

GRID RESOLUTION INFLUENCE ON SMOKE SIMULATION ACCURACY

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Abstract: *Given the destructive nature of fire, experimental research in fire safety engineering can be a particularly difficult endeavor, characterized by low repeatability, high risk for the researchers and test subjects, and high cost of materials, due to the destructive nature of fire. Numerical simulation provides a way to bypass these shortcomings, offering a faster, safer, cheaper and repeatable solution for the studying of fire related phenomena. One key aspect of numerical simulation is accuracy and fidelity to real life situations, and this can be achieved by proper validation of numerical simulations with the help of experimental testing. This paper validates a numerical simulation of a real life experiment regarding the determination of the optical properties of non-toxic, artificially generated smoke and evaluates its accuracy for different computational cell sizes, in relation with the experimentally determined values. For this purpose, the Computational Fluid Dynamics numerical simulation software PyroSim is used for simulating the experimental setup and applying different mesh resolutions to the computational domain in order to evaluate the relation between mesh refinement and results accuracy regarding optical properties of smoke.*

Keywords: *Fire safety, smoke, visibility, CFD simulation, mesh*

1. Introduction

The destructive nature of fire makes research in fire safety engineering and training of fire safety professionals a particularly dangerous and hardly repeatable endeavor. Minimizing the risks during experimental research is of paramount importance, both for the health of the researchers and that of the test subjects. In this regard, there is a continual search for methods of recreating in experimental conditions certain aspects of a fire that will not influence the health of the participants. One such method of recreating the visibility reduction caused by smoke in enclosed spaces is using non-toxic smoke produced by fog machines. This kind of smoke can be used for research regarding people evacuation from smoke filled environments, firefighter intervention techniques, ventilation tactics and smoke exhaust system testing, without having to expose test subjects and researchers to the toxic components of flame generated smoke, or the heat of an actual fire.

A repeatable experimental evaluation of fire and its various components is hard to achieve given the high number of factors that influence fire behavior and the high cost of replacing experimental materials and sometimes tools that are rendered useless after utilization in harsh conditions such as those that are developed during a fire. To help address this problem, there have been developed fire simulation computer programs that offer the possibility of using numerical simulations to conduct research that would be either more expensive or unrepeatable in an actual experimental environment. One such program is the Fire Dynamics Simulator developed and offered freely by the National Institute of Standards and Technology of the United States and PyroSim, a graphical user interface for the Fire Dynamics Simulator program, offered by Thuderhead engineering under a free for academic use license for the purpose of this research.

This paper proposes an evaluation of grid resolution influence on the accuracy of the simulation of smoke optical properties, namely the optical smoke extinction coefficient and visibility. To this end, the results from a full scale experiment that determine said properties are used as a benchmark for establishing an adequate grid resolution in a numerical simulation of the experiment, in an effort to provide a correlation between grid resolution and accurate smoke properties representation.

The terms used in this paper are defined by the Fire Safety Vocabulary Standard [1] as follows:

- Optical smoke extinction coefficient - natural logarithm of the ratio of incident light intensity to transmitted light intensity, per unit light path length (the typical unit is m^{-1}).

- Smoke transmittance - ratio of transmitted light intensity through smoke to incident light intensity, under specified conditions. It is reciprocal of opacity of smoke and is usually expressed as a percentage. In practice, the transmittance usually measures the obscuration of smoke, which causes a reduction in visibility.

The importance of this kind of study is that it provides information on whether a certain grid resolution is adequate to use in a numerical simulation in which the optical properties of smoke need to be rendered accurately. The delicate balance between using a finer grid and the increase in computational time, which also depends on the performances of the computer the software is used on, while aiming for greater accuracy is tough to achieve. Thus, this paper seeks to provide a comparison of results obtained using different mesh cell sizes in a numerical simulation designed to emulate the optical properties of smoke so that researchers in fire safety engineering can get a sense of the impact that grid resolution in numerical simulations has on results accuracy.

In fire safety engineering, the optical properties of smoke provide information regarding smoke behavior in terms of visibility reduction in case of fires. The visibility reduction, also known as the opacity of the smoke produced by a fire influences the speed at which people evacuate during a fire [2], thus being an important factor to be considered in prescriptive fire safety standards. For example, the National Fire Protection Association standard 130 (NFPA 130) mentions that a tenable environment during fires is one that is characterized by a smoke obscuration level that renders an 80 lx illuminated sign discernible at 30 meters and doors and walls discernible at 10 meters [3].

2. Methodology

In the full scale experiment a fog machine was used to produce increasing amounts of non-toxic smoke in an enclosed space over time. The optical smoke extinction coefficient was determined through the measurement of the decrease in intensity of a laser beam that crossed the smoke filled environment. For the measurement of the light intensity of the laser beam, a luminance meter was used to provide measurements before the activation of the smoke machine, value that was set as the initial light intensity, and during the experiment, as the quantity of smoke in the room increased. A representation of the light source and luminance meter can be seen in figure 1.



Fig. 1. Light source and luminance meter

The experiment was repeated for different distances of the luminance meter from the light source, respectively 5 meters, 7.5 meters and 10 meters. The target upon which the luminance meter was placed served as a visual aid for the comparison of calculated visibility and perceived visibility. The experimental setup was recreated in the simulated environment, with the exception of using three targets at the same time, set at the established distances, thus providing the possibility of simultaneous measurements. An actual image from the experiment can be compared with an image from the numerical simulation in figure 2.



Fig. 2. Simulation of the experiment

For the purposes of this paper, the measured values from target number 2, the one situated at 7.5 meters from the light source were compared with the ones calculated by simulation for the same distance from the observation point, for each of the three simulations involving different coarseness of the calculation grid. During the simulation, the smoke extinction coefficient and visibility for each target were being measured and their values logged for each incremental time step through the use of gas-phase devices positioned in the simulation environment that measure the user specified quantity, be it either visibility (m) or smoke extinction coefficient (m^{-1}).

In the experimental setup, the fog machine was activated for short, timed bursts of about 9 seconds after which the atmosphere was left to settle for ensuring the proper measurement of the analyzed parameters in a calm environment. To replicate the experimental conditions, the simulation time has been set to be 480 seconds, and the simulated vent that produces smoke has been programmed with a timed start/stop control logic that mimics the behavior of the fog machine during the experiment. Table 1 presents a correlation of experimental and simulation chronology.

Table 1: Simulation timetable

No.	Cumulative time of fog machine use (s)	Smoke liquid used (ml)	Simulation time (with pauses for atmospheric stability) (s)	Smoke to room volume ratio
1.	0	0	0	0
2.	5	6	5	0.061
3.	9	11	69	0.109
4.	18	22	138	0.218
5.	27	32	207	0.327
6.	36	43	276	0.436
7.	45	54	345	0.545
8.	54	65	414	0.654

The simulation was repeated for three different sizes of the computational cells that comprise the mesh which fills the simulated domain. The coarsest mesh had a number of 22,080 almost cubic cells with the average linear dimension of 20 centimeters. For the next two simulations the mesh was refined for an average of 15, respectively 10 centimeters average linear dimension resulting in a number of cells of 51,600, respectively 156,000. The visual difference between the three cases

can be seen in figure 3. The increase in the number of cells in the domain has led to a significant increase of the time needed for the simulation to complete.

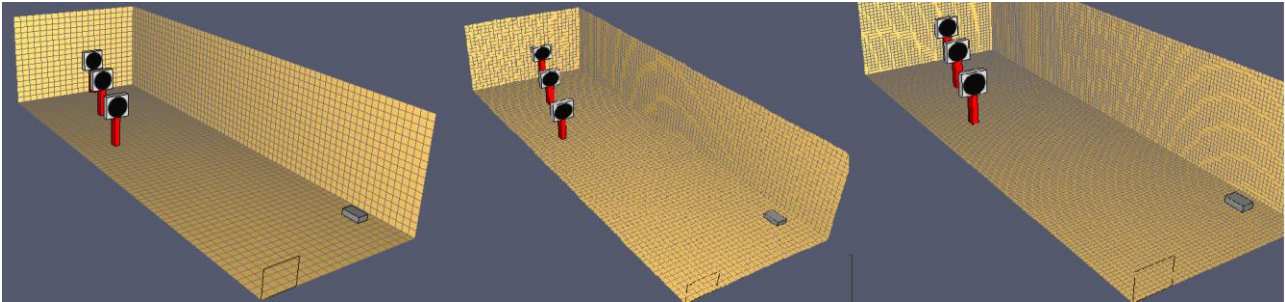


Fig. 3. Visual comparison of grid cells size

3. Results and discussion

This study sought to assess the influence that grid resolution has on the accuracy of the simulation of smoke optical properties by comparison of the values obtained by simulation using three degrees of coarseness of the simulation mesh with the results that were obtained by full scale experimenting. The optical smoke extinction coefficient, the first of the two optical properties of smoke that were analyzed in the present study, provides a measure of light attenuation as it passes through the smoke, or a measure of the capacity of the smoke to diminish the intensity of light as it passes through it, regardless of the nature of the smoke, be it generated by the burning of solid or liquid fuels [4]. The result obtained during the experiment and the simulations have been charted out on the same graph, as presented in figure 4.

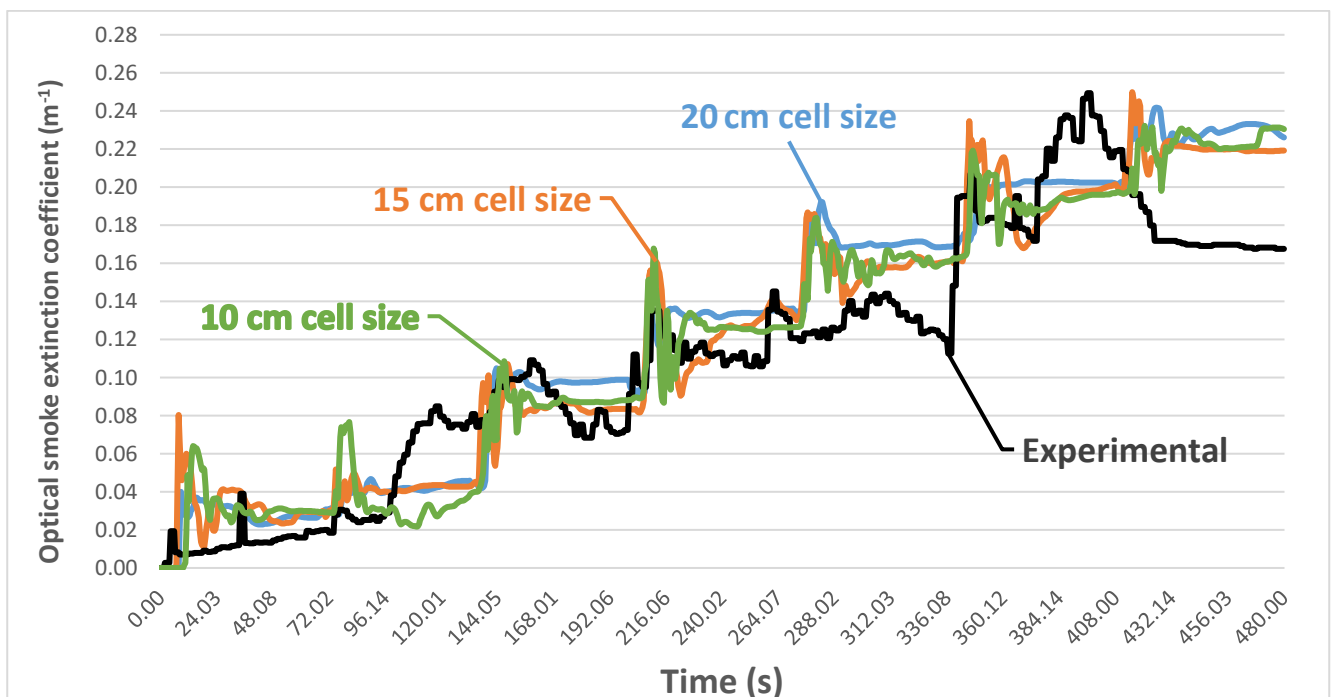


Fig. 4. Optical smoke extinction coefficient comparison for all grid sizes

The average difference between the values for the experiment and the 20 cm cell size simulation is 6.46%, which is a reasonable level of accuracy given the low computational grid resolution. For a better comparison of the differences, the values for the two instances are compared in figure 5, the

difference between the higher values and the lower ones being highlighted in the color that corresponds to the higher values method of determination, be it experimental or by simulation.

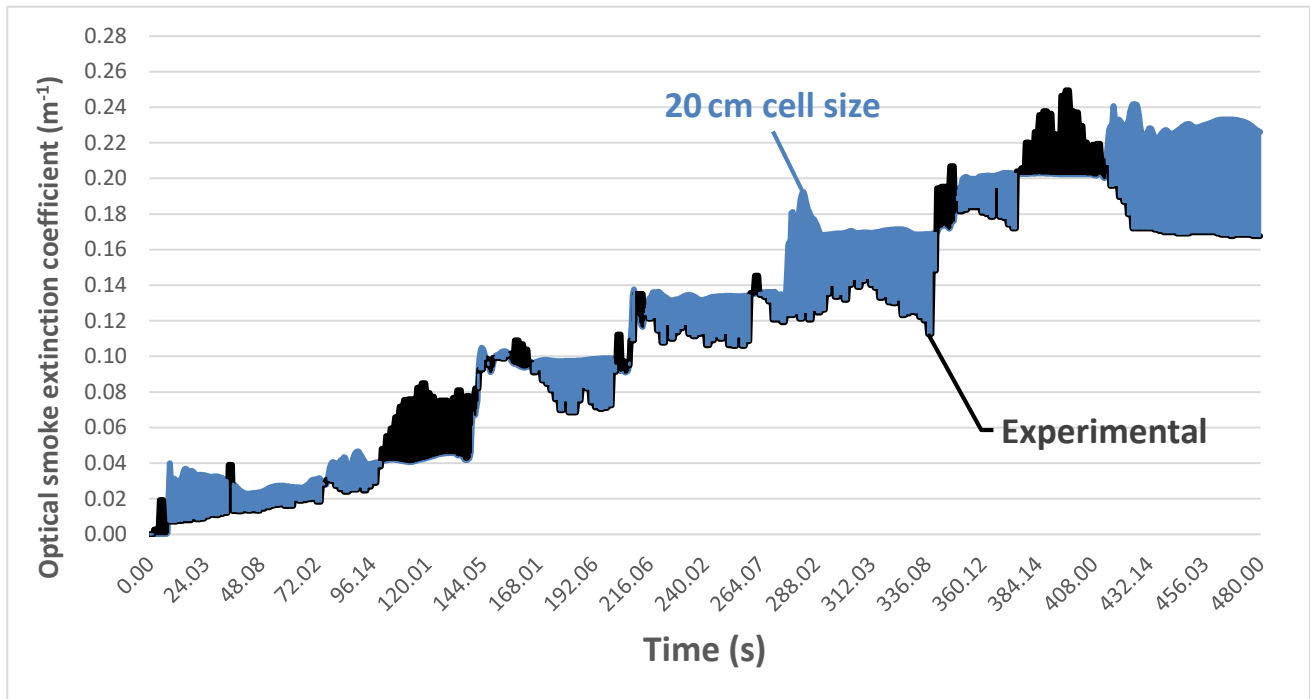


Fig. 5. Optical smoke extinction coefficient comparison 20 cm cell size

The values for the 15 cm cell size simulation differ with those obtained experimentally by an average difference of 4.21%, and the comparison of the two sets of data can be seen in figure 6.

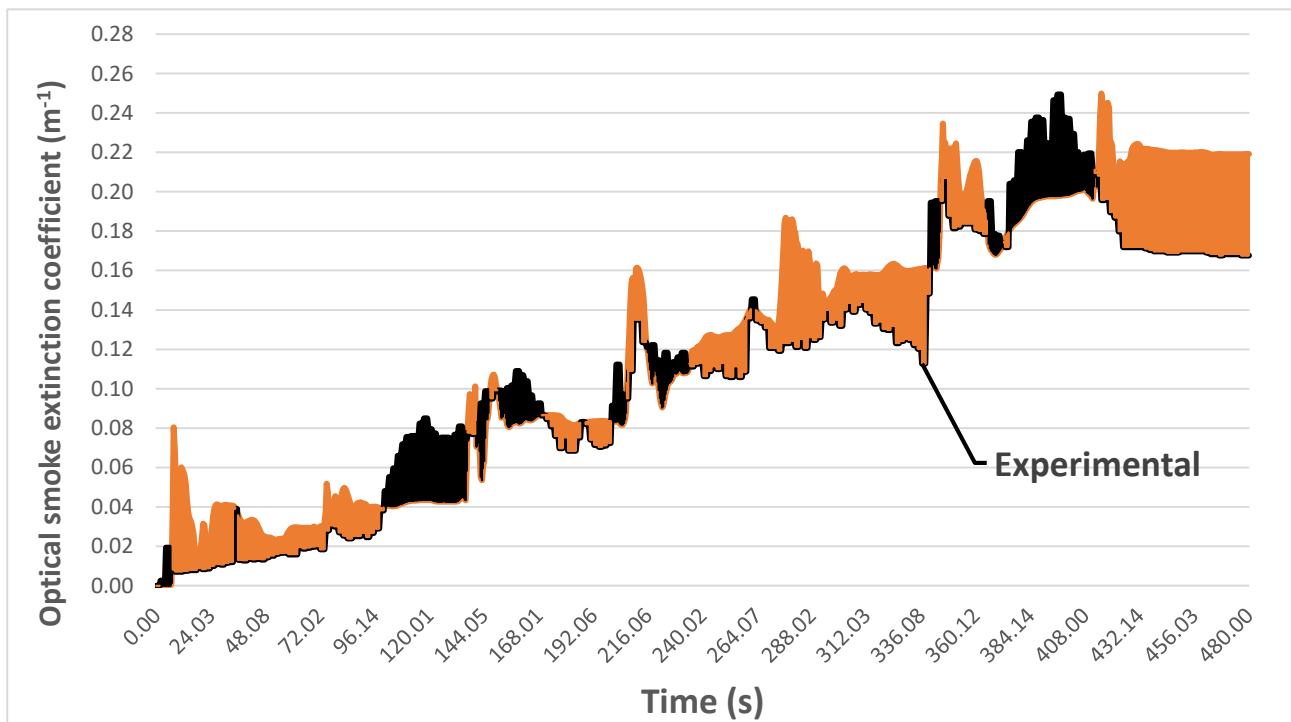


Fig. 6. Optical smoke extinction coefficient comparison 15 cm cell size

With the values obtained by running the simulation with an average linear dimension of 10 cm for the computational grid, there has been obtained an average difference of 4.16%. The comparison of the said values is represented in figure 7.

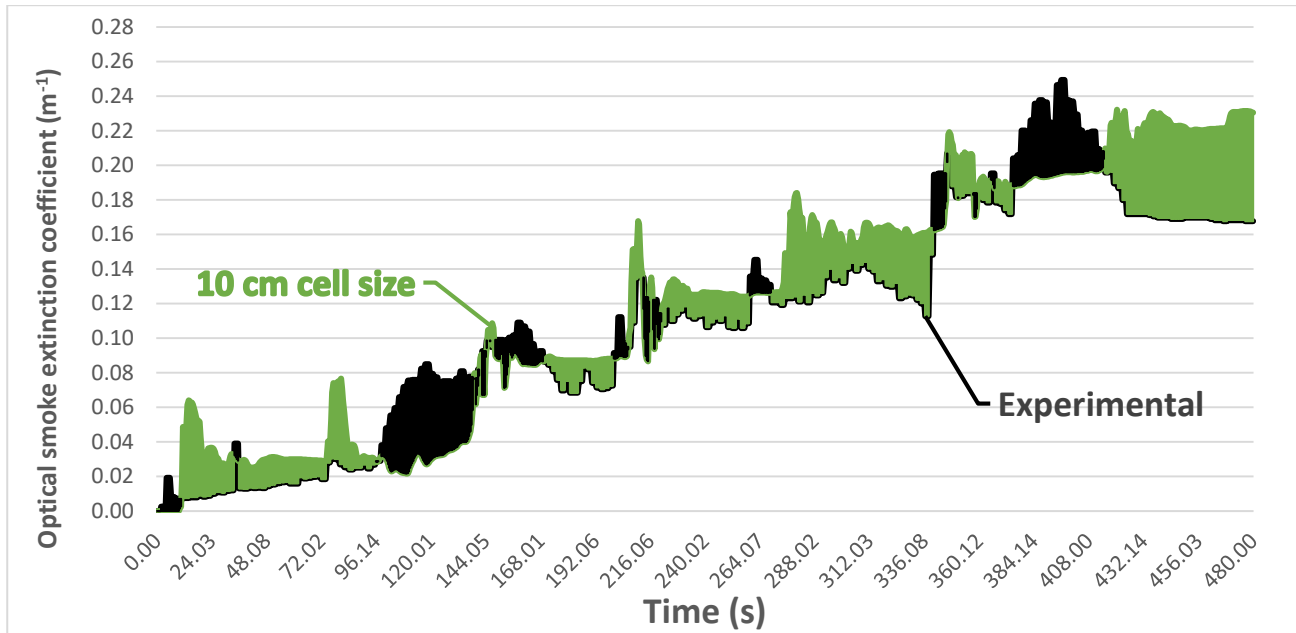


Fig. 7. Optical smoke extinction coefficient comparison 10 cm cell size

Visibility was also measured during the simulation and the results were compared with those obtained by calculation of the amount of light reduction as it passed through the smoke during the experiment. The maximum visibility in the simulation program is considered to be 30 meters [5] and so the reduction in visibility in both the experimental case and the simulations were calculated as percentages. The comparative chart for the visibility in experimental and simulations can be viewed in figure 8.

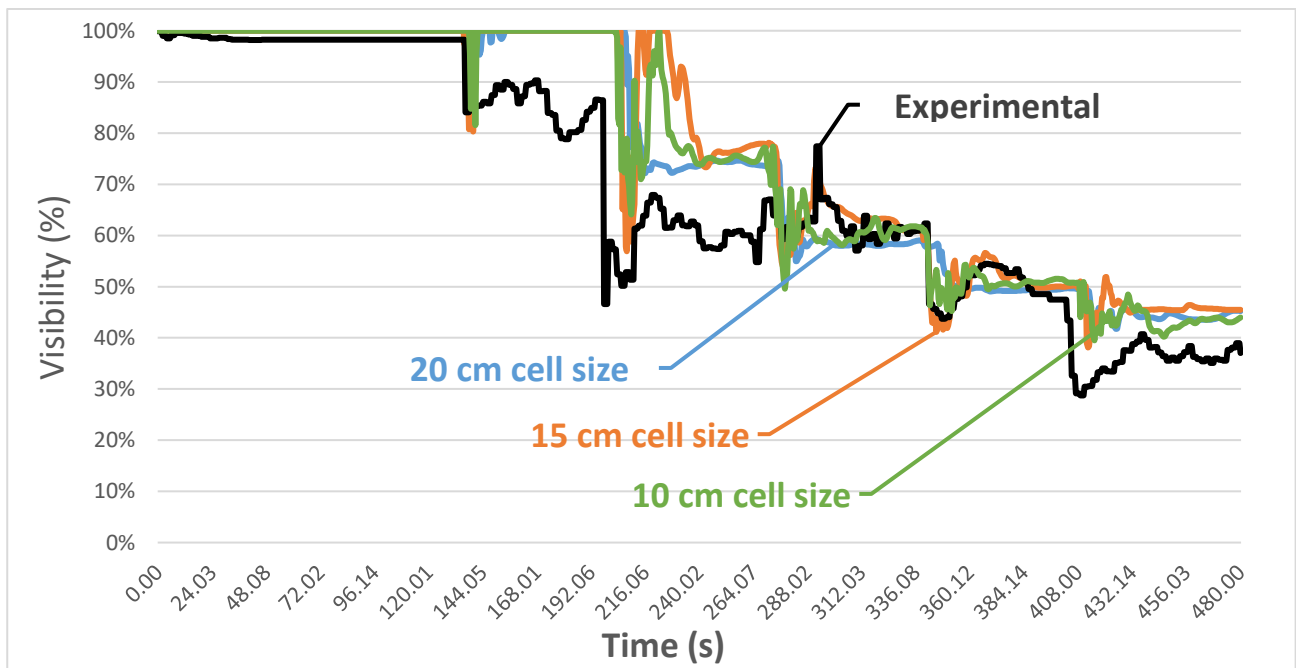


Fig. 8. Visibility comparison for all grid sizes

The average difference between the 20 cm cell size simulation and the experimental values in terms of visibility is 7.96%. For a better comparison of the differences, the values for the two instances are compared in figure 9, the difference between the higher values and the lower ones being highlighted in the color that corresponds to the higher values method of determination, be it experimental or by simulation.

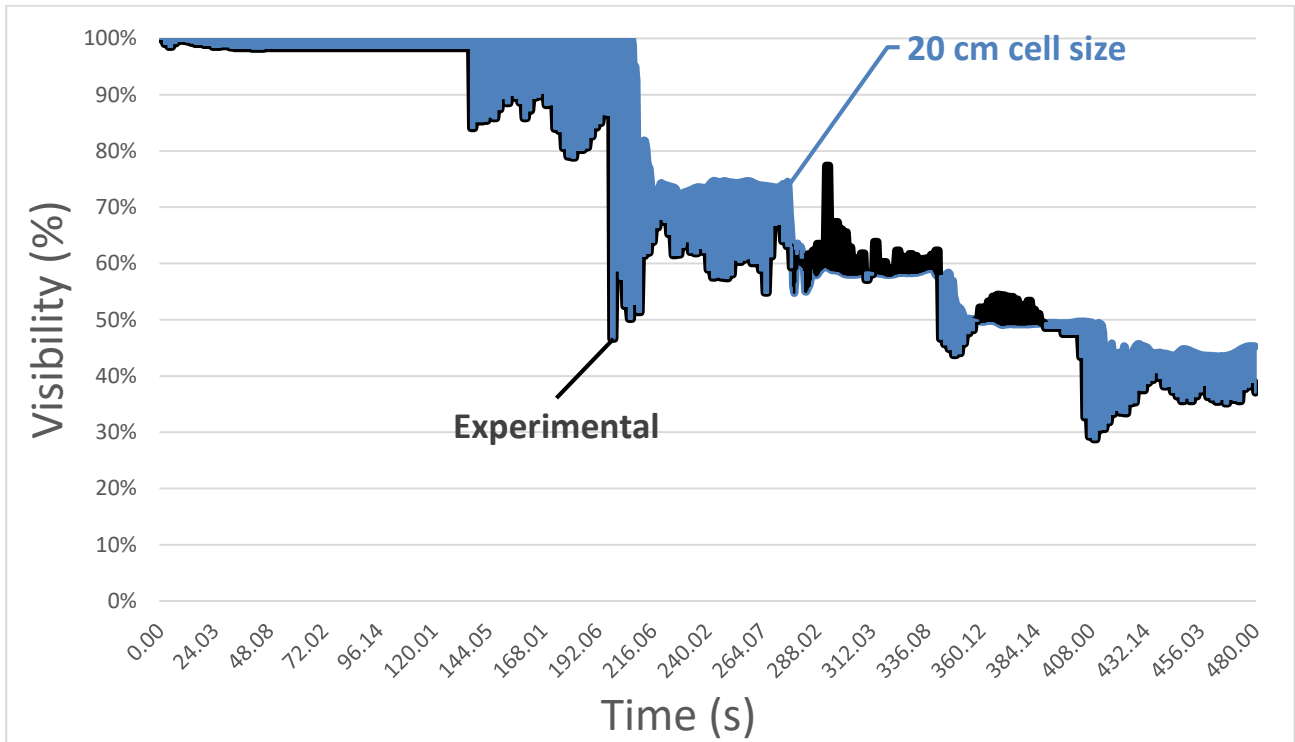


Fig. 9. Visibility comparison 20 cm cell size

The values for the 15 cm cell size simulation differ with those obtained experimentally by an average difference of 7.80%, and the comparison of the two sets of data can be seen in figure 10.

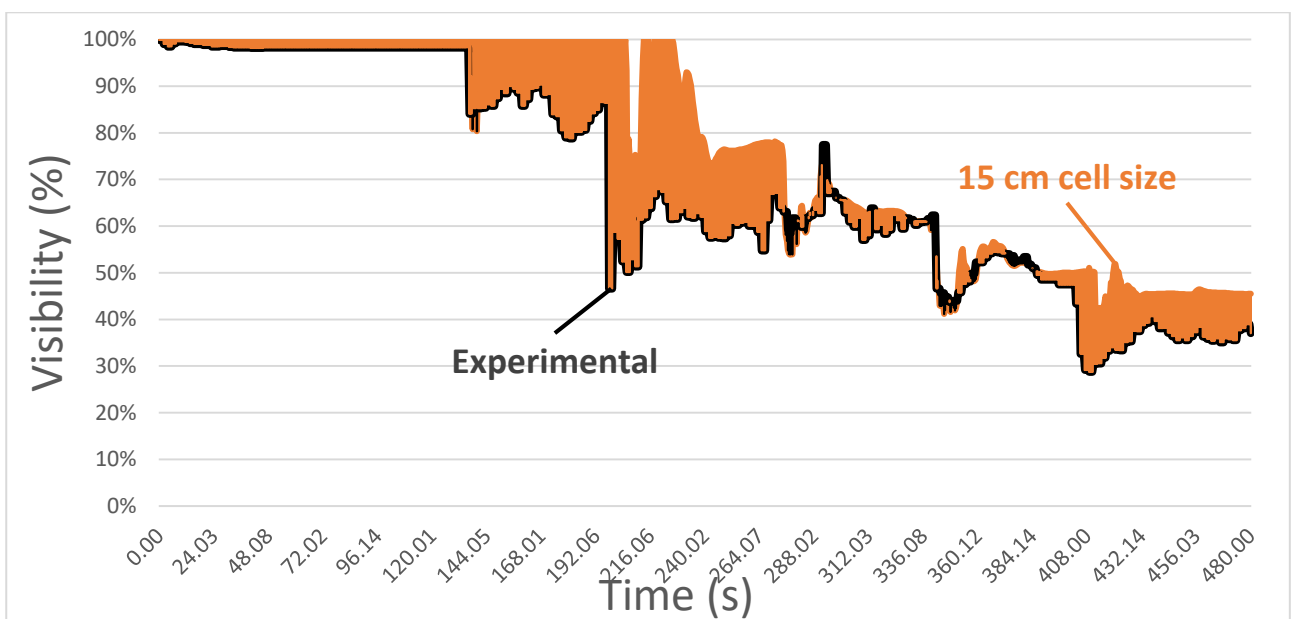


Fig. 10. Visibility comparison 15 cm cell size

With the values obtained by running the simulation with an average linear dimension of 10 cm for the computational grid, there has been obtained an average difference of 7.51%. The comparison of the said values is represented in figure 11.

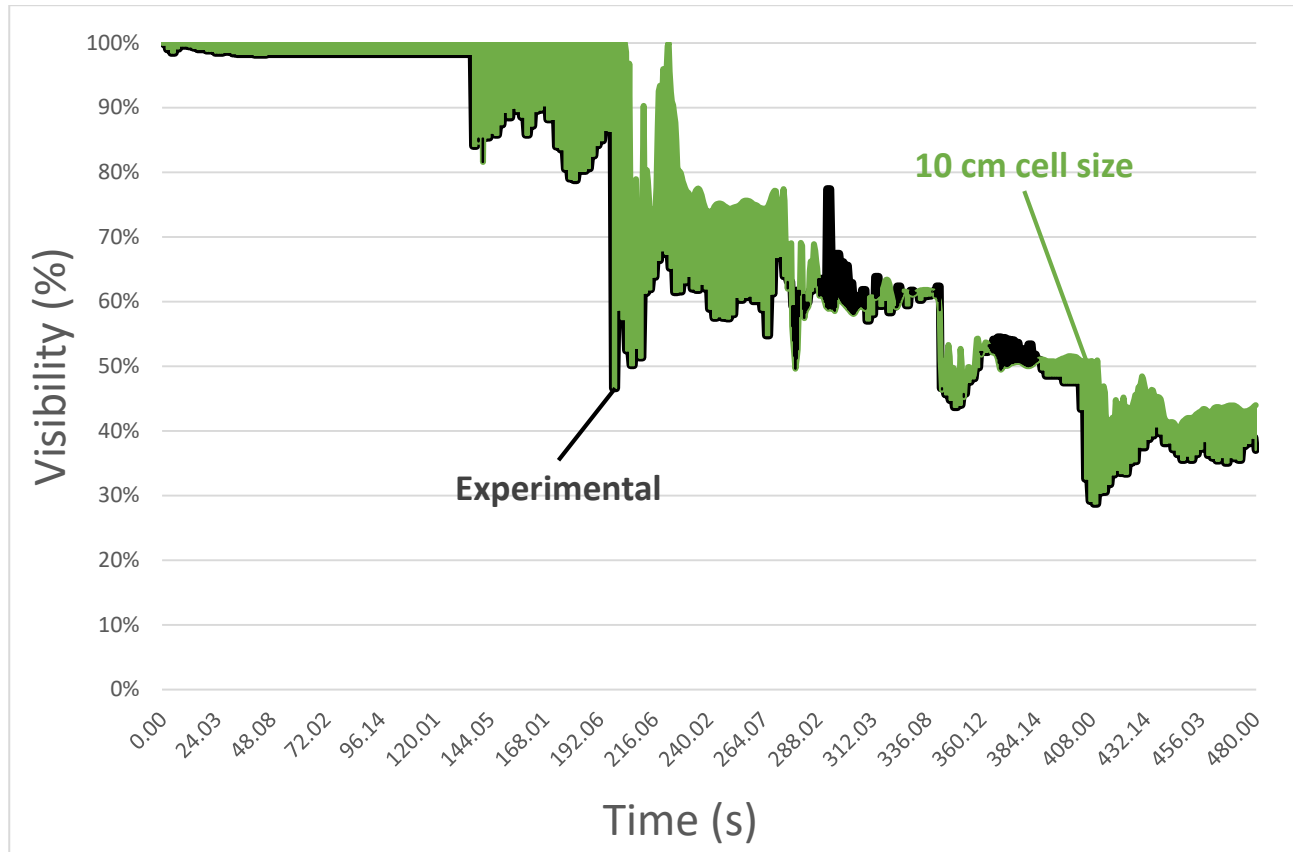


Fig. 11. Visibility comparison 10 cm cell size

A great influence in accuracy can be seen from the 20 cm cell average dimension to the 15 cm cell average dimension in terms of optical smoke extinction coefficient, of about 2.25%. Further increasing the number of cells has a much lesser impact, of only 0.05%, thus leading to the conclusion that for the given dimensions of the simulated space, a cell size of 15 x 15 x 15 cm is sufficient for ensuring an accuracy under 5%. In terms of visibility, a greater improvement in accuracy can be seen in lowering the computational cell average dimension from 15 cm to 10 cm, with an 0.29% improvement, which is not that significant, but still greater than the 0.16% improvement gained from decreasing the average cell dimension from 20 cm to 15 cm. Table 2 offers a detailed look at the improvements in accuracy from each incremental adjustment of the average dimension of the cells in the computational mesh.

Table 2: Accuracy improvement

No.	Average dimension of cells	Average difference	
		Optical extinction coefficient	Visibility
1.	20 cm	6.46 %	7.96 %
2.	Improvement	2.25 %	0.16 %
3.	15 cm	4.21 %	7.80 %
4.	Improvement	0.05 %	0.29 %
5.	10 cm	4.16 %	7.51 %

4. Conclusions

For the simulation of a full scale experiment involving smoke optical properties in a compartment or building, for a relatively good accuracy, cells with a size of 0.001 m^3 can be used, meaning that the average dimension of one of their sides can be 10 cm in length. Improvement in simulation accuracy of the optical properties of smoke has been shown to be rather insignificant with the further refinement of the mesh beyond this size. Further research can apply this knowledge to numerical simulations involving smoke generated by burning items, in cases where the optical properties of smoke are evaluated, such as people evacuation from buildings during fire, smoke exhaust systems performance, or firefighter training scenarios in buildings or compartments. Numerical simulations provide a cheaper, faster, more repeatable and less dangerous alternative to experimental research and choosing the right size of the computational cells ensures faster computational time and an adequate accuracy level that meets the needs of the fire safety engineer.

Acknowledgments

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