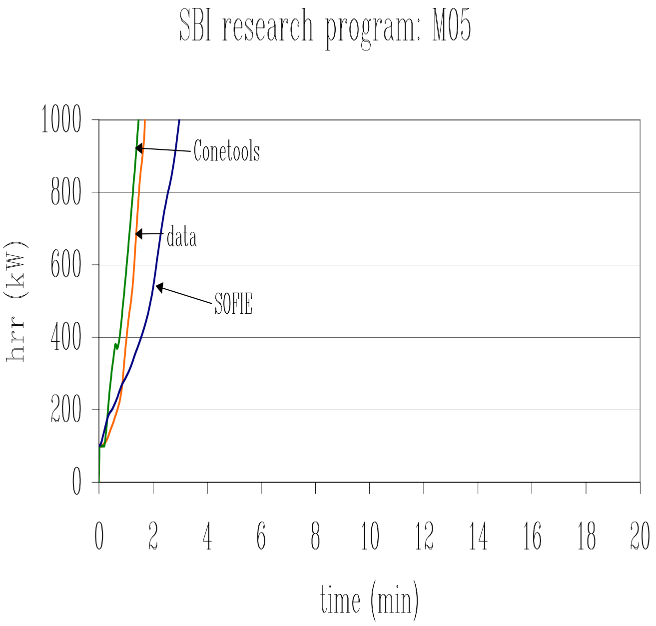


Figure 24. Varnished mass timbre, pine

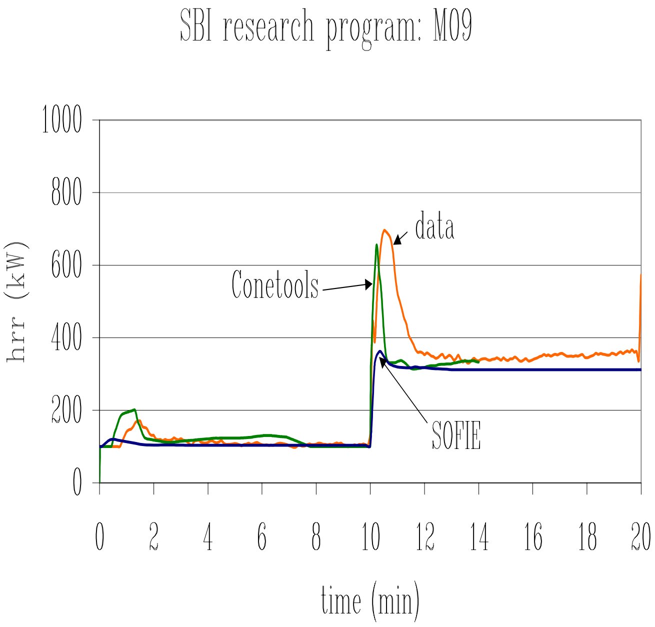


Figure 25. M09 Paper on plasterboard

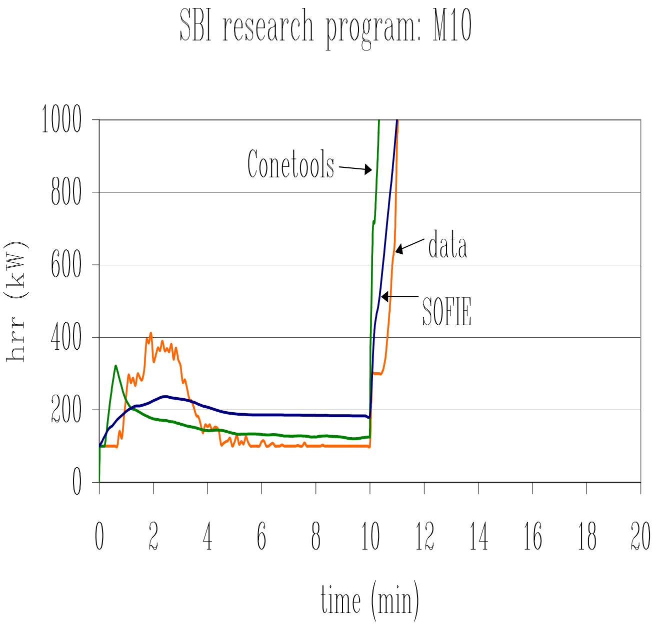


Figure 26. PVC on plasterboard

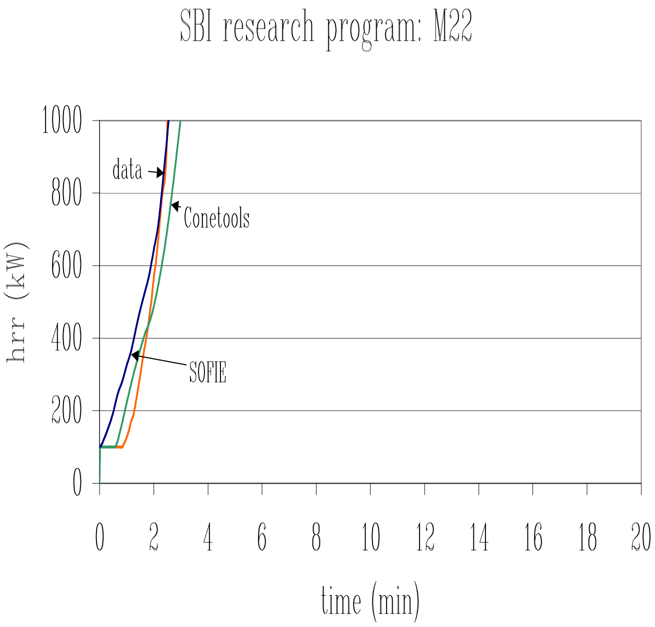


Figure 27. Ordinary particle board

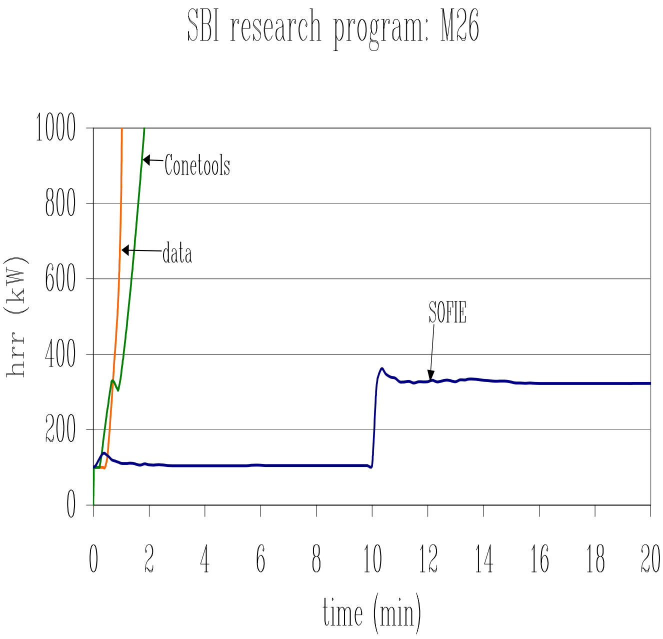


Figure 28. Low density fibre board

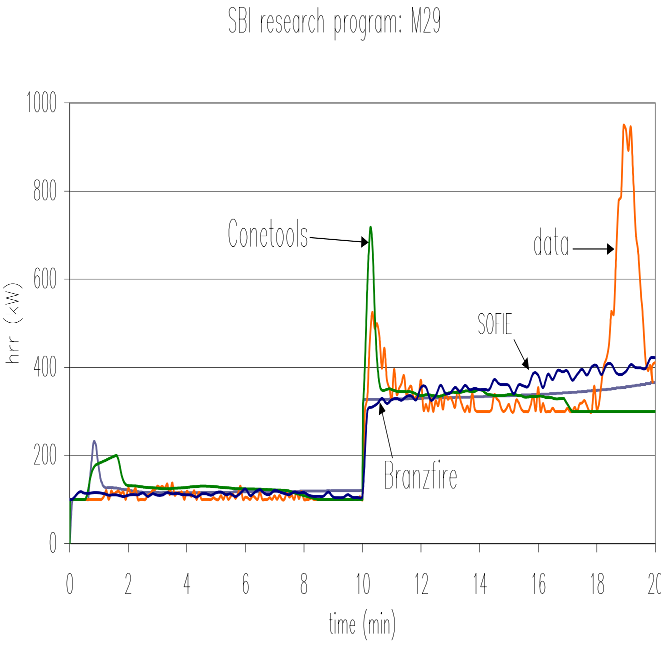
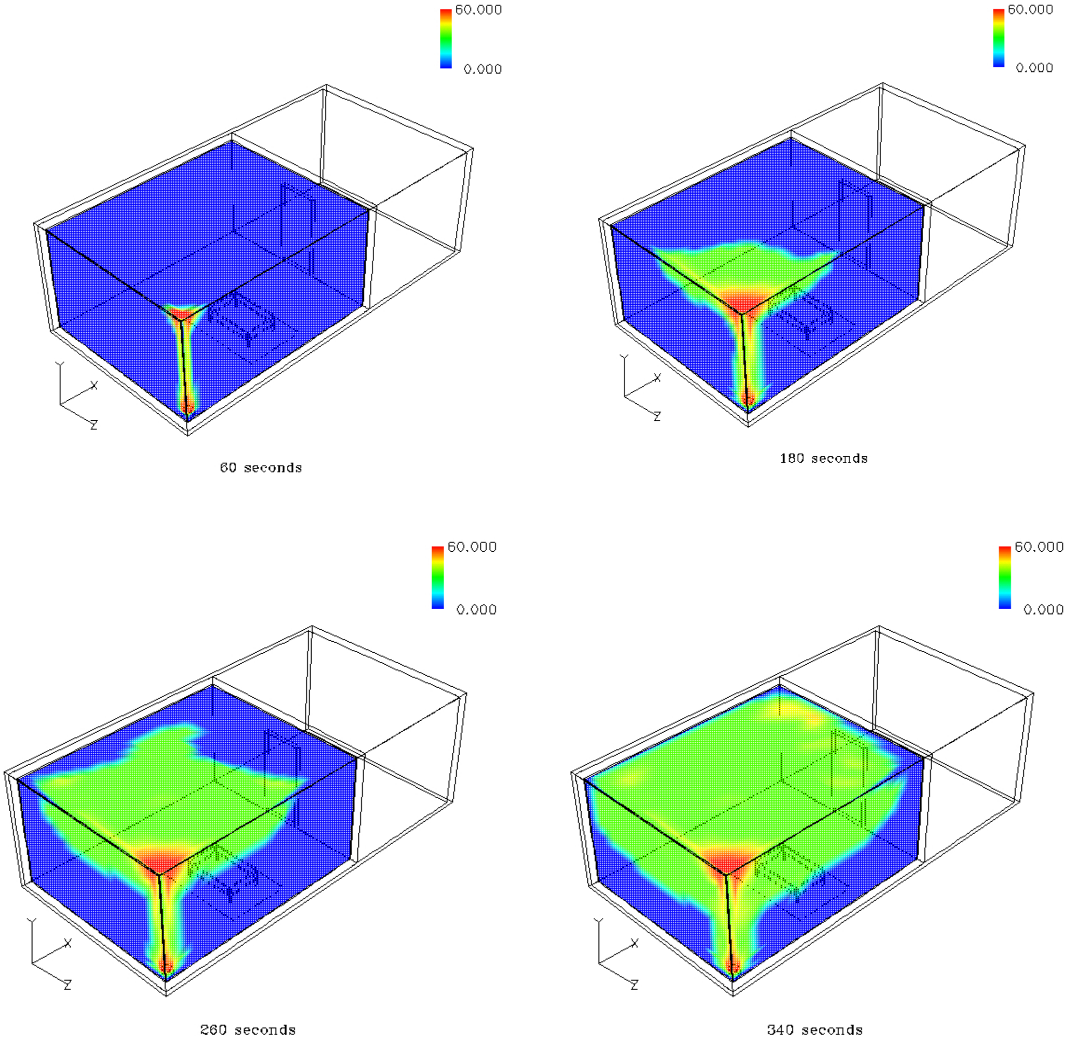


Figure 29. Textile on calcium silicate board



60 seconds

180 seconds

260 seconds

340 seconds

Figure 30. Snapshots of the flame spread at different times in the furnished room, 30 kW gas burner scenario and Euroclass D linings.

8 References

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