A Fire Dynamics Simulator approximation of non-toxic smoke

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Abstract. Experimental research in fire safety engineering is often characterized by a low repeatability mainly caused by the destructive nature of the fire phenomena. One of the ways that these shortcomings might be avoided is by using numerical simulation for research in this particular branch of engineering. Accuracy in numerical simulation comes through validation of the results by comparison with experimental testing, and in this regard, this paper presents the use of the PyroSim fire simulation program, which is a user interface for the Fire Dynamics Simulator software package, for the purpose of simulating non-toxic smoke in a way that accurately describes its behavior and properties observed in experimental testing. A full-scale experiment has been conducted for the purpose of determining the optical properties of non-toxic smoke produced by a smoke machine and this paper presents the way that this smoke can be accurately represented in the simulation program, for the purpose of providing a basis for future simulations of experiments using smoke machine generated smoke. The methodology employed can be used in further research involving simulated smoke, such as CFD representations of firefighter training, people evacuation from smoke-filled enclosures and smoke exhaust in buildings.

1. Introduction

Fire safety engineering is an area in which research and training are impacted by the particularly destructive nature of fires. Experiments in this domain are often difficult to conduct and repeat due to the dangers of exposing test subjects to the conditions created in such environments, the high cost of materials that are often destroyed in the testing process and of the special measuring apparatus that needs to withstand the high temperature conditions of the fires, the rapid cooling associated with the extinguishment and the high humidity content of the atmosphere caused by using water as an extinguishing agent.

For the purpose of making the experimental aspect of this particular branch of engineering more approachable, there arises the need for identifying less dangerous representatives of the various aspects of a fire, adequate for the purpose of the experiment. One element that can be used for such a representation of the smoke produced by a fire can be artificial smoke produced by smoke machines. This smoke is non-toxic, has a low temperature compared to that produced by a fire and can be used in different applications, ranging from firefighter training, assessing the reaction of people to smoke obscuration of an evacuation route in case of a fire, to evaluating the speed with which smoke can be cleared out from a compartment by ventilation equipment. The speed with which people evacuate in case of a fire depends on many factors, such as the toxicity of the smoke or the temperature in the vicinity...
of the fire. Among those factors, the opacity of the smoke produced by a fire, also known as the visibility reduction caused by the smoke is one of the main parameters that influence people’s displacement velocity during evacuation [1].

Another aspect in fire safety engineering research consists of using numerical simulations to provide a cheaper and more repeatable approach to actual experimenting. The drawback of such an approach consists in the necessity of validating the results, either by conducting a real experiment, or by using simulation properties already validated by others in the scientific community, in similar conditions with the simulation that the user wants to run. Thus, by using numerical simulations validated with experiments by others and made available through scientific publications, progress in this field of research can be made at an ever-increasing rate and testing for the compliance with standards in case of fires can be done more rapidly and with the use of fewer resources.

One of the standards that prescribes limits regarding smoke obscuration is the NFPA 130, a standard of the National Fire Protection Association. It lists keeping smoke obscuration levels continuously below the point at which a sign illuminated at 80 lx is discernible at 30m and doors and walls are discernible at 10m as a factor that should be considered in maintaining a tenable environment during fires [2]. These limits can be tested through the use of numerical simulation and experimentally through the use of non-toxic smoke, so as to not endanger the researchers and test participants.

This paper proposes a step by step scientific approach to recreate in a fire simulation program the non-toxic smoke that can be used for fire safety engineering experiments without the dangers of the real smoke caused by fires. To this end, a full-scale experiment has been conducted, with the purpose of gathering data about the optical properties of smoke and its appearance. That data has been used to represent that non-toxic smoke, both in regards to its optical properties, and visual appearance, in the numerical simulation program.

To this end, the software used was Thunderhead Engineering’s PyroSim, which is a graphical user interface for the Fire Dynamics Simulator (FDS) program, and disposes of a library of pre-set values for properties for the simulated elements, such as smoke. The approximation of non-toxic smoke presented in this paper can serve as a guideline for adaption of the pre-set values of smoke to match the needs of the simulation user, as a validated database that can be used for future simulations with this type of smoke.

2. Methodology

The full-scale experiment that represents a basis for the simulation consisted of using a smoke machine for the purpose of creating a smoke-filled environment in a compartment of known dimensions using timed bursts, in order to achieve different levels of smoke saturation in the testing area. A target that provides visual contrast for the purpose of evaluating visibility has been positioned at set distances of 10m, 7.5m and 5m respectively from the observation point, as the experiment was repeated for each of the distances. A luminance meter was used to determine the light intensity of a laser beam as it passed through the smoke layer, providing data for the calculation of the smoke’s transmittance and its light extinction coefficient. The laser source, target and luminance meter during the experiment can be viewed in figure 1.

The Fire Safety Vocabulary Standard [3] defines the smoke’s optical extinction coefficient and its transmittance as follows:

- 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 results obtained through the experiment are used in PyroSim for the customization through trial and error of a surface that can inject the soot species, representing the suspended carbon particles emitted from a fire, that constitute the primary cause of obscuration. Soot is what mainly makes the smoke visible, and it is already defined in the software’s library as a species. The purpose of the paper is to propose the modification of the quantity of soot injected into the simulation domain in such a way that the smoke’s properties in the simulation closely resemble those determined by the experimental setup. To do so, there have been set two areas of resemblance that are evaluated in order to ensure the proper representation in the simulation of the experimental smoke, namely, the accuracy of the simulated optical properties and the visual representation of the smoke in the results viewer. These two areas are determined by properties set by the user in two different stages of the simulation, respectively simulation setup and results post-processing.

The smoke optical properties were determined in the experimental conditions by measuring the reduction in intensity of a laser beam that crosses the smoke layer, and within the simulation by the use of specialized devices already defined in the program library. During the experiment, the smoke’s optical extinction coefficient and visibility were determined through calculations using the reduction in light intensity of a laser beam as it passed through the smoke layer, as measured by a luminance meter. In order to determine the same parameters in the simulation, each of the simulated targets was fitted with a device that can determine the optical smoke extinction coefficient, and one that can measure the visibility reduction in the path from the observation point to the target. The properties of the visibility device can be seen in figure 2.
The mesh in the simulation had the same dimensions as the testing area in which the experimental testing has taken place and is provided with a ventilation opening for the purpose of not over pressurizing while the soot species is injected. It consisted of 178,200 almost cubic cells with an average dimension of 10 centimetres. The main mesh was split into four smaller ones in order to facilitate parallel processing. The representation of the target and the mesh coarseness can be seen in figure 3.

The smoke machine is represented in the simulation through an object or obstruction that injects soot into the simulation area through one of its surfaces. The representation of the smoke machine in the simulation, along with the activated machine during the experiment can be viewed in figure 4. In order to limit the calculation time necessary for the simulation, details have been reduced as much as possible, and only the essential aspects of the experiment were represented.

The smoke machine specifications state that its maximum continuous output is $128 \, \text{m}^3/\text{min}$, thus the surface that injects soot into the domain has been defined as a supply surface with a $2.125 \, \text{m}^3/\text{s}$ volume flow. The soot introduced by this surface has been defined as a mass fraction of soot per air introduced of $0.00025 \, \text{kg/kg}$, this value having been determined through trial and error type testing, the success
indicator being the simulated smoke’s optical extinction coefficient matching the one calculated using the experimental measurements. The soot injecting surface properties can be viewed in figure 5.

![Properties of smoke injecting surface](image)

**Figure 5.** Properties of smoke injecting surface

The simulated time of the experiment has been chosen to be 460 seconds, given that after each release of smoke for the prescribed amount of time, the smoke layer was left to settle for 60 seconds, thus ensuring the stability of the environment during the measurements. Given the output of the smoke machine, and the volume of the testing compartment, their ratio has been calculated, so as to provide information for further research regarding scale reduction of the experiment. The time of smoke machine use, the quantity of smoke fluid used, the simulation time and smoke machine output to room volume ratio can be consulted in table 1, which provides a comparison of experimental and simulation time.

| No. | Cumulative time of smoke machine use (s) | Smoke fluid (ml) | Simulation time (with pauses for atmospheric stability) (s) | Smoke machine output 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 dynamics of the simulation were controlled using a stop/start control logic that governed the deactivation and activation of the soot injecting surface, triggered by certain moments in the simulation, that would match the experimental time of smoke machine usage and rest periods between consecutive
smoke bursts. This control logic is presented in figure 6, and regards the soot injecting surface as activate at the start of the simulation and then deactivated and reactivated intermittently at the specified moments.

![Figure 6. Dynamic control logic](image)

### 3. Results and discussion

In order to provide an accurate representation of the smoke in the simulated environment, the quantity of soot introduced was adapted so that the optical smoke extinction coefficient would match the experimentally determined values. During the experiment, the intensity of the laser beam was measured both continuously and discretely after each settling period. The comparison of the experimental values and the ones in the simulation for the first target, the one 5 meters away from the measuring point can be viewed in figure 7 for the discretely measured values and figure 8 for the continuously measured ones.

![Figure 7. Discrete measurement smoke extinction coefficient comparison](image)

As can be seen from the data, the optical smoke extinction coefficient has no correlation between the experimental scales, other than the upward trend associated with increasing smoke concentrations as the experiments progressed. However, after calculating the smoke extinction area, plotting the values and comparing the charts, it can be seen that this parameter greatly matches across experimental scales. The values of the smoke extinction areas from the full-scale experiment have been compared for each of the measuring distances with the corresponding ones pertaining to the small-scale experiments. The differences were then averaged and calculated as percentages of the maximum value of the smoke extinction area between the full-scale experiment and the small-scale that it’s being compared to. Table 3 presents the average difference between the experimental scales for the smoke extinction areas.
The simulation values of the optical smoke extinction coefficient in the discrete measurements chart provides more of an approximation of the trend of the experimental values, given that the measurements were performed after the settling period, when the smoke extinction coefficient would not be at its highest value for the given soot injection session. The continuous measurements chart provides a more qualitative comparison of the values. Discrete measurements therefore do not provide enough accuracy for the simulation of smoke using computational fluid dynamics software, such accuracy being provided only by continuous measurement. The frequency with which the continuous measurements were taken was that of one measurement every two seconds. Given that the light extinction coefficient \( k \) for monochromatic light is calculated \([4]\) from light transmittance \( I/I_0 \) \((I – transmitted light intensity, \ I_0 – incident light intensity)\) using equation (1), and the its values are in the orders of \( m^{-1} \), it can be stated that the simulated values present a reasonable similarity to those determined by experimental measurements.

\[
\frac{I}{I_0} = \exp(-k \cdot L)
\]

(1)

The way that the smoke optical extinction coefficient influences visibility has been determined experimentally \([5]\) and is presented in equation (2), where \( S \) (visibility) depends on \( C \) (proportionality constant) and \( k \) (optical extinction coefficient of smoke). The proportionality constant used by the simulation program \([6]\) is 8 for illuminated signs and 3 for reflected signs or building components viewed in reflected light, such as is the case of the targets used in the experiment and simulation.

\[
S = \frac{C}{k}
\]

(2)

The simulation software provides values and visual representations for the reduction in visibility due to the obscuration of smoke. The maximum visibility set for the program is 30 meters, and the experimentally determined values can be used to provide a percentage of visibility reduction. That is why the maximum visibility value of the program was regarded as being the 100% threshold for the purpose of comparing the simulated and experimental measurements, and the visibility loss in the experiment was calculated from the values provided through the measurements by determining what percentage of light intensity was lost by the laser beam passing through the smoke layer. A comparative chart of the values for the experimental measurements and those in the simulation can be viewed in figure 9, while a visual representation of the visibility loss in the compartment during the simulation can be viewed in figure 10.

**Figure 8.** Continuous measurement smoke extinction coefficient comparison
The second area of resemblance between the experiment and simulation is that of the visual representation of the smoke in the results viewing section of the software. By default, the simulation program represents the soot particles as being black, but the non-toxic smoke used in the experiment is white, so the representation of it in the results viewer of the simulation must be adapted accordingly. The experimental conditions were recorded using digital cameras and the smoke brightness has been deducted from the images thus obtained by determining the value of each of the basic colours that comprise a digital image, namely red, green and blue [7]. The initial appearance of the simulated smoke before and after the brightness has been adjusted can be seen in figure 11.

![Figure 11. Smoke appearance before and after brightness adjustment](image)

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![Figure 9. Visibility reduction representation](image)

![Figure 10. Visibility reduction comparison](image)
4. Conclusions

The low repeatability of experimental research in fire safety engineering can sometimes be avoided by the use of numerical simulations, but in order to provide the best accuracy for a numerical simulation, it has to be validated either by the user itself, or by the use of peer reviewed methods and properties that match the case study at hand.

This paper provides a methodology for approximating in a numerical simulation non-toxic smoke used in a real-life experimental environment, by the appropriating two resemblance areas, that of optical properties matching and that of visual representation. In terms of optical properties, the optical extinction coefficient, which is a defining characteristic of smoke, has an average 11.45% difference in the experimental values than in the simulated ones, representing roughly 0.0251 m$^{-1}$ for a maximum extinction coefficient of 0.22 m$^{-1}$. In terms of visibility, the average difference between the simulated and experimental values is 5.36%, representing about 1.6 meters of visibility for a threshold of 30 meters. Even though the average differences are relatively high, it is seen from the charts that the values do have quite a powerful resemblance.

One aspect that can be further investigated is the influence of the grid size on the accuracy of the representation of simulated smoke.

In terms of visual resemblance, by the use of digital imagery, the simulated smoke brightness has been adapted to fit that of the experimental one.

The paper proposes a methodology for approximating non-toxic smoke in the Fire Dynamics Simulator software to a certain level of similitude that is satisfactory for applications like evaluating compliance for visibility thresholds specified by fire safety standards, simulation of firefighter training, people evacuation from smoke-filled enclosures and smoke exhaust in buildings scenarios.

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