Fire tests with "Hedera helix" on different scales to enable fire simulation on green facades

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INTRODUCTION

Large-scale fire tests are state-of-the-art methods for assessing the burning behaviour of green facades and formulating effective fire protection measures [1]. In addition to these selective tests, numerical fire simulations offer a cost- and time-efficient way to calculate fire spread on green facades for varying conditions or measures. However, accurately simulating fire propagation using mathematical models remains a significant challenge in fire safety science and requires fundamental material investigations and model validations on different scales.

The Fire Dynamics Simulator (FDS) incorporates a Complex Pyrolysis Model to estimate the combustible gas emitted by materials. Additionally, FDS features a Lagrangian Particle Model capable of representing vegetation in fire simulations. This combination enables the prediction of fire propagation in scenarios such as wildland fires [2] or, as discussed in this paper, along green facades.

While valid results can already be obtained for wildland fires [3], predicting fire propagation along green facades using complex pyrolysis models remains an unexplored area. As part of a master's thesis at the University of Applied Sciences Magdeburg-Stendal [4], a fundamental database for such fire simulations on facades planted with ivy (Hedera helix) was developed. This involved conducting fire tests at various scales, including micro- and macro-scale experiments like thermogravimetric analysis in a Tube Furnace [6] and bench-scale tests in a Furniture Calorimeter.

The FDS complex pyrolysis model relies on fuel’s reaction kinetics and thermophysical parameters. These parameters cannot be directly measured but are derived from experiments conducted at both micro- and macro-scales, employing an Inverse Modelling Process (IMP).
Additionally, investigations were conducted on the geometry and density of ivy leaves on facades. A total of 600 leaves were weighed, and their surface areas were measured. Subsequently, the thickness of 350 leaves was recorded, and the moisture content of 75 leaves was analysed. Counting leaves on facades allows for the accurate determination of the particle packing ratio.

The burning behaviour of green facades in bench-scale tests was investigated using a furniture calorimeter. An FDS model was constructed solely based on TGA data, realistic particle geometry, and gravimetry to forecast fire propagation in bench-scale scenarios. While the determination of suitable parameters is in progress, the simulation results presently depict a functional state. Nevertheless, comparable results with bench-scale tests have already been attained on this basis.

KEYWORDS: green facade, green wall, fire simulation, fire spread, Fire Dynamics Simulator (FDS), pyrolysis modelling, inverse modelling, Hedera helix, ivy

GREEN FACADES AND COMPUTATIONAL FIRE DYNAMICS

Green walls serve crucial urban ecological functions: Climbing plants on building facades regulate the microclimate in the surrounding area, improve air quality, and contribute to biodiversity. Thus, facade greenery is becoming increasingly significant. However, it should not compromise the fire protection of multi-storey buildings. In Germany, ivy (Hedera helix) is frequently utilized for green facades.

When calculating the production of combustible gas using FDS (pyrolysis modelling), several parameters need to be specified. However, for ivy, many characteristics remain unknown. While mass, size and shape can be easily determined, examining thermophysical and reaction kinetic parameters such as Arrhenius-Parameters for multiple reactions is more challenging. In combination with inverse modelling, FDS can be used to determine suitable parameters.

To gain clarity on the material decomposition, individual ivy leaves need to be analysed using thermogravimetric analysis (micro-scale). Following this, the experiments are rebuilt in FDS. In cases where the calculations do not align with the experimental results, a substitution of the input parameters is required. This process continues until the input parameters match the experiments. By optimizing only a few parameters, the user can carry out the process themselves. However, the more parameters that remain unknown, the more complex and time-consuming the process becomes. Transferring the task to a computerized algorithm proves beneficial. For this purpose, the computerised optimisation algorithm called PROPTI [5] was used.

Subsequently, the parameterised model must undergo a validation process. Bench-scale fire tests, which include significantly more degrees of freedom than micro- and macro-scale experiments, confirm the parameters' appropriateness in predicting a realistic fire. Once a valid modelling concept is established, it will enable the investigation of large-scale fires as well.

IVY LEAVES: DISTRIBUTION OF MASS, SIZE AND SHAPE

To consider the distribution of mass, size and shape of ivy leaves when modelling the natural planting, random samples of facade greenery were taken to determine these characteristics.

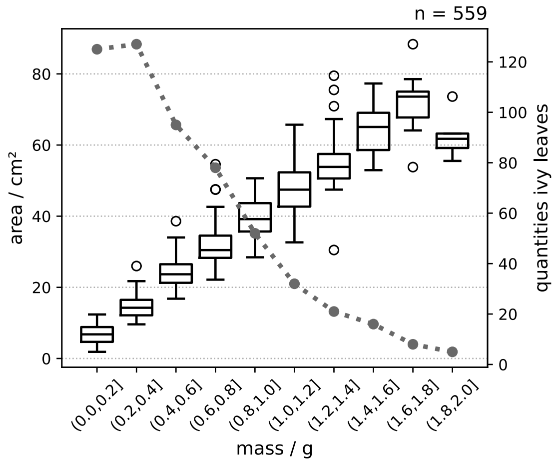

Figure 1 Correlation of mass and area

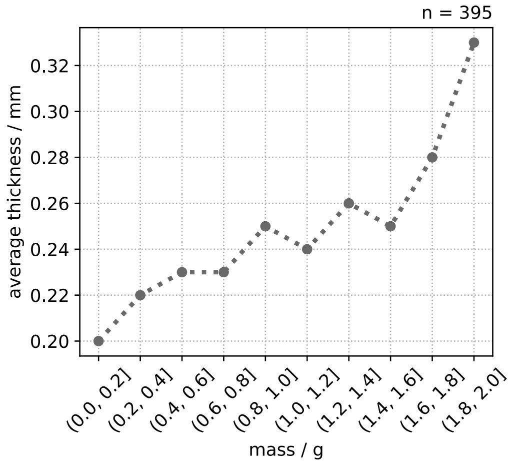

Figure 2 C. of mass and averaged thickness

Five areas (40 cm x 40 cm) were harvested under summer conditions in Leipzig, Germany. Each component was weighed separately. The mass fraction of wooden branches was approximately 60 %, while the leaves' mass fraction (including stems) was around 40 %. Figure 1's boxplots illustrate typical area characteristics based on mass. The dashed line shows a clear overrepresentation of small leaves in the sample. Figure 2 demonstrates the correlation between mass and thickness.

TUBE FURNACE WITH MASS LOSS MEASUREMENT: MICRO-SCALE EXPERIMENTS

Thermogravimetric Analysis (TGA) are often used to determine reaction parameters. Typically, a TGA sample weighs a few milligrams. An ivy leaf, on the other hand, weighs up to 2 g. Given the heterogeneous nature of the plant components, it is advantageous to analyse the entire sample. Therefore, the experiments were performed inside a tube furnace at Forschungszentrum Jülich [6], see Figure 3. The modified tube furnace was equipped with a balance, allowing for precise measurement of the mass change during heating of individual ivy leaves. Single fresh ivy leaves (approximately 0.3 g each) with a moisture content around M = 200 % were analysed. The leaves were heated from ambient temperature to 900 °C at a rate of 5 K/min. The tube furnace was purged with air at a flow rate of 10 l/min. The change in mass of one representative test are presented in Figure 4 and Figure 5.

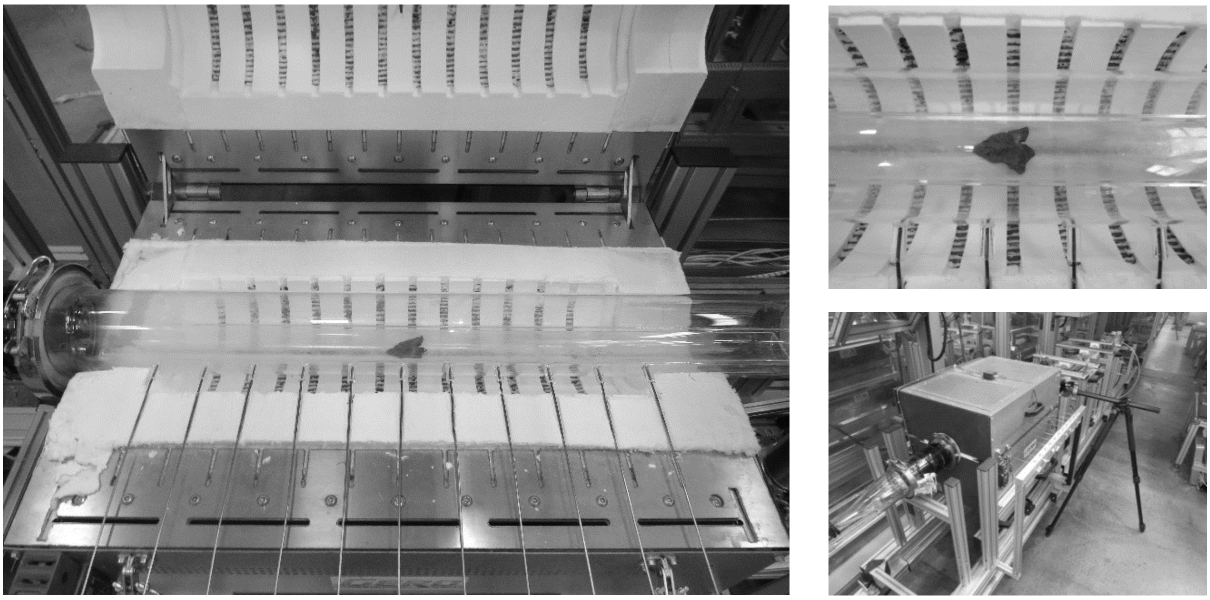

Figure 3 Tube Furnace with single ivy leave (Forschungszentrum Jülich)

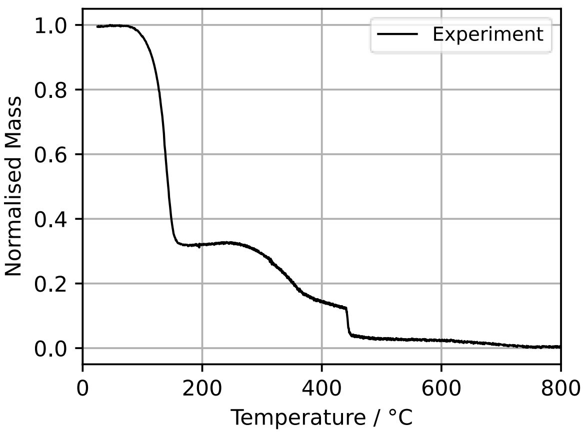

Figure 4 Mass loss for single ivy leaf

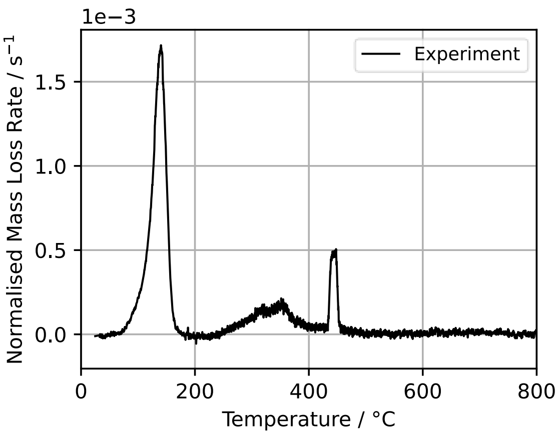

Figure 5 Mass loss rate for single ivy leaf

At around 80 °C, the mass begins to decrease, indicating moisture evaporation. Between 160 °C and 240 °C, the mass remains constant. Subsequently, two more phases are observed. The first phase occurs between 240 °C and 400 °C, likely representing the transition from dry ivy to char. The final mass loss occurs between 430 °C and 450 °C, during which ash is formed. Accordingly, at least three predominant reactions can be observed [2]:

1. Endothermic moisture evaporation:

$$\text{Wet Vegetation} \rightarrow v_{moist}\ \text{Moisture} + (1 - v_{moist})\ \text{Dry Vegetation} \quad ; \quad v_{moist} = M/(1+M)$$

2. Endothermic pyrolysis of dry vegetation:

$$\text{Dry Vegetation} \rightarrow v_{char}\ \text{Char} + (1 - v_{char})\ \text{Fuel Gas}$$

3. Exothermic char oxidation:

$$\text{Char} + v_{O_2,char}\ O_2 \rightarrow \left(1 + v_{O_2,char} - v_{ash}\right) CO_2 + v_{ash}\ \text{Ash}$$

The Arrhenius parameters, which consist of the pre-exponential factor A and activation energy E, are crucial for describing temperature-dependent reactions. Within FDS, a feature `TGA_ANALYSIS = T` is employed to estimate these parameters, considering the temperature range relevant to pyrolysis. Two key parameters, `REFERENCE_TEMPERATURE` and `PYROLYSIS_RANGE`, are introduced for this purpose (for more details, see [2]). The six reaction parameters for the three predominant reactions (see Table 1), as well as the moisture fraction, were determined using the inverse modelling framework PROPTI. This determination was based on the analysis of the test depicted in Figure 4 and Figure 5.

Table 1 Reaction parameters for fresh ivy (Hedera helix) determined using the Tube Furnace with 5 K/min heating rate and 10 l/min air flow rate, FDS and inverse modeling.

	Unit	Moisture evaporation	Pyrolysis of dry vegetation	Char oxidation
`REFERENCE_TEMPERATURE`	°C	139.4	343.1	444.8
`PYROLYSIS_RANGE`	°C	71.3	227.0	42.5
Pre-Exponential Factor A	1/s	2.947E+11	4.999E+03	7.980E+37
Activation Energy E	J/mol	1.079E+05	7.550E+04	5.481E+05

The `MOISTURE_FRACTION`, related on a dry weight basis, was determined as M = 194 % = 1.94.

In Figure 6 and Figure 7, the results from the best fitting FDS simulation (`TGA_ANALYSIS = T`) are compared to the test described in the previous chapter. The results show an almost perfect match between the experimental data and the calculated predictions.

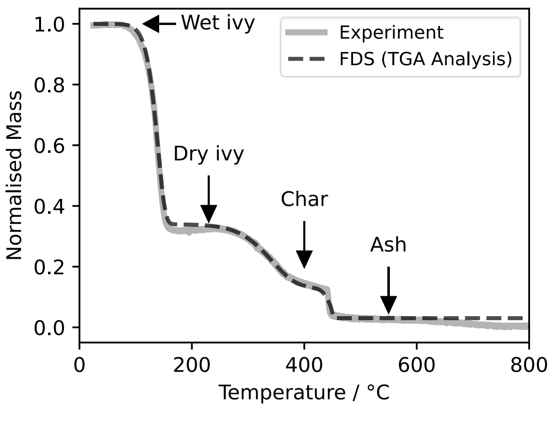

Figure 6 Comparison of experimental and calculated results for mass loss

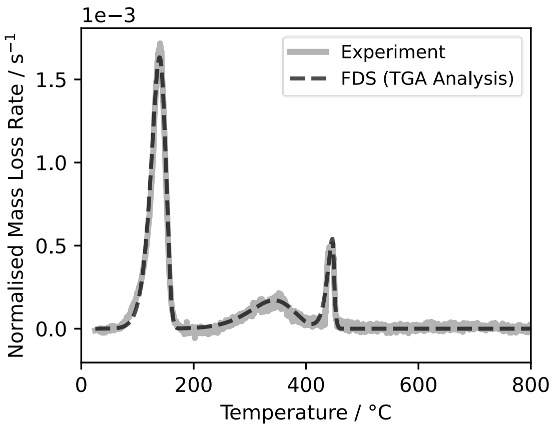

Figure 7 Comparison of mass loss rate

FURNITURE CALORIMETER: BENCH SCALE EXPERIEMENTS

To validate the FDS model fitted with the pyrolysis parameters determined from micro- and macro-scale experimentes, bench-scale experiments were carried out under controlled boundary conditions.
The experimental setup is depicted in Figure 8 and consisted of a prefabricated vertical greenery system (VGS) positioned on a calcium silicate board.
The dimensions of the VGS, consisted of ivy tendrils on a steel grid, were 1.3 m in height and 1.0 m in width. The depth of the vegetation was 0.15 m.

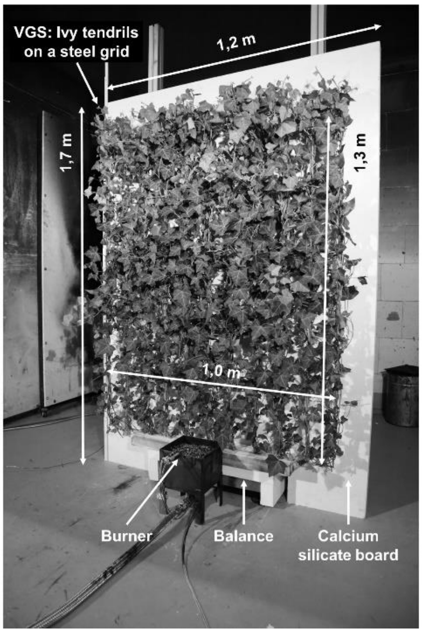

Figure 8 Bench-scale setup

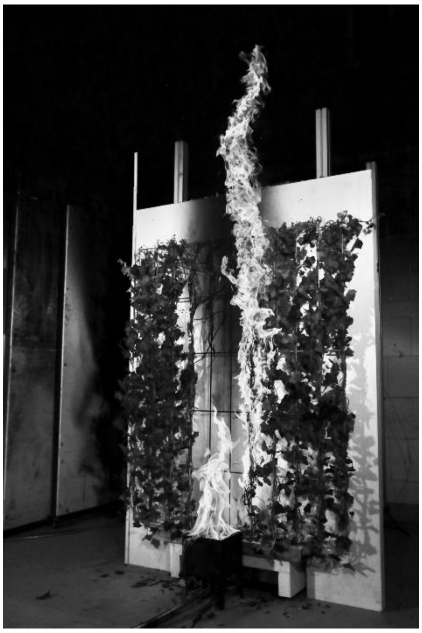

Figure 9 Straw fire-like burning

A propane-fueled gas burner was placed directly in front of the middle of the vertical greenery system, emitting 20 kW. The vertical greenery system was placed on a balance with a resolution of 0.5 g. The tests were conducted inside a furniture calorimeter according to ISO 9705. The heat release rate was determined using oxygen consumption calorimetry. Each test took about one hour.

In total, two series of experiments with two tests each were performed. Test 1 and 2 were conducted with fresh VGS, with the plant roots cut off right before starting the test. The plant mass was approx. 3 kg and the moisture content was approx. 190 %. Tests 3 and 4 were carried out with wilted VGS, with the roots cut five days before starting the tests. The plant mass was approx. 1.9 kg and the moisture content was approx. 150 %. The moisture content was determined by taking and weighing 10 leaves before each test and weighing them again after complete drying.

The burning behaviour can be characterized by two phases. First, the flame dries the VGS. Once the leaves and branches are sufficiently dried, the vegetation burns like a straw fire, with combustion taking only a few seconds (see Figure 9). The fire spread primarily in a vertical direction rather than horizontally. Tests with fresh ivy resulted in burned stripes of approximately 20 to 30 cm. Tests with dried ivy led to burned stripes with diameters ranging from approximately 30 cm at the bottom to 50 cm at the top.

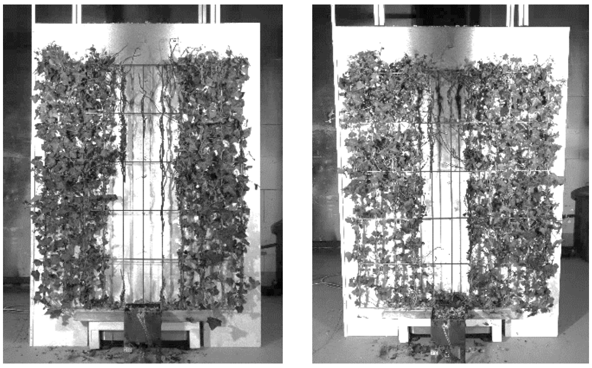

Figure 10 Test 1 and 2 (M ~ 195 %)

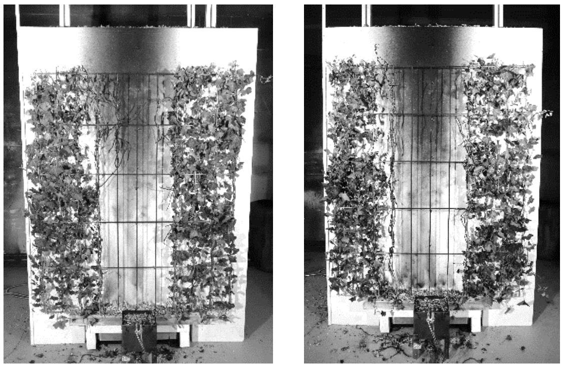

Figure 11 Test 3 and 4 (M ~ 150 %)

Figure 10 and Figure 11 present the VGS after the tests. The pictures illustrate that the drier the VGS, the more its vegetation burns.

Plant masses in tests 1 and 2 decreased to 1.9 kg by the end of the tests. In tests 3 and 4, the mass decreased to 1 kg. Approximately one-third of the initial mass burned in the first two tests, while almost half of the initial mass burned in tests 3 and 4. The balance was also used to determine the effective heat of combustion, the results of which are shown in Figure 13, together with the results from additional cone calorimeter experiments.

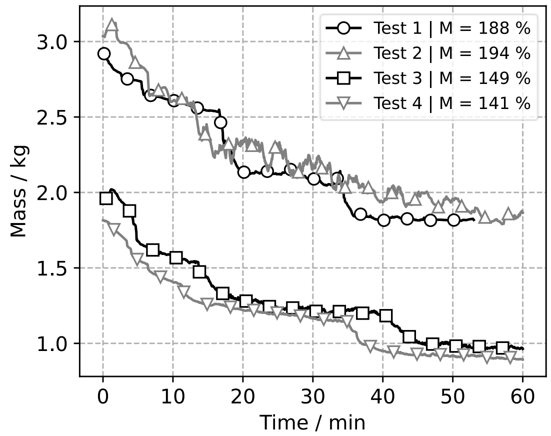

Figure 12 Mass loss during bench-scale tests

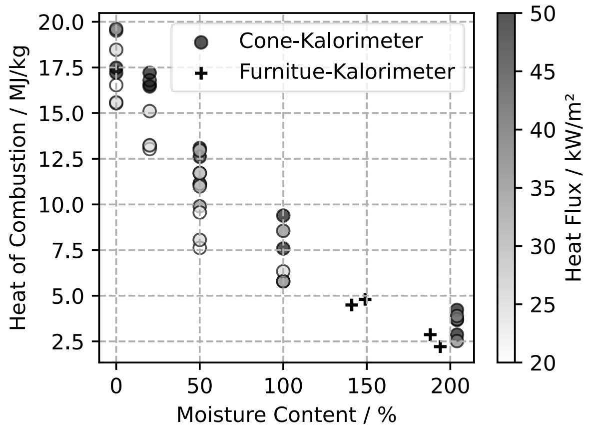

Figure 13 Effective heat of combustion dependent on moisture content

CFD: DEVELOPMENT AND VALIDATION FDS MODEL

The experimental setup described here differs from that of typical large-scale green facades. Nonetheless, the development of an FDS model at the bench-scale offers advantages. Smaller-scale fires have more controlled boundary conditions and require fewer computational resources, which speeds up the optimisation process. Finding a suitable bench-scale model streamlines the path to conducting large-scale simulations.

The used FDS model employs a coarse mesh resolution with a grid width of 2.5 cm. The entire ivy input is defined across multiple lines within the FDS file, including `MATL`-, `SURF`-, `PART`-, and `INIT`-lines. Within the `SURF`-line, information regarding particle size, shape, and moisture content is specified.
Analysis revealed that the branches' mass fraction (excluding foliage) was approximately 60 %, while the leaves' mass fraction (including stems) was around 40 %. The leaves were further categorized into small, medium, and large categories. For each category representative mass and area, taken from Figure 1, was selected to represent a leaf. The density of dry leaves was determined as 320 kg/m³. The particles were assumed to be rectangular in shape and between 0.2 to 0.3 mm thick. Wooden branches were also integrated into the model and simplified with the pyrolysis parameters of the leaves.

The `INIT`-line contains information about the area and mass of the VGS. The initialized plant total mass corresponded to the test conditions in a volume of 0.21 m³ (1.4 m x 1.0 m x 0.15 m). Thermophysical properties for the `MATL`-line, such as specific heat capacity, conductivity, and emissivity, were taken from the FDS verification case `Morvan_TGA` [7].

Figure 14 presents an exemplary comparison between the measured and calculated heat release rates and masses for Test 1 (M = 194 %). The graphs demonstrate that the assumptions made in the FDS model closely resemble the actual measurements, particularly during the first 17 minutes. The burning behaviour is characterized by drying and combustion phases. Straw fires also occur, as can be seen in

Figure 15. The peak values of the heat release rate are comparable to those of the fire tests. While mass loss continues after the 20th minute due to drying of the plants, no further burning occurs.

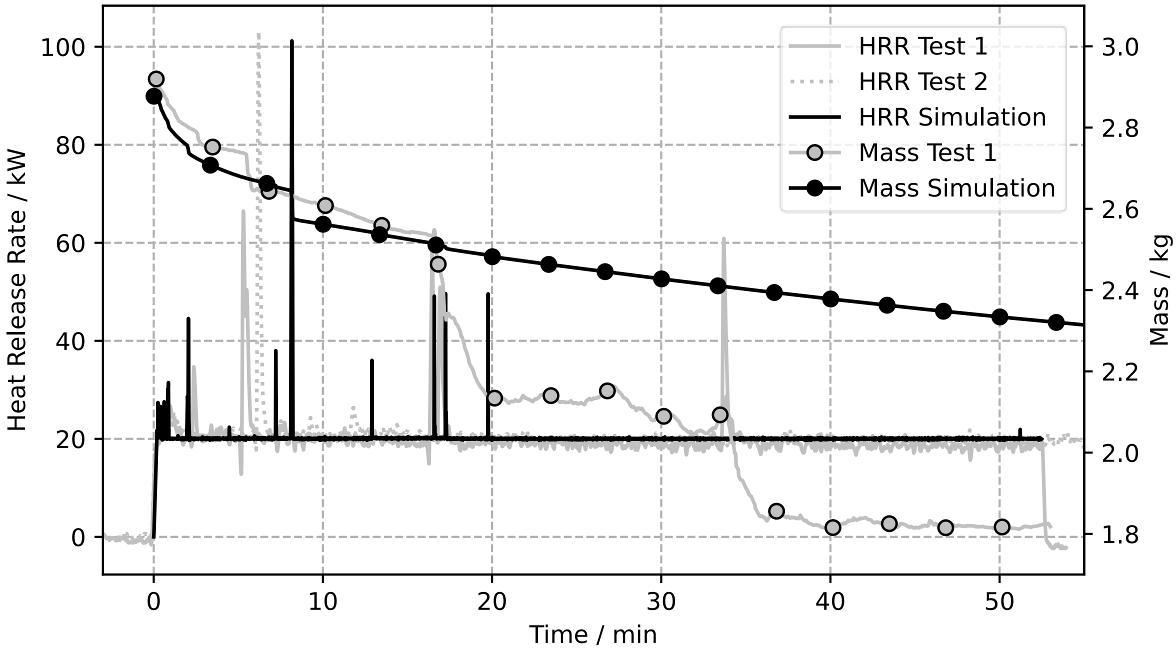

Figure 14 Comparison of measured and calculated HRR and mass (Test 1 | M ~ 194 %)

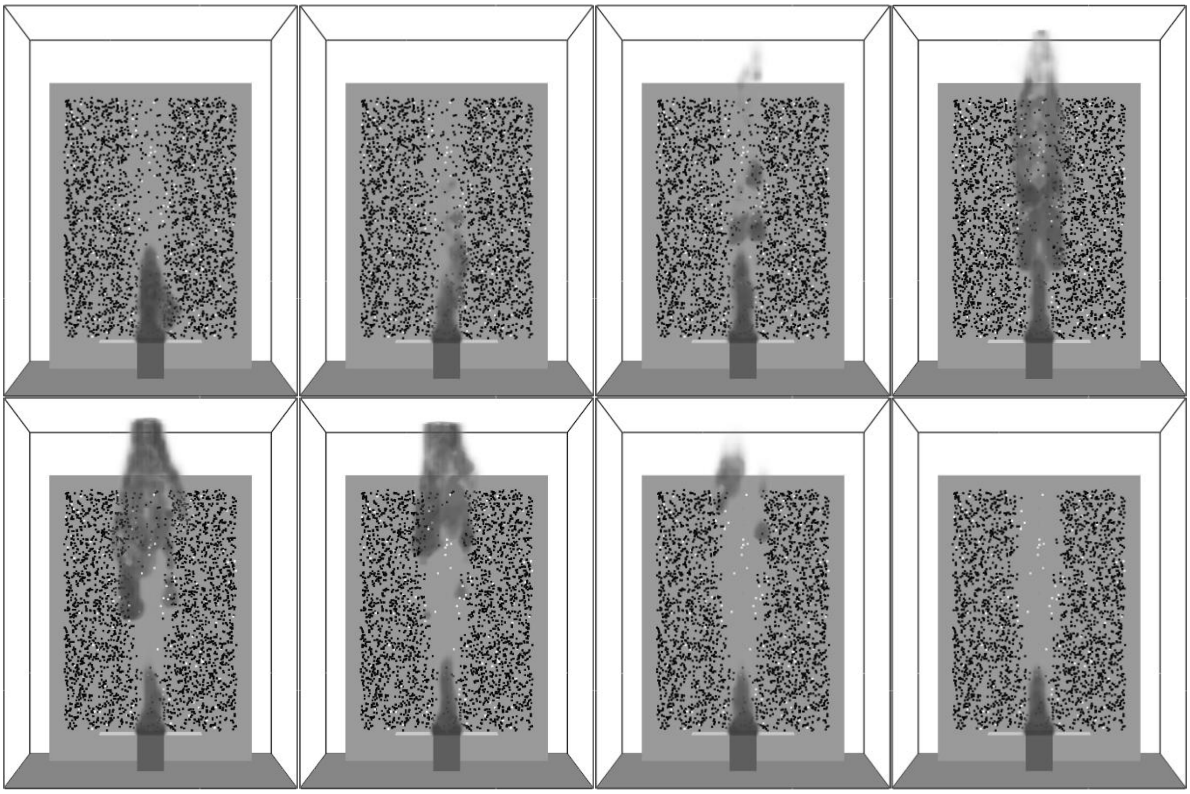

Figure 15 Straw fire-like burning between 486 and 493 seconds

CONCLUSION AND OUTLOOK

The cross-scale fire experiments have provided valuable insights into modelling ivy leaf pyrolysis. Through micro-scale fire tests in a tube furnace and inverse modelling, we have identified essential parameters necessary for application the complex pyrolysis model into FDS. Initial validation calculations of bench-scale fire tests with FDS have yielded plausible results.
Further thermogravimetric investigations involving stemmed leaves and branches of different moisture contents as well as additional bench-scale fire tests with less moisture contents are planned or in progress. With a validated FDS model for ivy pyrolysis modelling, we aim to recalculated large-scale fire tests.

REMARKS

All FDS simulations ran at FDS-6.8.0-0-g886e009-release.
Key data are made publicly available: https://github.com/openbcl/hederahelix

ACKNOWLEDGEMENT

Special thanks are extended to Forschungszentrum Jülich, Germany for making it possible to conduct thermogravimetric analyses in the Tube Furnace.
We extend our gratitude to the Verein zur Förderung der Ingenieurmethoden im Brandschutz e.V. (VIB) for their co-financing of the bench-scale experiments.

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