FIRE SPREAD AND TENABILITY IN SINGLE FAMILY DWELLINGS: COMBINING LIVE FIRE EXPERIMENTS AND FSE-MODELING

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ABSTRACT

This paper presents a brief overview of the combination of live fire experiments and Fire Safety Engineering (FSE) modeling, with the aim to find out if the used technique of FSE-modeling could provide more insight in the observed phenomena in fire spread during a series of fire experiments. A technique of inverse modeling is used to determine the heat release rate (HRR) of the fires in the live experiments. A predictor-corrector method and the Consolidated Model of Fire and Smoke Transport (CFAST) are used to calculate and compare the hot gas layer (HGL) temperatures. The calculations of the HRR are then compared to the data from the live fire experiments.
The results show that this technique can provide more insight in the observed fire spread and helps to explain why the fire spread stopped in most cases shortly before reaching the flashover stage. Therefore the conclusion is that the use of FSE-modeling is of great value to the analysis of the live fire experiments. Vice versa it is also concluded that the live fire experiments are of great value for the input of principles and preconditions in fire models such as CFAST. With a better understanding of the principles and preconditions, fire models can possibly be used as an addition to live fire experiments. With better principles and preconditions, fire models could possibly be used to reduce the number of expensive and environment threatening live fire experiments.

INTRODUCTION

The live fire experiments carried out by the Fire Service Academy, with the aim to gain insight into fire development and survivability in dwellings, took place against the background of the following figures for the Netherlands:

- There are some 14,000 fires in dwellings, and companies every year;
- These fires claim between 800 and 900 casualties[1] a year, 32 of which – on average – are fatalities[2].

The expectation is that the ageing population, combined with the increase in the number of people with reduced ability to leave a building without assistance and who live on their own, will lead to a 16 percent[3] increase in the number of fire casualties in the next few years.
Furthermore, these 14,000 fires, roughly speaking, in dwellings and companies, plus the approximately 20,000 outdoor fires negatively affect the health of local residents and the environment (air, water, soil). And some fires, especially major industrial fires, lead to a certain degree of community disruption because local residents and companies have to be advised to stay indoors and keep their doors and windows closed to keep smoke out.
The joint (Dutch) fire brigades have defined their strategic ambition in '*De Brandweer over morgen*' (The Fire Service for tomorrow), which includes the following points:

- The fire service wishes to minimize the number of fires and casualties (both civilians and firefighters) of fires;
- The fire service wishes to increase the effectiveness of its deployment, resulting in fewer economic losses, less community disruption and a lower environmental burden.

Implementing these strategic ambitions requires an understanding of the manner in which fires develop in dwellings, so that the fire service can take action more effectively in all links of the safety chain in order to prevent fires and reduce the effects of fires.
Furthermore, firefighters have noticed that the actual conditions of fires in dwellings have changed the last 20 years. Different furniture and better insulation seem to cause fires to get hotter and grow faster, but fewer fires seem to develop fully. This presumed change in fire development might lead to other risks for firefighters and call for a different approach to fires. This explains the need for research into how fires develop.

METHODOLOGY

Live fire experiments

From October 20 till October 24, 2014 the Fire Service Academy conducted, in close cooperation with Netherlands Fire Service, a unique series of live fire experiments in a block of dwellings in the town of Zutphen. The aim of the experiments was to research the fire spread and tenability in an average Dutch dwelling. To accomplish this aim, six virtually identical dwellings were identically furnished with modern furniture. In Figure 1 the floorplans including furniture are shown.

Figure 1. Floorplans of the ground and first floor including furniture

Six fires were started (common scenarios were adopted from statistics) and were allowed to grow unimpeded for one hour or until neighboring dwellings were threatened. Temperature, heat radiation, oxygen, carbon monoxide and nitrogen dioxide concentrations were monitored in each of the five major rooms during the fire growth. The effect of closing and opening (inner) doors between different spaces in the dwelling were of special interest (see for the complete setup Table 1). Fire spread and tenability could be determined afterwards by analyzing the data and watching attained video footage.

Table 1. Setup of the six fire tests

Burn	Location of start of fire	Object on which the fire started	Hallway door	Bedroom doors	Ventilation
1	Bedroom	Bed	Closed	Both closed	Everything closed, only bedroom window ajar
2	Kitchen	Deep fat fryer	Closed	1 open/ 1 closed	Everything closed, kitchen door open halfway
3	Living room	Sofa	Open	1 open/ 1 closed	Everything closed, only bedroom window ajar
4	Living room	Sofa	Closed	1 open/ 1 closed	Everything closed, only bedroom window ajar
5	Living room	TV	Open	1 open/ 1 closed	Front door open
6	Bedroom	Bed	Closed	Both open	Exterior doors closed, both bedroom windows ajar

The live fire experiments provided the Netherlands Fire Service very worthwhile new insights into fire spread, tenability and relevant factors when putting out fires. Among other things, it was observed that[4]:

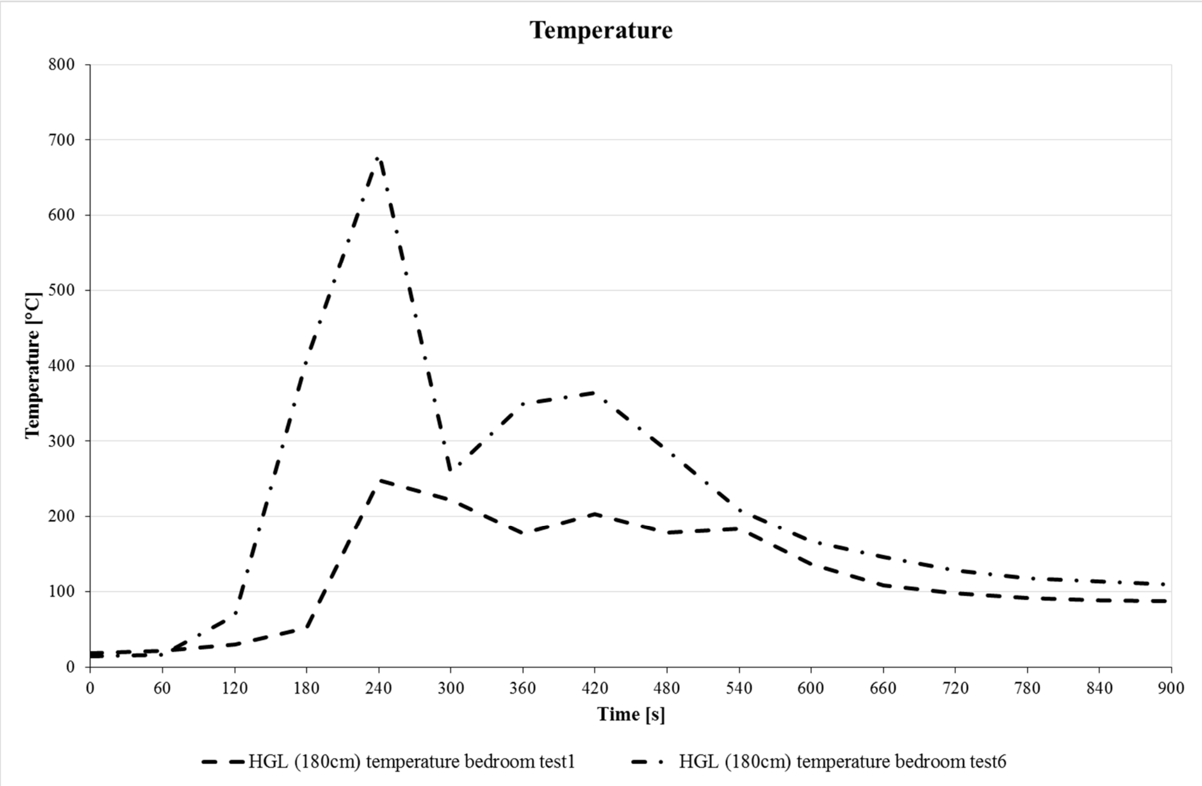
- Smoke spreads very rapidly and is the main danger of fires in modern furnished dwellings;
- Closing inner doors reduces smoke spread – and thus the main danger – considerably;
- 'It depends': fire spread and tenability depends on many factors, therefore predictability of dwelling fires is low.

The obtained data and images of the live fire experiments have since been put to use in course materials and fire safety education.

Under ventilated fires

Though the live fire experiments were very valuable and productive in terms of obtained data, several limitations of the experiments were also noted. Firstly: it was concluded that it was not possible to generalize all conclusions on the basis of (just) six live fire experiments. To draw generic conclusions about fire spread and tenability (in all Dutch dwellings), it would be necessary to perform many more fire tests in many more types of dwellings. Secondly: when examining the obtained data from the six live fire experiments, several observed phenomena in fire spread were difficult to explain. It turned out to be particularly difficult to explain why the fire spread stopped in several cases (no flashover occurred). At first it was concluded that all the fires in the experiments were under ventilated; the fires in the experiments were smothered or went out due to limited ventilation in the pre-flashover stage. Although this seemed highly probable the data gave insufficient guidance to conclude with certainty. For example: the first test in the bedroom (test 1) was clearly a smothered fire with measured temperatures in the hot gas layer (HGL) less than 300 degrees Celsius (Figure 2). In this case only the object (bed) where the fire was started was partly burned.

Figure 2. Measured temperatures test 1 and 6

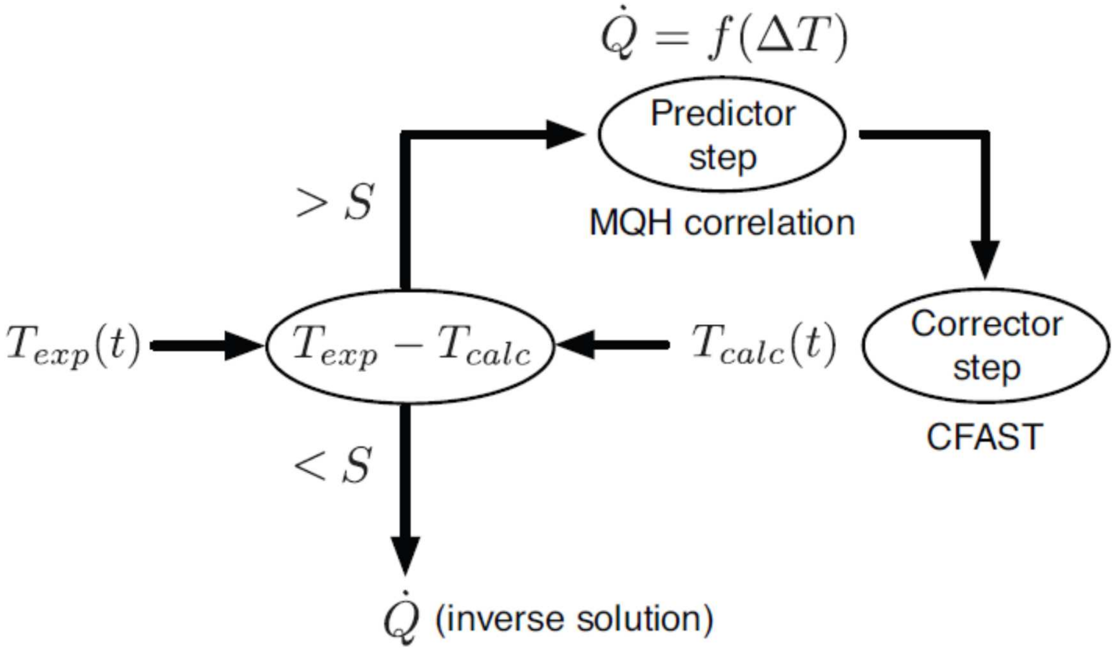


Test 6 was almost the same as test 1 with the exception that the bedroom door was open during the test. In this case the measured HGL temperature reached temperatures around 700 degrees Celsius (Figure 2). The temperature of the HGL were higher than the common known flashover criteria for convective and radiative heat transfer. However, the fire spread stopped in the object and no flashover took place to for example the adjacent open wardrobe with clothes in it. In the experiments the heat release rate (HRR) of the actual wasn’t measured. This was one of the reasons why the obtained data could not provide a definitive answer on why the fire spread stopped in certain cases.

HRR search procedure (inverse modeling)

To provide more clarification and explanation to the obtained data of the live fire experiments a simulation model was applied. A technique of the Inverse Heat Release Rate Solution Methodology[5] was used. The method searches for a HRR to satisfy pre-specified temperature conditions at a given time, then continues to the next time step. In this case the pre-specified temperature conditions are the measured HGL temperatures obtained in the live fire experiments. The flowchart in Figure 3 illustrates the inverse HRR search procedure.

Figure 3. Inverse HRR search procedure



For the predictor step an analytical correlation[6,7] is used. This physical correlation is used to compute the required change in the HRR (dQ) based on the difference between the measured and predicted temperatures (dT).

$$dT_g = 6.85\ (Q^2/A_0(H_0 h_k A_T)^{0.5})^{1/3} \qquad [1]$$

Where dT_g is the change in the HGL temperature (Celcius), Q is the HRR (kW), A_0 is the ventilation area (m^2), H_0 is the ventilation height (m), h_k is the effective heat transfer coefficient of the boundaries (W/m^2-K), and A_T is the boundary surface area (m^2).
A simple iterative procedure[8] was used to obtain the vector of unknown parameters, as shown in equation 2.

$$Q^{k+1} = Q^k + J^{-1}\,(Y - T(Q^k)) \qquad [2]$$

Where $(Y - T(Q^k)) = dT$ is the difference between the measured an predicted temperatures and the sensitivity coefficient J = dT/dQ.
For the corrector step the fire model CFAST is used to calculate HGL temperatures. For the tolerance between the measured and calculated temperatures a relative error S(Q) is used, as shown in equation 3.

$$S(Q) = \sum^n (Y_i - T_i(Q))^2 / \sum^n (Y_i)^2 \qquad [3]$$

Where Y_i are the measured temperatures at time i and $T_i(Q)$ are the estimated temperatures found from the direct solution of the problem using some proposed time evolution of Q. For parameterizing the HRR the following piecewise linear function was used, as shown in equation 4.

$$Q(t) = Q_i\ (t - t_{i+1}/t_i - t_{i+1}) + Q_{i+1}\ (t - t_i/t_{i+1} - t_i) \qquad [4]$$

Where Q(t) is the HRR (kW), and Q_i are the calculated HRR values at each time t_i that the temperature data are sampled.

The inverse HRR search procedure is summarized in the following steps.

- Step 1: For a temperature difference (Y - T) between the measured and predicted temperatures, the predictor step computes dQ for all times t_i by using the sensitivity, J, (i.e., dT/dQ) found from the MQH correlation in equation 1. An intermediate value of Qk+1 based on the MQH correlation is then computed using equation 2.
- Step 2: For the corrector step, the CFAST model is run with the MQH-derived HRR values Qk+1 to generate temperatures Tk+1 at the next iteration.
- Step 3: If the error is less than a specified tolerance (S(Q) $\leq$ 1 x 10-3), then the resulting Q is returned. Otherwise, Steps 1 and 2 are repeated as the predictor-corrector procedure iterates. The result of the inverse HRR method is a piecewise linear function of HRR vs. time, as shown in equation 4.

Zone model setup

The zone model, CFAST version 6.2.0, was used in this research. The graphical interface was used for the input of all parameters. The predictor step was performed in Excel by using the measured and predicted temperatures. The resulting HRR for different time steps was manually imported into CFAST. The calculated temperatures were then imported in Excel from the data files generated by CFAST. This procedure was repeated until the invers HRR solution was reached.
In the CFAST zone model, all of the input parameters (e.g., combustion, solid phase, geometry) were fixed to simplify the search process, and the HRR was the only parameter that was varied. Following the procedure as illustrated in Figure 2, the predictor step computes a HRR that satisfies the first input temperature point at the first chosen sample time (i.e., 60 seconds). Next the predictor step computes a HRR that satisfies the temperature condition at 120 seconds. This process continues until all of the time-temperature points have associated HRR's. Then, the corrector step involves running the CFAST model to compute the resulting HGL temperatures, and the new error between the measured and the predicted temperatures is calculated. This process continues until a complete inverse HRR solution curve is determined. The sample resolution of the measured HGL temperature data was 0.2 seconds. For computational reasons the sample resolution of the input HGL temperature was set to 60 seconds.

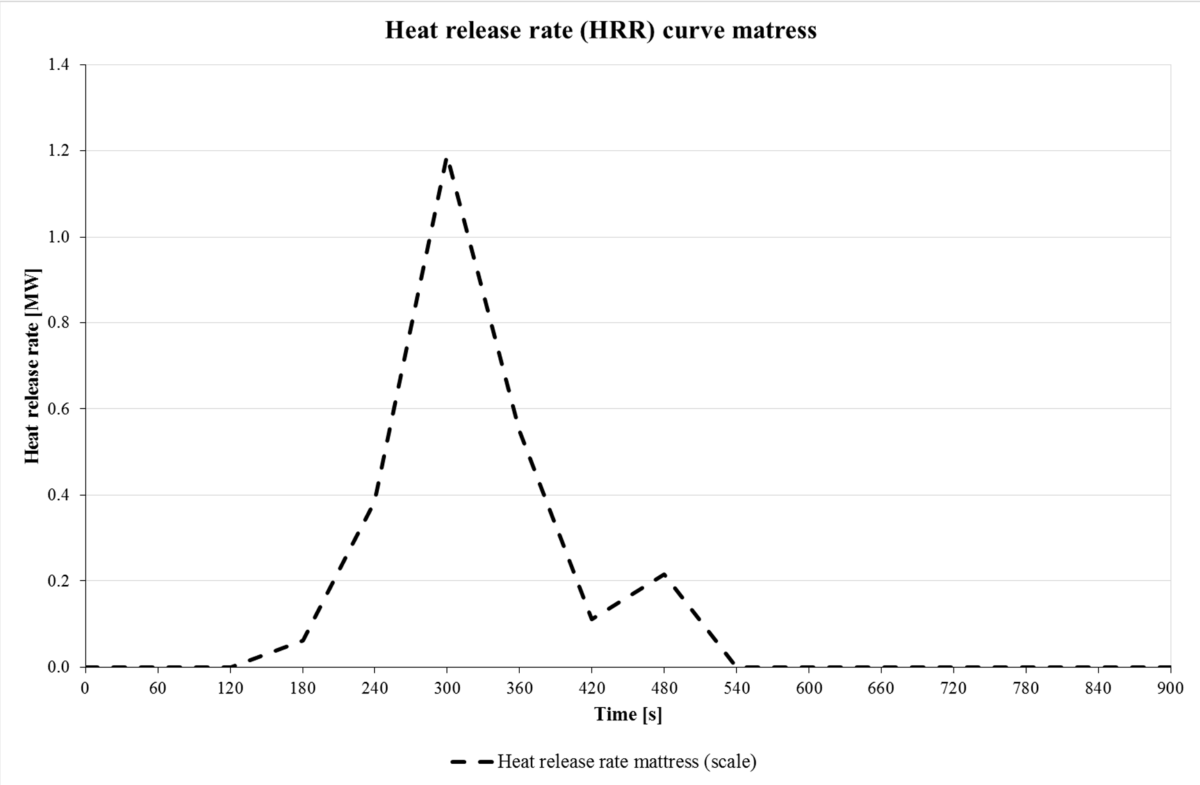
Applicability of inverse modeling

It appears from the mentioned article[5] that the inverse HRR solution had a relative error between 0.04 and 0.24 compared to actual measured HRR. For a lot of cases the inverse method effectively detects changes in the HRR steps. However, in case where the HRR is not measured directly, it is difficult to quantify the amount of error in the inverse solution. It is concluded that qualitatively, the presented method captures a change in the HRR and exhibits potential for obtaining an inverse solution from these types of scenarios in which the measured HRR is unknown and only temperature data are available.

HRR and sensitivity analysis

To get a better understanding of the HRR of the burning object the mass loss rate of two burning objects was measured on a scale in a fuel controlled environment. In case of test 1 and 6 a mattress identical to the mattresses used in the furnished homes was burned on a scale. From the mass loss rate the HRR was calculated by using a calorific value corresponding to the materials in the mattress. This calorific value was estimated by the use of common prefixes. In Figure 4 the chart of the measured HRR curve for the mattress is displayed.

Figure 4. Measured HRR curve mattress on scale



The input parameters in the CFAST model were configured to closely match the actual parameters from the live fire experiments. As mentioned before all of the input parameters (e.g., combustion, solid phase, geometry) were fixed to simplify the search process for the HRR. Because not all the input parameters were precisely defined or measured during the experiments, they were estimated by using common prefixes. All those parameters could provide a different simulation result. In fact, all parameters with uncertainty (stochastic) need to be considered in a sensitivity analysis in order to determine which of the stochastics are most important to the simulation result.[9] In the study of Vossestein[9] a sensitivity analysis is carried out for all the combustion parameters in the CFAST model. Vossestein concludes that the stochastics 'fraction radiative heat' and the 'HRR' have influence on the temperature in the fire compartment (model). It is also concluded that variation of the HRR in all scenario's by far has the most influence on the temperature in the fire compartment. This is why, even when not all stochastics are known, the method of inverse modeling is useful for calculating the HRR based on the HGL.

RESULTS

In the following figures the results are presented. Figure 5 and 6 show the measured HGL temperatures vs. the (calculated) inverse HGL temperatures of test 1 and 6. The inverse HGL temperatures are almost the same as the measured HGL temperatures.

Figure 5. Measured temperatures vs. inverse temperatures test 1

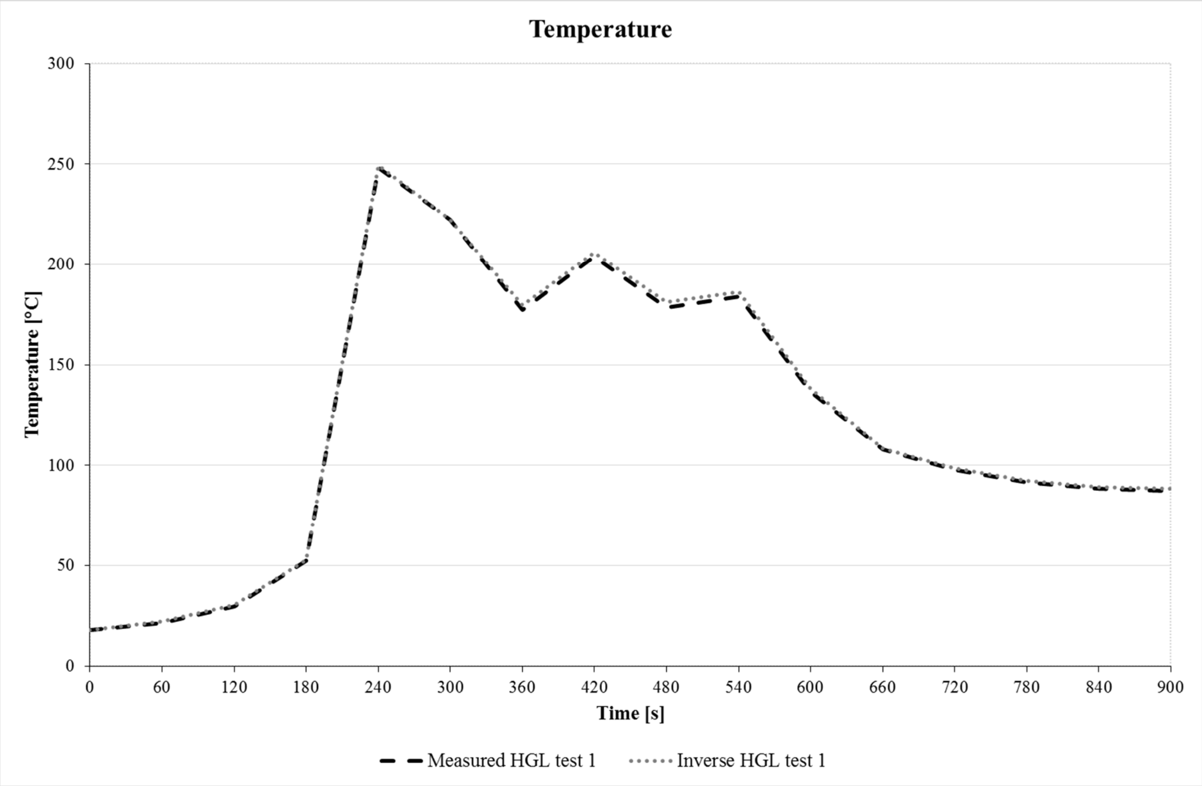


Figure 6. Measured temperatures vs. inverse temperatures test 6

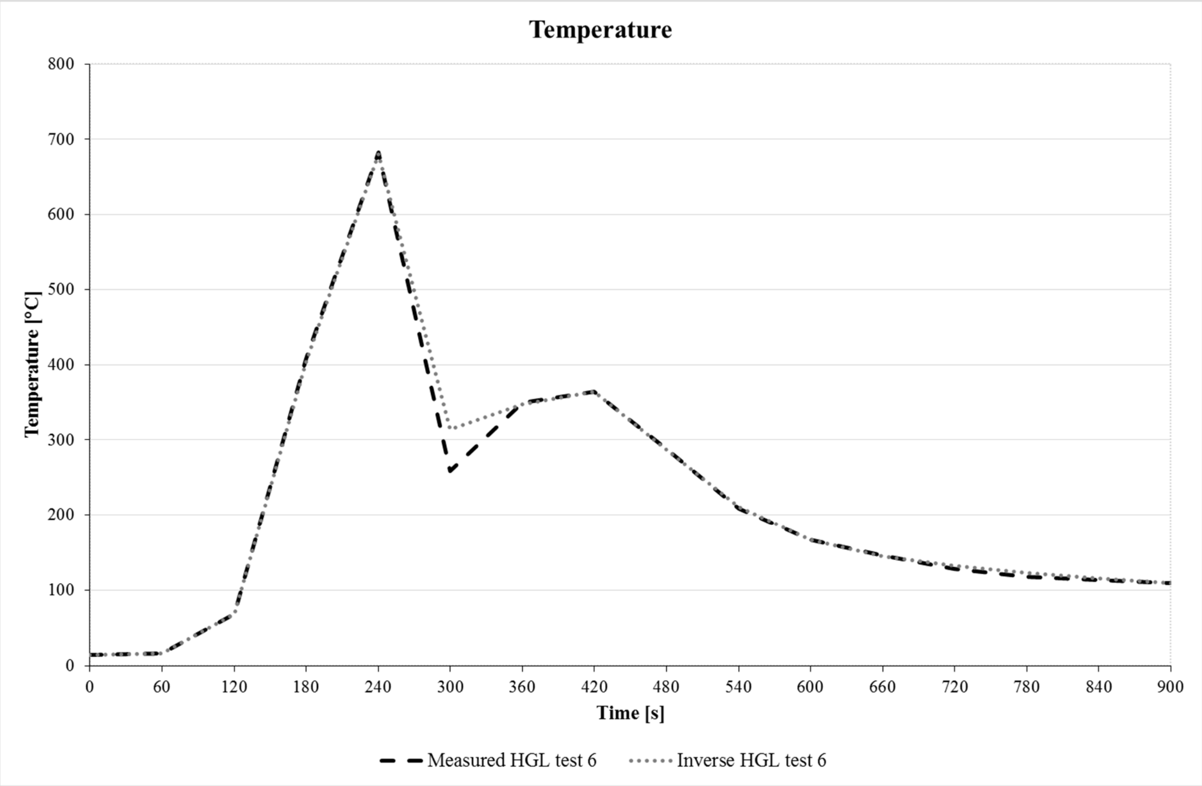


Figure 7 and 8 show the measured oxygen concentration (OC) in the cold gas layer (CGL) vs. the inverse oxygen concentration (OC) in the CGL and the oxygen limit (OL) for flame extinction. The OL is calculated by using a model for flame extinction as described by Mowrer[10]. This limit is only used to evaluate whether flame extinction may have occurred due to lack of oxygen.

Figure 7. Measured OC vs. inverse OC and OL test 1

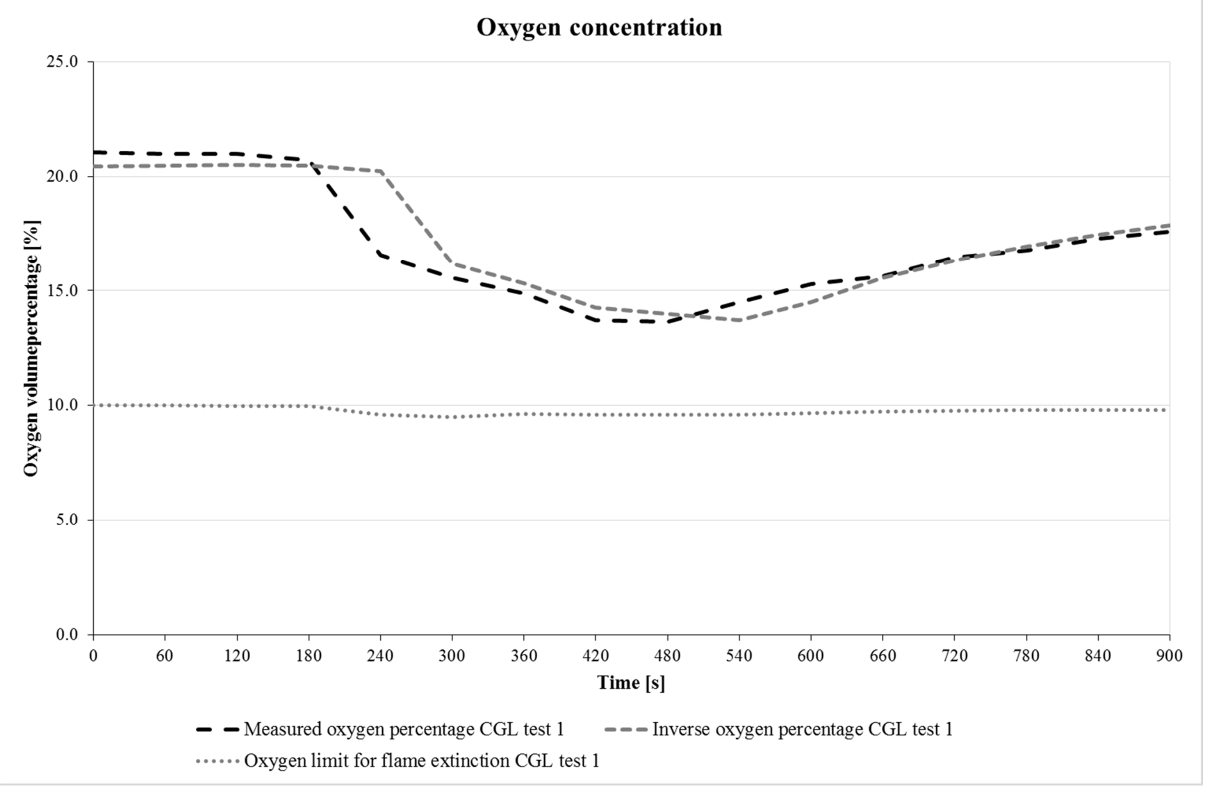
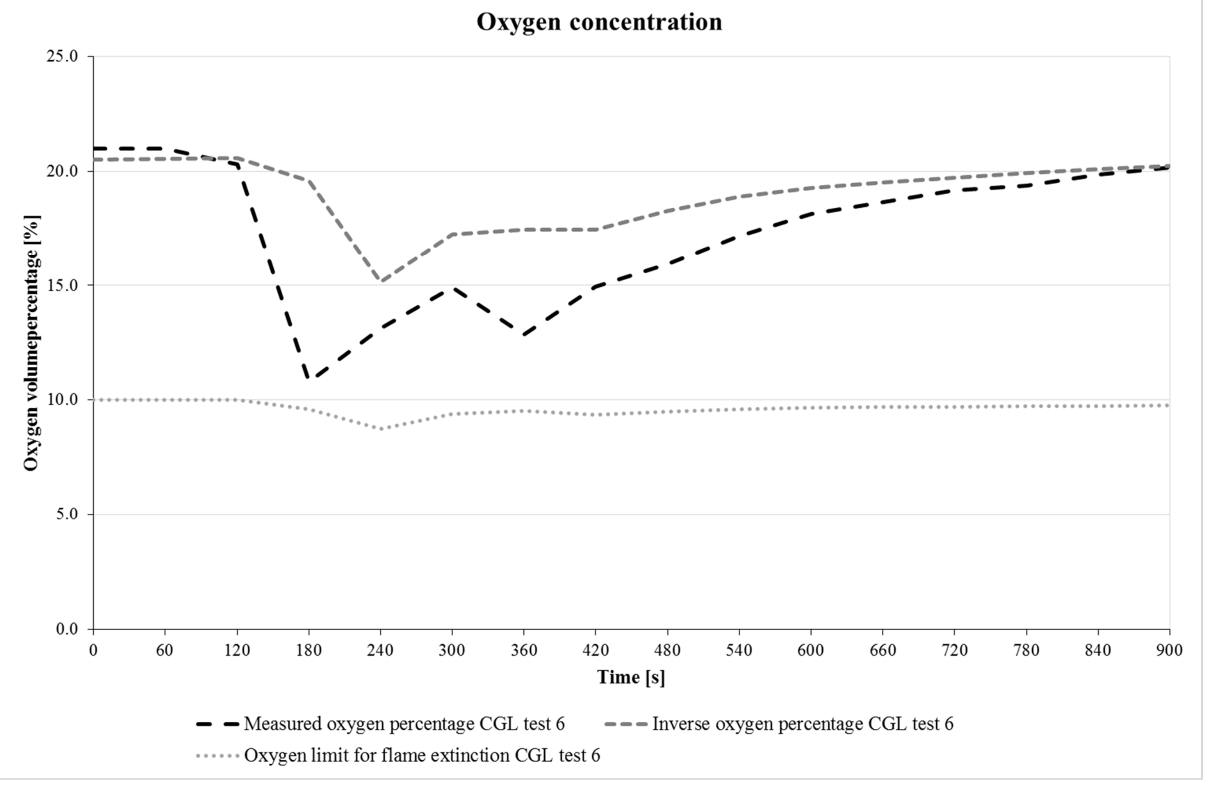


Figure 8. Measured OC vs. inverse OC and OL test 6



As shown in Figure 7 the measured OC and the inverse OC of test 1 are quite similar. The lowest level of the OC is around fourteen percent. The limit for flame extinction is not reached during the test, although the bedroom door was still closed. After eight minutes the OC starts to increase.
In Figure 8 it is apparent that the measured OC and the inverse OC of test 6 are quite different. The measured OC decreases to about eleven percent after three minutes. However, the inverse OC reaches its lowest level of around fifteen percent after four minutes. The bedroom door was all the time open in this experiment. After six minutes the OC starts to increase again.
In both tests, as shown in the Figures 5 till 8, the time of the maximum value for the HGL temperatures are not equivalent to the time of minimum value of the OC. In test 1 the maximum value for the HGL temperature is reached at four minutes while the minimum value for the OC is reached at eight minutes. In test 6 the maximum value for the HGL temperature is reached at four minutes while the minimum value for the OC is reached at three minutes. In case of test 1 this could be an indication of a smoldering fire which consumes the oxygen present in the room. In case of test 6 the early drop in oxygen could be an indication for a rapid fire spread over the burning object. However, only based on the OC data, it is not exactly clear whether or when during the tests there is an under ventilated fire.

Figure 9. Measured HRR vs. inverse HRR test 1 and 6

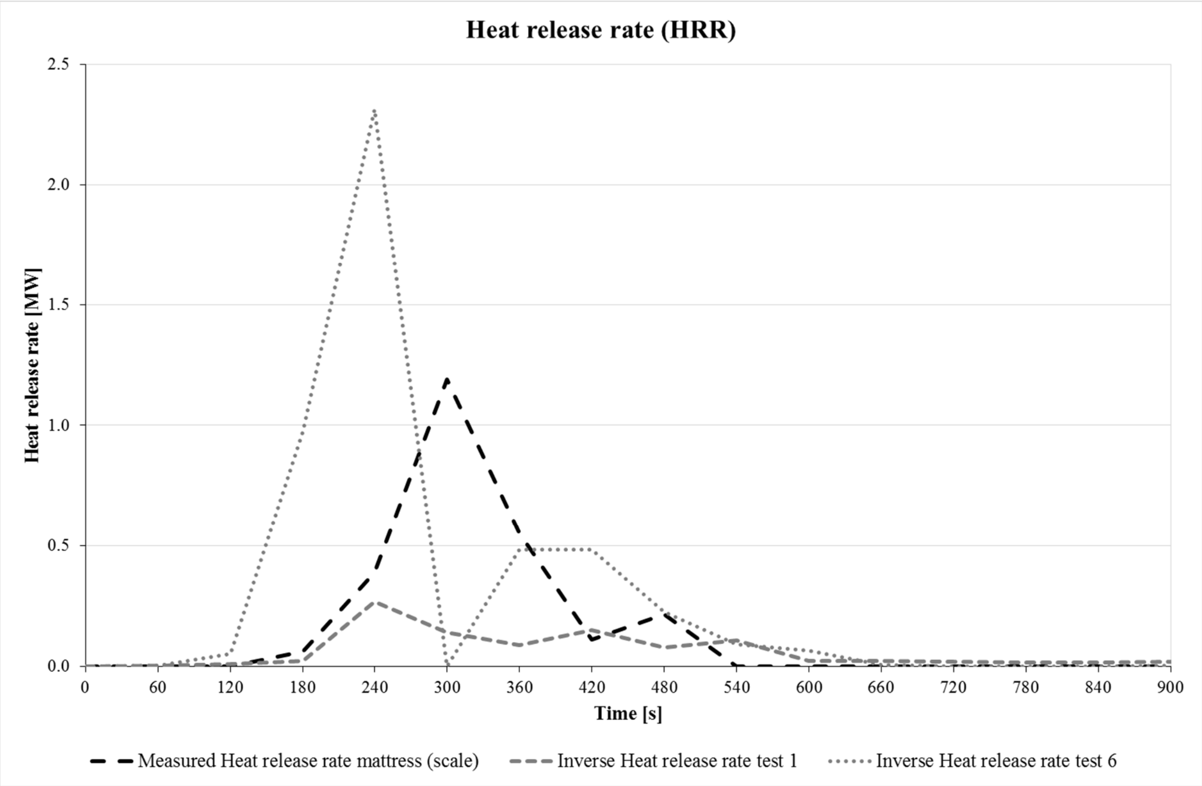


Figure 9 shows the measured HRR of a mattress (scale) and the inverse HRR of test 1 and 6. It is apparent from Figure 9 that in test 1 not the same HRR has occurred as in case of the measured HRR on the scale. The HRR in test 1 reaches a maximum value of around 0,3 MW (300 kW). After the maximum value the HRR decreases to a constant level of around 100 kW until nine minutes. After nine minutes the HRR decreases further to a constant level of around 20 kW. From the Figures 5, 7 and 9 it is clear that test 1 is an example of an under ventilated fire in a bedroom.
It is apparent from Figure 9 that in test 6 the HRR is higher than the measured HRR on the scale. The HRR in test 6 reaches a maximum value of around 2,3 MW. The HRR is almost twice as high as the HRR calculated from the mass loss rate in open air. The higher value of the HRR can be explained by the fact that only the mattress was burned on the scale. In the actual experiment the bed consisted besides the mattress off a bed frame, a bed base, a comforter and pillows. In addition, a carpet was present under the bed. All those elements were partly or completely burned. Together this could result in a HRR of 2,3 MW. After the first four minutes the HRR rapidly decreases to approximately 0,5 MW. As stated

earlier the fire did not spread to the adjacent open wardrobe even though the HGL temperatures where above the flashover criteria. During and after the experiment it was observed that only the object of origin of the fire was burned. As mentioned before, at first it was concluded that the fire in test 6 was also an under ventilated fire. However from the Figures 6, 8 and 9 it is clear that there is enough oxygen and fuel present for a further fire spread to adjacent objects. This means that the fire in test 6 is not a typical example of an under ventilated fire.
From the obtained data it is not exactly clear why the fire spread stops in the object of origin. A possible explanation could be that the lightweight materials in the bed burned very rapidly. Shortly after the peak in the HRR the fuel of the object runs out and the peak in the HGL temperature is too short to ignite the other objects in the bedroom. Possibly this had to do with the thermal load of the other objects in the bedroom.

LIMITATIONS

The results of the combination of live fire experiments and FSE-modeling are of course only valid for the configurations studied in this research and strictly speaking cannot be generalized, except with common sense and caution. There are some factors that may have introduced deviations in the calculations.
In the dwelling in each room only one data point (thermocouple) was used to measure the HGL temperature (180 cm) and the OC (50 cm). Although the collected data was sufficient for the purpose of live fire experiments, this was insufficient to exactly explain all the observed phenomena in fire spread, even with the use of FSE-modeling.
The calculated HRR of the mattress from the mass loss rate in open air is also an uncertainty. As stated before an estimated calorific value was used to calculate the HRR. Because this calorific value was estimated the actual HRR of the mattress is probably different. However, in order to reduce this uncertainty the same calorific value is used in the HRR search procedure.
From Figure 9 it is also clear that the burning rate is situational dependent. Although the fires are started at the same time, the burning rate in test 6 is higher than test 1 (and the mattress test). An explanation could be a difference in the method of igniting the fire or other small differences such as the placements of the fire objects. This is not further explored, due to the lack of sufficient data.
As stated before the sample resolution of the input HGL temperature was set to 60 seconds, although the actual sample resolution of the measured HGL temperature data was 0.2 seconds. This decision is made to reduce the calculation time of the HRR search procedure.
A limitation of the used methodology is that the boundary conditions must be pre specified. The inverse HRR solution is sensitive to the selection of these conditions. As stated before boundary conditions were estimated (ventilation conditions and material properties). Therefore, other boundary conditions could lead to a different inverse HRR solution.
Taking into account all the above limitations, the calculated HRR may differ from the actual HRR, although it corresponds to the expectations and common prefixes. However, the comparison and the differences between the found HRR of live fire experiments are of great value because it provides more insight in the observed phenomena in fire spread.

CONCLUSION

The use of FSE-modeling is of great value to the analysis of the live fire experiments. This combination not only gives a better understanding of the occurred HRR in the actual experiments, it also gives a better understanding and explanation of the fire spread during the actual experiments. Vice versa it is also concluded that the live fire experiments are of great value for the input of principles and preconditions in fire models such as CFAST. For example, the data obtained by experiments of fire spread in dwellings can lead to adjustments in common prefixes for principles and preconditions. With a better understanding of the principles and preconditions, fire models can possibly be used as an addition to live fire experiments. For a correct understanding of fire spread it would in theory be necessary to perform live fire tests in all types of buildings with several types of furniture and under several conditions (interior doors open or closed, etcetera). This will lead to thousands of tests and for practical reasons this will not be attainable. With better principles and preconditions fire models can possibly be used to reduce the number of expensive and environment threatening live fire experiments. We advise all other research institutes to combine FSE-expertise and data from live fire experiments wherever possible: both to validate fire models and to provide new or additional insight into fire spread.

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