Experimental and Numerical Investigation of Visibility in Compartment Fires

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Abstract

This study presents the experimental and numerical investigation of visibility in a real scale compartment fire using an innovative experimental approach to measure spatio-temporal resolved extinction coefficients and the corresponding simulations with the Fire Dynamics Simulator (FDS). The temporal evolution of local measurements as well as profiles of the temperature and the extinction coefficient over the height of the compartment at certain points in time were considered. The measurements of the extinction coefficient profiles were locally verified by means of the well-established MIREX-measurement technique. The results were in a good agreement. Thus, they can be considered as reliable. As part of the simulations a grid sensitivity analysis regarding the evolution of the temperature and the extinction coefficient was carried out.

Keywords: Compartment Fire, Visibility, Extinction Coefficient, CFD, FDS

Introduction

In life safety analysis, the simulation of smoke propagation, toxicity and visibility can be used to predict the tenability criteria during evacuation [1]. The visibility strongly affects evacuation strategies and is closely related to the smoke density [2] which is dependent on various parameters, i.e. soot yield, particle size, particle deposition, agglomeration and the transport mechanism. Increasingly, computational fluid dynamic (CFD) models, like the Fire Dynamics Simulator (FDS, [3]) are used for the prediction of the quantities mentioned above, thus safety measures can be deduced from numerical simulations. But for validation purposes spatio-temporal experimental data regarding light extinction coefficients for real scale applications are not yet available.

This study presents the experimental investigation of visibility or extinction coefficients for a n-heptane pool fire in a closed compartment and compares it with the predicted values by FDS. To measure spatio-temporal extinction coefficients a new experimental approach was applied, which is discussed in detail in [4]. Basically, the light extinction of vertical aligned LED strips is observed by a CCD camera. The experiments were conducted in the Heinz Luck Fire Detection Laboratory of the University of Duisburg-Essen. The compartment has a square base area (10.5 x 9 m^2) and a variable height of the ceiling. For the experiments in this study a height of 3.37 m was chosen. To create relatively simple boundary conditions for the numerical simulations, n-heptane was used, because this is a well-studied and validated test case. The mass loss rate of the fuel with an initial mass of 450 g was measured by a mass balance. Besides the innovative measurement of spatio-temporal light extinction coefficients, reference measurements were carried out by the established MIREX (mid infrared extinction) measurement technique. Further an array of vertically aligned thermocouples close to the LED strips, which were shielded from the radiation of the pool fire, has been used to capture the temperature evolution and distribution.

In the FDS simulations carried out, the smoke density, which serves as the basic parameter for determining visibility, is determined by the fuel-dependent soot yield. While the visibility depends on the specific mass extinction coefficient K_m and the visibility factor C. Aerosol phenomena like deposition and agglomeration affect the particle distribution in the smoke and thus the visibility. But, by default aerosol deposition and agglomeration is not considered in the model. This study presents the effect of taking the different parameters into account in the numerical simulations and outlines a comparison to the experimental results.

Experimental Investigation

As the laboratory is mainly used for fire detection measures following the European standard EN 54 [5], the laboratory boundary conditions are well known, thus they can easily be applied to the FDS model. In Fig. 1, a sketch of the top view of the experimental setup is shown. The location of the pool fire is on the floor in the center of the room, thus the visibility of the LEDs is not disturbed by the flame. The distance of the vertical LED strips to the fire is about 3 m. The shortest line of sight (horizontal view) from the CCD camera to the LED strip is about 4.4 m. The length of the vertically aligned strip was 2.35 m, starting about 5 cm below the ceiling and it contained 141 LED units. The MIREX is about 13 cm below the ceiling.

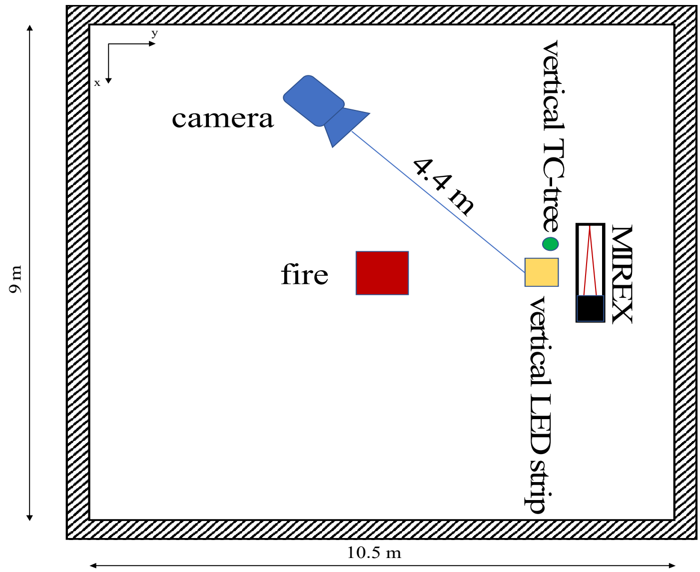


Fig. 1. Top view of the experimental setup. [4]

The irradiance of the LED strip was captured by a CCD camera with a sampling rate of 1 Hz. For the data analysis a special software was developed in Python. Within the analysis the position, the spot radius, the spot width, and the irradiance of each LED are determined and transferred to a model by means of a cost function. To compute spatially and temporally resolved information of the extinction coefficients, a simple model based on spatial discretization, here in horizontal layers, is applied. It is assumed that the light absorption properties for each layer are homogeneous, which is in a good agreement with the results in FDS, as can be seen in the numerical results in the following section. The intensities detected are used to determine the most appropriate set of extinction coefficients based on the amplitude. This approach applies the line-of-sight integral of the Beer-Lambert law in an inhomogeneous medium, here with homogeneous horizontal layers. A more detailed description of the data analysis is given in [4].

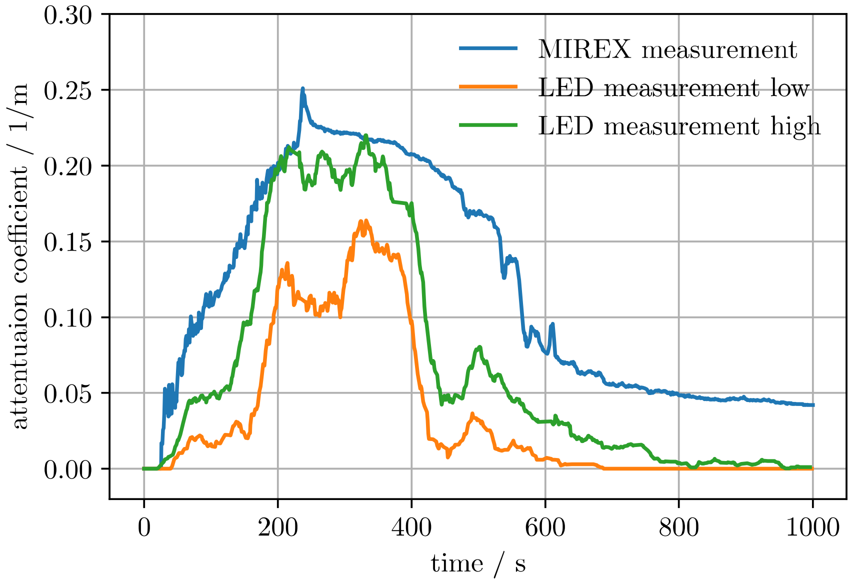


Fig. 2. Comparison of a MIREX measurement with the results of the LED-measurements. The data based on the LED measurement shows the results of an optimization towards low as well as high extinction coefficients.

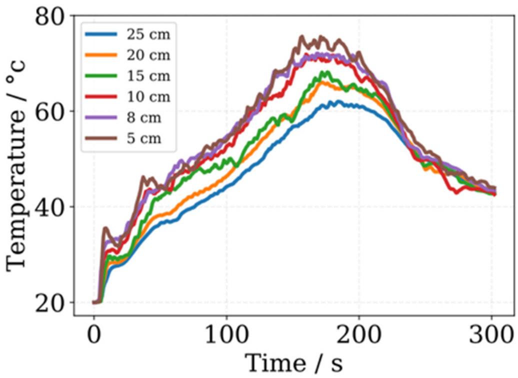
Fig. 2 shows the temporal evolution of the extinction coefficient measured by the MIREX (blue) and the extinction coefficient determined by the new approach at the height of the MIREX. In this figure two data sets of the measurements based on the LED technique are shown. One is the result of an optimization where low extinction coefficients are favored (orange). A second one where high values are favored (green). This is necessary as the MIREX is located just beneath the ceiling, i.e. in the top layers of the model, which have the highest uncertainty as only few light paths cross them. With this approach, a kind of upper and lower limit for the extinction coefficients is estimated, where both limits still lead to reasonable representation of the experimental data. The comparison of both measurements demonstrates that the proposed method is able to capture the dynamics as well as the amplitude of the extinction coefficients the same way as the MIREX measurement. However, the MIREX system seems to be more sensitive, i.e. indicates higher extinction coefficients, especially in the initial phase and in the decaying phase.

Numerical simulations and comparison to experimental results

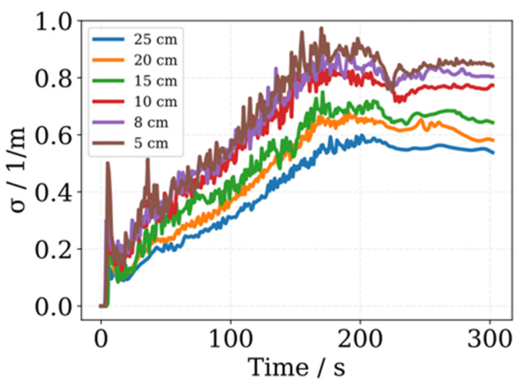
The simulations were carried out with FDS and the simulation setup is given by the experiment:

- room geometry and fire location, as shown in Fig. 1
- heat release rate is given by the measured mass loss rate
- fuel properties are those of n-heptane, i.e. the default values in FDS version 6.7.0

The compartment was assumed to be fully closed. This assumption is idealized, since there are small leaks in the ceiling of the room. The walls are assumed to be insulated, which leads to neglected convective heat transfer to the walls. The initial temperature of the walls and the ceiling is set to ambient. In order to find the adequate grid resolution, a sensitivity study was carried out. Here, only the quantities of interest, i.e. light extinction coefficient and gas temperature, were considered in the analysis. Fig. 3 presents the set of time series of these quantities for grid resolutions ranging from 5 cm to 25 cm. As the results do not significantly change for resolutions below 8 cm, this value was chosen for all simulations.



a



b

Fig. 3. Sensitivity of temperature (a) and extinction coefficient (b) w.r.t. the numerical grid resolution.

Table. 1. x-y-Coordinates of the evaluated z-profiles for the extinction coefficient.

Position	Coordinates in m (x/y)
1	(2.8/5.04)
2	(6.4/5.52)
3	(1.6/6.48)
4	(6.0/7.2)
5	(2.0/8.48)
6	(8.6/3.54)

Besides the following comparison between the numerical and experimental results, the hypothesis of homogeneous extinction coefficient layers was checked, which was assumed for the numerical analysis of the LED-measurements. The considered positions are listed in Table. 1 with respect to the coordinate system introduced in Fig. 1.

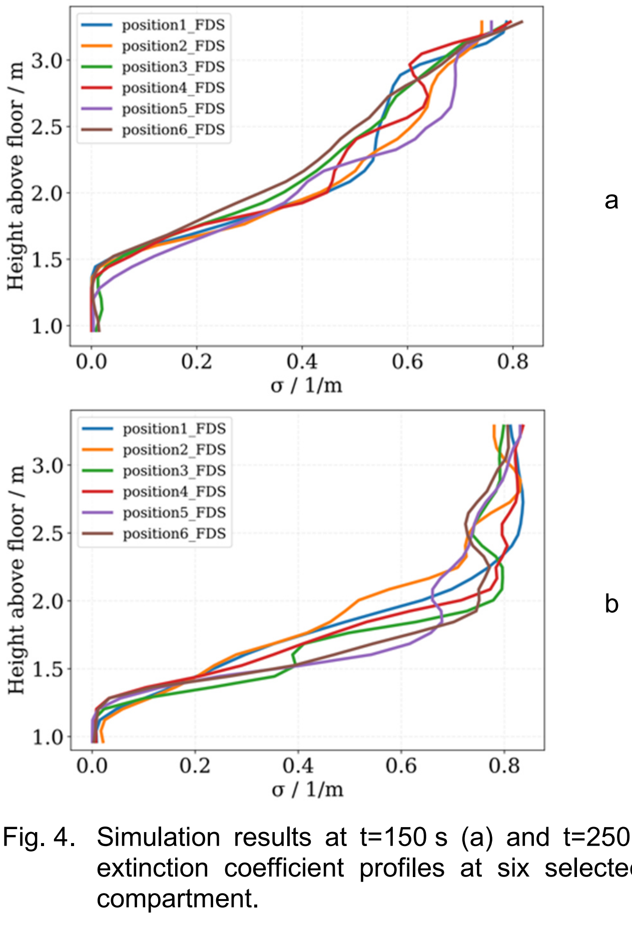
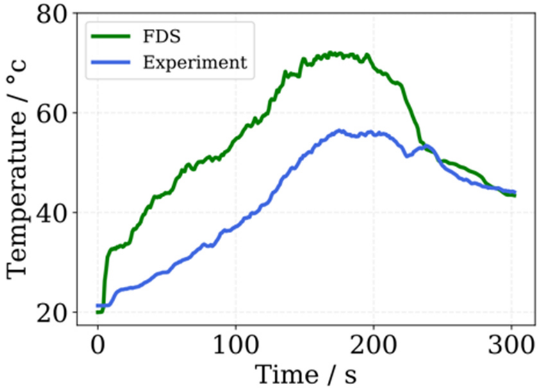


Fig. 4. Simulation results at t=150 s (a) and t=250 s (b) for the light extinction coefficient profiles at six selected positions in the compartment.

Fig. 4 shows the profile of the extinction coefficient as a function of height at the selected positions for two points in time. The data indicates, that there are no significant variations at these positions and therefore the assumption of homogeneous layers is confirmed by the simulations. This indicates, that this is probably also correct for the conducted experiments.

The following comparison of experimental and numerical data is carried out with respect to the temporal evolution at a selected location (Fig. 5) and as function of height at a selected point in time (Fig. 6).



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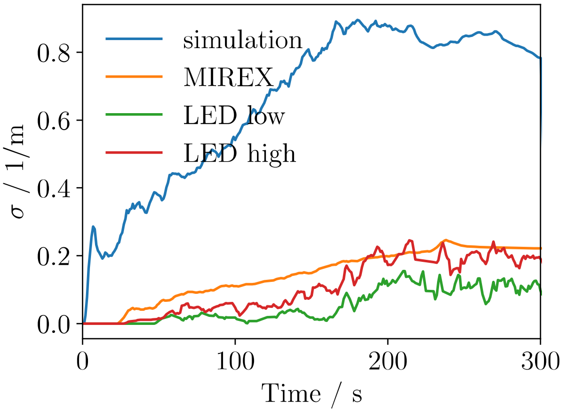
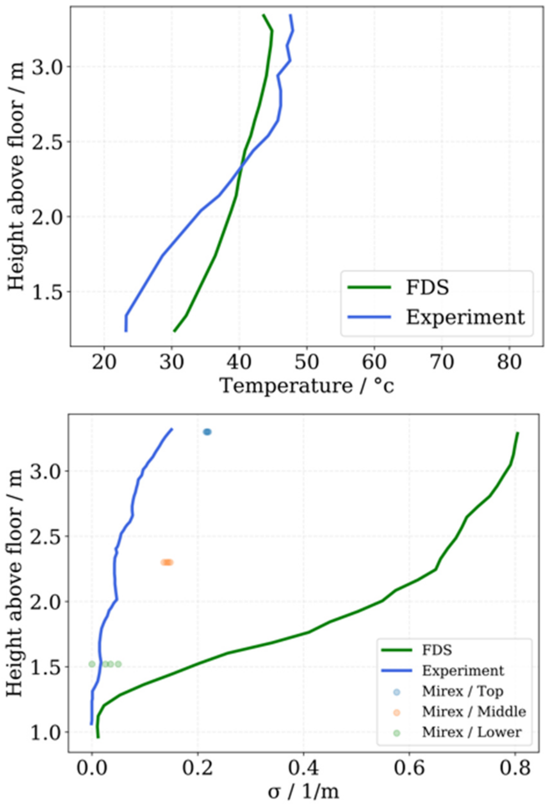


b

Fig. 5. Simulation results for the temperature development (a) and light extinction coefficient (b) during the experiment.

The temporal evolution in Fig. 5 is evaluated at the location of the MIREX. Both quantities, the gas temperature and the light extinction coefficients show significant deviations. The numerical simulation predicts higher values for both quantities. The difference in temperature is in the order of 15 °C, where the experimental values span a range of about 35 °C.



a

b

Fig. 6. Simulation results for the temperature development (a) and light extinction coefficient (b) at t = 300 s as a function of height.

The plot indicates, that there seems to be a constant difference in the temperature values, during the time period at which the fire is on, i.e. up to t = 200 s. Regarding light extinction, the numerically predicted values are up to a factor of 4 higher than the experimental values. In contrast to the temperature plots, not a constant difference, but a constant ratio seems to describe the relation of the numerical and experimental data.

The comparison with respect to height, at t = 300 s, is shown in Fig. 6. At this time, the temperature profiles show a similar pattern, but with significant deviations. With the new measurement technique outlined above, the profile of the extinction coefficient can be investigated. The right plot in Fig. 6 shows the data based on MIREX and LED measurements, as well as the numerical prediction.

Conclusion and outlook

Although the experimental and numerical setups are very elemental, both approaches result in very different values for the light extinction coefficient and the temperature. As visibility depends directly on this coefficient, the difference is also valid for visibility. Therefore, in the case studied here, the numerically predicted visibility would be shorter by a factor of about four and thus have a major impact on the tenability criteria in a life safety assessment. This observation agrees with other authors validation efforts, like [6] or [7], which suggests that the determination of visibility by means of FDS for the purpose of life safety analysis is to be improved and new experimental data is needed. The development of a new model in FDS taking agglomeration and deposition into account only led to small improvements.

As a n-heptane pool fire can be well modelled and the modelled transport process can be assumed to be valid, there is the hypothesis, that the specific mass extinction coefficient K_m is not well-chosen here. The value of K_m is determined in small scale experiments, like in a cone calorimeter [8,9] Thus, scaling effects on the shape and size of the particles are not taken into account. The default value of 8700 m^2kg^{-1} may have to be reconsidered, as well as the process to determine this value for real scale applications. The testing of this hypothesis and the proposal of a new determination method is the focus of future work. Further, the effects of (i) the leaks at the ceiling and (ii) the convective heat transfer at the compartment walls on the particle distribution and therefore the visibility will be investigated.

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