Small scale measurement of artificial smoke optical properties

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Abstract. For the assessment of the quality and behavior of building materials in the case of fire, standard testing methods which classify these products based on their performance have been developed. This testing covers among other parameters the smoke emission of the materials in case of fire. The testing methods require various quantities of the products in order to provide accurate results, hence they can rarely be used in the research and development phase of a product. Standard tests that are used to classify building materials, usually employ the principle of light intensity attenuation for the determination of information regarding the smoke emission of the product. This paper presents the 1:10 and 1:20 scale reduction of an experiment used to determine the optical properties of artificially generated smoke based on the same principle of light attenuation. The scale reduction was carried out by means of proportionally reducing each of the test compartment dimensions and the amount of smoke fluid used. For the assessment of the scale reduction accuracy, the extinction area of smoke, which is a parameter that can correlate the light intensity values measured in the different experimental scales was used as a benchmark.

1. Introduction

Due to the destructive nature of fire and the hazards associated with experimental testing, fire safety engineering is often a costly and dangerous endeavor. This aspect, along with the high costs associated with the research and development of innovative building materials, and the low quantities in which they may be produced in incipient phases makes standard testing for fire reaction and resistance of such materials an often inadequate option. In order to provide a more accessible approach for testing building materials in the research and development stage, small scale testing can be used to assess some of the properties needed to describe the material’s behavior as it is exposed to fire [1], [2].

The optical properties of smoke can be correlated between small scale and full scale experiments with the help of a quantity named the smoke extinction area. This quantity can be calculated with the help of another smoke parameter named the optical smoke extinction coefficient, obtained from the measured reduction in intensity of a light beam crossing a known distance through the smoke layer produced by a certain material, also named smoke transmittance [3]. These terms are defined by the Fire Safety Vocabulary Standard [4] as follows:

- Extinction area of smoke - product of the volume occupied by smoke and the extinction coefficient of the smoke. It is a measure of the amount of smoke (the typical unit is m²).
- 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.

In order to determine the light extinction coefficient (k), for the purpose of this paper, the smoke transmittance \( \frac{I}{I_0} \) has been calculated (\( I \) – transmitted light intensity, \( I_0 \) – incident light intensity) by measuring the reduction in intensity of a monochromatic light beam that crossed the smoke layer on a path of a certain length (\( L \)), using equation (1).

\[
\frac{I}{I_0} = e^{-k \cdot L}
\]  

(1)

As described in the Fire Safety Vocabulary Standard, the smoke transmittance is the \( \frac{I}{I_0} \) term found in equation (1). The extinction area of smoke can be calculated by knowing the volume of smoke that is produced by a certain source, be it natural or artificial, and determining the extinction coefficient of that smoke, based on the measurements of the attenuation of light intensity. Thus, the relationship between the extinction area of the smoke (\( A \)), the volume of produced smoke (\( V \)) and the extinction coefficient of the smoke (\( k \)) is presented in equation (2). The light extinction coefficient is a hypothetical parameter that aids in comparing the obscuration properties of smoke at different experimental or simulated scales.

\[
A = k \cdot V
\]  

(2)

There is a study [5] that uses the smoke extinction area to correlate data between small scale and full scale experiments, but they involve using scales greater than the standard cone calorimeter test that has the minimum specimen dimensions of 10 x 10 cm. In comparison, this paper provides insights regarding experimental scales that use smaller quantities of materials than the standard testing procedures.

This paper proposes an experimental approach for correlating full and small scale data regarding the optical properties of smoke for lower smoke flows, by using artificially generated smoke. For this purpose, a large scale experiment described in detail in reference [6] has been conducted with the aim of determining the optical properties of artificially generated smoke. Based on the setup of the large scale experiment, there have been conducted two additional experiments using the 1:10 and 1:20 scale, the three sets of results being compared in this paper.

The data sets obtained from the two reduced scale experiments have been compared to the ones in the full scale experiment in order to identify the closest values, the measuring distances they pertain to, and the experimental setup of the reduced scale that best mimics the full scale phenomena.

2. Methodology
The full scale experiment that was used to identify the benchmark values for the subsequent two small scale experiments involved using a smoke machine that was activated for timed periods within a large confined space in order to create an increasingly smoke filled environment. The measurement of the decrease in intensity of a laser light source of 1 mW power and 635 nm wavelength was carried out using a Testo 480 lux meter with a 0 to 100,000 Lux measuring domain as the testing environment continued to be filled with smoke. The data values for the light intensity were logged at a 2 second interval during the experiment.

Before each activation of the smoke machine, there was a 60 second pause in order for the atmosphere to settle, to ensure accurate measurements. The measurements were carried out for distances of 10, 7.5 and 5 meters from the light source, by moving the measuring device to the right distance from the light source, and repeating the experiment. The manufacturer specifications for the smoke machine listed a 128 m³/min flow and a 72 ml/min consumption of glycerol based smoke fluid for the setting used during the full scale experiment. These specifications led to a 1.77 ml smoke fluid consumption for 1 m³ of smoke produced, this value being used for the calculation and correlation of the smoke extinction area for all of the three scales.
The lux meter was attached to a high contrast target that served as a visual reference for the visibility decrease as the experimental compartment was filled with smoke. The experimental setup during the full scale experiment can be viewed in figure 1, and the chart that presents the light intensity values that were measured during the experiment for each of the three distances is presented in figure 2.

Figure 1. Full scale experimental setup.

Figure 2. Full scale light intensity measurements.

By its definition, the extinction area of smoke is dependent on the volume of smoke produced by the machine, and the smoke extinction coefficient, calculated as presented in equation (1). The smoke extinction coefficient is dependent upon the measured light intensity and the distance that the light beam travels through the smoke. Because of the dependence on this linear distance of the extinction area of smoke, the scale reduction of the experimental setup was done through the reduction of every dimension of the testing compartment. The dimensions of the testing compartment for the 1:20 scale should be 0.5 x 0.15 x 0.225 meters, with a total volume of 0.016875 m$^3$, but in order to be able to use the same
reduced size compartment as in the 1:10 scale, only the length of the compartment was reduced proportionally, in order to obtain the same volume, and the other two dimensions were kept the same. Thus, the dimensions of the 1:20 scale testing chamber were 0.125 x 0.3 x 0.45 meters, and the measuring distances were no longer considered across the length of the testing compartment, as in the 1:10 scale, but across the side. The scale reduction process for the dimensions of the testing compartment is illustrated in figure 3. The full scale experimental setup is noted 1 on the figure, the 1:10 scale setup is noted 2, and the 1:20 scale experimental setup is noted in figure 3.

Figure 3. Scale reduction illustration.

The other element that was scaled accordingly is the amount of smoke fluid used for the generation of smoke in the small scale experimental setups. The total quantity of smoke fluid used in the full scale experiment was 65 ml, distributed in almost equal amounts as the smoke machine was used in timed bursts to ensure an incrementally greater amount of smoke in the testing enclosure. The 1:10 scale smoke liquid consumption was 6.5 ml, with 10 times less smoke fluid than the full scale experiment, and in the 1:20 scale the smoke fluid consumption was 3.25 ml, with 20 times less smoke fluid than the full scale experiment. The amount of smoke fluid used in the small scale experiments was linearly reduced compared to the full scale experimental setup.

For the 1:10 scale, a model testing enclosure made out of acrylic sheet was used for the containment of the smoke generated with the use of an electrically heated copper coil with an inside diameter of 2 millimeters that vaporized calculated amounts of smoke fluid. The vaporization temperature was monitored with the use of an electronic thermometer with a -50 to +300°C measuring domain. A 635 ±5% wavelength, 1mW power laser provided the light source, and the light intensity was measured with the UNI-T UT383 BT lux meter, having a 0 to 9,999 Lux measuring domain, 1 Lux sensibility and ±4% precision. The measuring interval for all of the experiments was two seconds, and the measuring distances for the 1:10 scale experiment were 100, 75 and 50 centimeters. The experimental setup for this scale can be viewed in figure 4.
Because two different smoke producing devices were used for the full scale and small scale experiments, the time needed for the atmosphere to settle between consequential uses of the smoke production mechanisms in each of the experiments was different, as was the time needed to vaporize a certain amount of smoke fluid by the two different devices. In order to facilitate comparison, the charts depicting the experimental results were plotted by assuming a linear increase in the amount of smoke fluid vaporized by the devices, from the start of their activation, up to the target amount of smoke fluid for each of the device uses. This threshold for the maximum amount of smoke fluid use for each consecutive burst corresponded to the lowest value of recorded light intensity for that particular smoke injection. For all of the experiments, during the time that the smoke layer settled, the linear increase in smoke fluid consumption was assumed to continue, in order to facilitate chart plotting. The atmosphere was left to settle until the measured light intensity would no longer continue to grow, as the smoke layer became uniform in the testing enclosure, thus the peak in recorded light intensity provided a benchmark for the next activation of the smoke producing device. In all of the experiments, the smoke was injected into the testing enclosures in seven equal bursts that used a fraction (about 15%) of the total amount of smoke fluid used during each of the experiments. The chart for the continuous measurements for the 1:10 scale experimental setup, for the three measurement distances can be seen in figure 5.

As can be seen from the chart in figure 5, the shorter the distance between the light source and the light intensity measuring device, the higher the values for the light intensity. This was true for the full scale experimental setup as well.

For the 1:20 experimental setup, the same equipment was used as in the 1:10 scale, and the measuring distances used were 50, 37.5 and 25 centimeters. The smoke fluid used for each interval of time was dosed with the help of appropriately selected syringes. Due to changes in the smoke production mechanism and size of the experimental compartment, a 120 seconds interval between consequent uses of the smoke producing device was necessary in the small scale experiments. The experimental setup for the 1:20 scale is presented in figure 6.
The chart for the continuous measurements of the light intensity for the 1:20 scale, for each of the three distances can be seen in figure 7. Due to the fairly short distances that the light beam has to travel, it can be seen that the maximum intensities, the ones recorded without any smoke, are less differentiated than in the other two cases, given that the distance the light source was moved away from the receiver with each repetition of the experiment was proportionate, but objectively shorter than its larger scale correspondent.
The use of the extinction area of smoke as the main parameter by which the experiments were compared meant that an accurate perception on the volumetric quantity of the smoke produced by the fluid consumed was needed. This testing methodology can only provide correlations between small scale and full scale experiments conditioned by the knowledge of the amount of smoke produced per unit of material burned, in the case of flame generated smoke, or produced in case of artificially generated smoke. A lot of factors can influence the smoke production of burning materials, and that is why for the purpose of this paper, artificially generated smoke was used. The cumulated smoke fluid consumption and the values for the light intensity as measured after the atmospheric settle period are presented for each experimental scale in table 1.

Table 1. Small scale experiments measurements.

| Smoke fluid (ml) | Scale 1:10 | Scale 1:20 |
|------------------|------------|------------|
|                  | Light intensity (Lux) | Smoke fluid (ml) | Light intensity (Lux) |
|                  | 50 cm | 75 cm | 100 cm | 25 cm | 37.5 cm | 50 cm |
| 0                | 3585  | 2261  | 2054  | 0     | 2922    | 2796  | 2618 |
| 0.5              | 2909  | 1771  | 1575  | 0.25  | 2110    | 1872  | 1793 |
| 1.5              | 1747  | 1437  | 1024  | 0.75  | 1687    | 1112  | 1145 |
| 2.5              | 1339  | 1106  | 650   | 1.25  | 1413    | 1065  | 681  |
| 3.5              | 1163  | 911   | 674   | 1.75  | 1399    | 1108  | 510  |
| 4.5              | 1107  | 621   | 321   | 2.25  | 1504    | 1095  | 445  |
| 5.5              | 1088  | 601   | 652   | 2.75  | 1005    | 1074  | 503  |
| 6.5              | 1116  | 570   | 237   | 3.25  | 1161    | 881   | 417  |
3. Results and discussion
With the help of the measured light intensity values from each of the experiments, the optical smoke extinction coefficient (k) was calculated. The volume (V) occupied by the smoke produced in each of the experiments has been calculated based on the premises that, as per the technical specifications of the smoke machine, 1 milliliter of smoke fluid can produce about 1.77 cubic meters of smoke. These two parameters (k and V) were multiplied in order to obtain the smoke extinction area for each of the experimental scales. Table 2 presents the values of the optical smoke extinction coefficient, averaged over the three measuring distances, for each of the experimental scales and each consequential use of the smoke generating device.

Table 2. Average smoke extinction coefficients.

| Smoke fluid (ml) | k (m⁻¹) | Smoke fluid (ml) | k (m⁻¹) | Smoke fluid (ml) | k (m⁻¹) |
|------------------|---------|------------------|---------|------------------|---------|
| 0                | 0.00    | 0                | 0.00    | 0                | 0.00    |
| 6                | 0.03    | 0.6              | 0.34    | 0.3              | 0.52    |
| 11               | 0.05    | 1.1              | 0.91    | 0.55             | 1.05    |
| 22               | 0.09    | 2.2              | 1.36    | 1.1              | 1.36    |
| 32               | 0.11    | 3.2              | 1.53    | 1.6              | 1.45    |
| 43               | 0.12    | 4.3              | 1.98    | 2.15             | 1.45    |
| 54               | 0.14    | 5.4              | 1.77    | 2.7              | 1.69    |
| 65               | 0.16    | 6.5              | 2.11    | 3.25             | 1.74    |

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 that it’s being compared to. Table 3 presents the average difference between the experimental scales for the smoke extinction areas.

Table 3. Average difference for the smoke extinction area.

| Scale (cm) | Distance (cm) | Maximum value (m²) | Average difference Value (m²) | % of Max | Max difference Value (m²) | % of Max |
|------------|--------------|--------------------|------------------------------|----------|--------------------------|----------|
| 1:10       | 50           | 28.71              | 2.73                         | 9.53%    | 12.64                    | 44.04%   |
| 1:10       | 75           | 24.03              | 2.43                         | 10.13%   | 11.91                    | 49.58%   |
| 1:10       | 100          | 25.53              | 4.16                         | 16.32%   | 13.97                    | 54.73%   |
| 1:20       | 25           | 28.71              | 2.86                         | 9.98%    | 16.93                    | 58.98%   |
| 1:20       | 37.5         | 17.71              | 1.05                         | 5.93%    | 5.38                     | 30.39%   |
| 1:20       | 50           | 21.60              | 3.30                         | 15.32%   | 9.81                     | 45.43%   |
The table highlights the smallest average differences, the 1:20 scale bearing the closest resemblance to the full scale experiment for the values of the smoke extinction area, with an average difference for the three measuring distances of 10.41%. Figure 8 presents a comparative chart of the smoke extinction area values measured at the intermediate distances for each of the three experimental scales.

![Figure 8. Smoke extinction area scale comparison.](image)

In the case of the intermediate distance, the average difference between the values for the extinction area of smoke obtained in the full scale experiment and the 1:10 scale is 10.13%, while those measured in the 1:20 scale experiment present a 5.93% difference when compared with the full scale experiment ones. On average, the 1:20 scale values present the closest resemblance to the full scale experiment ones, demonstrating that the experimental methodology can be used to determine the optical properties of smoke even on small scales.

4. Conclusions
The small scale experiments present promising results when compared with the full scale experiment values of the smoke extinction area. This indicates that scale reduction can indeed be used for the determination of the optical properties of smoke, but conclusions about the properties of smoke produced in full scale conditions by the same mechanism cannot be drawn without data regarding the volumetric quantity of smoke produced by a certain amount of fuel, data that can be inferred from the mass specific extinction coefficient [7]. The use of artificially generated smoke for the purpose of demonstrating the applicability of the experimental methodology to small scale measurement of the optical properties of smoke has ensured the production of consistent quantities of smoke for the amount of smoke fluid consumed. In the case of flame generated smoke, there are a lot of factors that can affect smoke production, such as the nature of the material, its properties, flame exposure, and environmental factors such as ventilation, pressure and oxygen availability [8].

Given that the experimental methodology is appropriate for the measurement of the optical properties of smoke, the same experimental setup can be used for same scale comparative studies involving...
comparable quantities of building materials, as to bypass the need to measure the exact quantity of smoke produced by the unit mass of fuel, needed to draw conclusions about full scale behavior of such materials. The small scale experimental setup can theoretically be used to compare the optical properties of the smoke produced by different burning materials at the same reduced scale, with comparable proportions in a full scale setting, experimental work in this area being part of research to look forward to.

Further research can also be done in using the data obtained through this kind of experimentation for the validation of numerical simulations of the small and natural scale experiments. Numerical simulation programs might also prove helpful in defining materials based on their small scale determined optical properties and running simulations intended to approximate their full scale counterparts’ smoke emission.

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