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SIMULATION OF VISIBILITY IN SMOKE LADEN ENVIRONMENTS

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ABSTRACT

Exposure to the products of combustion, both particulate smoke and gaseous, rather than to the fire itself, is the most significant cause of injury and death in fires. The exposure time of individuals in a smoke environment depends upon their speed of movement and the direction they choose to travel, nominally towards a safe exit. Consequently in the fire safe design of modern buildings, the provision and correct location of emergency exit signs is of paramount importance in minimising such exposure, especially in large spaces, where the occupants are unfamiliar with safe egress routes.

A considerable body of research has been accumulated regarding human behaviour in fires and the simulation of the movement of individuals in smoke laden environments. A necessary input to such models is the perceived visibility of the surroundings, whether hazards, obstructions or safe exits.

This paper introduces the methodology and presents initial results from the quantitative simulation of visibility through a smoke laden environment. The simulations take account of direct illumination, indirect illumination from surfaces and particulate scattering. The underlying smoke movement is obtained from a prior time dependent CFD simulation and, with appropriate assumptions on soot particle properties, post-processed in a second phase to determine the visibility of, for example, an illuminated exit sign.

INTRODUCTION

Many different endurance limits have been proposed for movement through smoke, for example a maximum temperature limit of 150 ^{o}C, a limit of visibility without a wayfinding system ('turn back' limit) of 5 m and an accumulated dose of CO of 30 000 ppm. Combinations of these factors further reduces safe evacuation distances. Statistics suggest that 90% of survivors move less than 16m through smoke. Reduction of visibility and the presence of CO are the prime risk factors when evacuating in smoke [1]

The visibility of exit signs in smoke has been extensively studied through human field trials resulting in established guidance criteria for visibility in terms of the optical density of the smoke layer. The most widely cited works are those of Jin [2], where the amount of smoke was related to the visibility distance of internally illuminated and reflecting signs. Jin also postulated the main reasons for decrease in visibility through smoke as a reduction in light intensity of the sign and background due to the obscuring smoke, and scattered light off smoke particles from other light sources that reach the subject's eye. Collins *et al.* [3] studied exit sign visibility in clear and smoke obscured conditions and observed that sign luminance, and to some extent uniformity and contrast, are important in sign visibility in smoke. The study by Ouellette [4] on exit sign visibility in smoke examined the effects of ambient illumination and suggested that brighter exit signs are needed to compensate for the luminous veil created by ambient lighting when smoke is present, or lighting along lines of sight to exit signs should be reduced when smoke is detected. Of direct relevance in the UK, Cook *et al.* [5] reported recent trials, where visibility distances of internally illuminated elements of emergency lighting systems were studied under different ambient lighting in smoke.

The simulation of illumination through participating media has been an active area of computer graphics research since the seminal work of Blinn [6]. Most, if not all, of the algorithms first sample the density and the optical properties of the gas on a grid and then solve for illumination. In a first pass, the effects of multiple scattering are resolved. Depending on the scattering distribution functions employed, different possibilities arise. For isotropic or constant scattering, a zonal radiosity style method has been employed. For arbitrary scattering, researchers have used spherical harmonics expansion, a discretisation of the angles or brute-force ray-tracing. These approximations are known respectively as the zone method, discrete ordinates and Monte-Carlo simulation in the traditional scientific literature on radiative heat transfer. Cerezo et al. [7] provide an excellent review of general global illumination algorithms in the presence of participating media, both appearance-based and physically-based media methods, including single-scattering and more general multiple-scattering techniques.

The simulation of visibility in smoke laden environments by fire safety engineers has received far less attention. The typical procedure, as for example outlined in the SFPE Handbook [8], is to assume an empirical relationship between extinction coefficient and visibility distance, such as proposed by Jin [2], and also to assume a homogenous smoke distribution. The procedure is reliant upon appropriate empirical data for different targets (illuminated signs, fluorescent signs etc.) and does not take into account the true spatial and time varying smoke concentration or any local effects of light scattering or secondary illumination.

A fundamental aspect is the recognition that in a three dimensional fire field model, the distribution of smoke particulates has typically already been established by computationally expensive techniques using computational fluid dynamics, which ironically may already take account of infra-red radiative transfer in a participating media. One subtle difference between the simulation of radiative heat transfer and visibility, is that typically estimates of visibility are required from a point in space, where an individual is positioned, to specific surrounding objects, such as emergency egress signs. In such instances line of sight approaches may be more suitable than alternative algorithms more recently employed for general illumination in participating media [8]. As a consequence of this dichotomy the alternative approaches for solving the Radiative Transport Equation (RTE) require careful review in the context of algorithms for the prediction of visibility as opposed to volumetric heat loss, surface heat transfer or global illumination.

In addition to the solution of the RTE, the non-homogenous distribution of particulates (and gas composition) are required. In this respect, existing models for smoke transport can be utilised, recognising the existence of models of differing complexity. At the very minimum the transport of a passive scalar is required, where the optical properties can be empirically related to scalar concentration. More sophisticated models, for example [10,11] allow the formation, oxidation and coagulation phenomena to be accounted for in more detail.

Whilst computational fluid dynamics has become a standard tool for the assessment of smoke movement, the coupling of such results to quantitative predictions of visibility is relatively uncommon. Staubli et al [12] recently reported one such attempt, using real-time volume rendering to visualise transient smoke propagation. However, their objective was not photorealistic realism, but a technical visualisation of given smoke concentration through a simple translation of smoke concentration data to opacity using the empirical relations proposed by Rasbash et al. [13]. A related approach is adopted by Smokeview [14], in which a series of parallel planes are displayed with transparency values according to the local soot densities. The transparencies are adjusted in real time to account for differing path lengths through the smoke as the view direction changes. The graphics hardware then combines the planes together to form one image.

GLOBAL ILLUMINATION ALGORITHMS

In order to create a photo-realistic image, the average radiance perceived through each pixel of the image needs to be computed. Light transport algorithms can be roughly divided into two groups, Monte Carlo methods, and finite element or Radiosity methods. These may be equally classified as either direct computation of pixel intensities in a pixel-driven approach, or by projection of a pre-computed object-space radiance solution.

Pixel-driven algorithms directly compute the average radiance in each pixel without first computing an object-space representation of the radiance on the surfaces in the scene. The classical example is Monte Carlo ray tracing. Monte Carlo methods have been used for neutron transport problems since the 1950’s [15], and have been studied extensively there [16]. In graphics Monte Carlo methods arose independently, starting with Appel [17] who computed images using random particle tracing. Whitted [18] introduced ray tracing (the recursive evaluation of surface appearance), and also suggested the idea of randomly perturbing viewing rays. Cook et al. [19] implemented this idea and extended it to random sampling of light sources, lenses, and time. This led to the first complete, unbiased Monte Carlo transport algorithm as proposed by Kajiya [20], who recognized that the problem could be written as an integral equation, and could be evaluated by sampling paths. Since then, many refinements to his *path tracing* technique have been adapted from the particle transport literature [21].

There has also been a great deal of work on biased Monte Carlo algorithms, which are often more efficient than path tracing. These include the *irradiance caching* algorithm of Ward et al. [22], the *density estimation* method of [23], and the *photon map* approach of [24].

Object space approaches first compute a representation of the radiance function on the surfaces of the objects. In order to then create an image from a given viewpoint, the visible surfaces through each image pixel are determined and the average radiance in each pixel computed from the average radiance radiated towards the viewing position from the surfaces that are visible in the pixel. Such methods are analogous to Hottel's Zone Method in classical radiative heat transfer [25].Finite element methods for light transport were originally adapted from the radiative heat transfer literature. Goral et al. [26] introduced these methods to the graphics community, where they are typically known as radiosity algorithms.

EQUATION OF RADIATIVE TRANSFER

Global illumination draws from many fields, two of which are of particular relevance, radiative transfer and illumination engineering. The origins and underlying physical model of global illumination can be traced directly to the theory of radiative transfer while the aims and methodologies of global illumination are today most closely aligned with those of illumination engineering.

The equation of transfer is the fundamental equation that governs the behaviour of electromagnetic radiation in some medium that absorbs, emits, and scatters [27]. It describes the equilibrium distribution of radiance in terms of the incident radiance in the medium and the medium's scattering properties. Most rendering algorithms in computer graphics focus on solving the equation of transfer in order to compute the radiance leaving the scattering medium or geometric objects and arriving at a sensor. Conversely, in traditional heat transfer algorithms, the radiative transfer equation is solved in order to compute the incident heat flux upon all surfaces within a domain.

As radiance travels along a beam, a number of processes contribute to change its distribution. Radiance can be increased due to emission and in-scattering radiance from other beams that is scattered into the path of the beam under consideration. Conversely, radiance can be decreased due to absorption and out-scattering.

In a space filled with an aerosol such as carbonaceous particulates, the attenuation of monochromatic light can be described by Bouguer's law as

$$\frac{I}{I_0} = e^{-\int_o^l \alpha_{ext} dz} \tag{1}$$

Where l is the distance between the light source and the observer. I_0 and I represent the incident and transmitted light intensities. α_{ext} is the extinction coefficient. Assuming $p(d_p)$ is the probability density function of size distribution of polydisperse particles in a unit volume then

$$\alpha_{ext} = \int_0^\infty c_{ext} p(d_p) dd_p \tag{2}$$

where c_{ext} is the cross section of extinction for a single particle with diameter d_p. In a cloud of monodisperse particles with number density N

$$\alpha_{ext} = c_{ext} \int_0^\infty p(d_p) dd_p = Nc_{ext} \tag{3}$$

Therefore α_{ext} is the collective effect of extinction from all particles in a unit volume of particle cloud such as smoke.

More often in combustion related studies, the mass specific extinction coefficient σ_{ext} is utilised in preference to α_{ext}. The two are related by

$$\sigma_{ext} = \frac{\alpha_{ext}}{M_s} \tag{4}$$

where the mass of soot in a unit volume of smoke is expressed as

$$\begin{aligned} M_s &= \rho_p \int_0^\infty \left(\frac{1}{6} \pi d_p^3 \right) p(d_p) dd_p \\ &= \rho_p f_v \end{aligned} \tag{5}$$

where f_v is the volume fraction of soot.

In optics and computer modeling, it is often more convenient to use the dimensionless extinction efficiency:

$$Q_{ext} = \frac{4c_{ext}}{\pi d_p^2} \tag{6}$$

Physically light extinction is the combined result of light absorption and scattering. The cross section of extinction is the sum of the two:

$$Q_{ext} = Q_{abs} + Q_{sca} \tag{7}$$

For spherical particle, Q_{ext} and Q_{sca} can be obtained from the solution of Maxwell equation for electromagnetic field [28],

$$Q_{ext} = \frac{2}{x^2} \operatorname{Re} \sum_{n=1}^{\infty} (2n+1) [a_n + b_n] \tag{8}$$

$$Q_{sca} = \frac{2}{x^2} \sum_{n=1}^{\infty} (2n+1) \left[|a_n|^2 + |b_n|^2 \right] \tag{9}$$

where the coefficients a_n and b_n are expressed in terms of Riccati-Bessel functions of the n^{th} order, [29].

where x_p is the particle number defined as

$$x_p = \frac{\pi d_p}{\lambda} \tag{10}$$

There are widely available computer programs to calculate Q_{ext} and Q_{sca} from (8) and (9). Q_{abs} is then calculated with (7).

In combustion generated smoke, the primary particles of soot are nearly monodisperse and spherical, the average diameter is between 40 - 90nm depending on whether the smoke is from pyrolysis, smoldering or flaming fire as well as the size of the fire [30, 31]. In theory, equations (7) - (9) can be used to calculate light scattering for such particles. In practice it is often unnecessarily expensive and may not offer the most accurate result as expected due to the irregular shape of the particles and their aggregation. There are various approximate solutions offering much simpler ways than (8) and (9). The approximations are based on the relative importance of the terms in the series expansion determined by the particle number x_p. An extensive review is provided by Jones [28]

SIMULATION

Prior to the development of the dedicated visibility simulation package preliminary results have been obtained using PBRT (Physically Based Rendering Toolkit) [32] to demonstrate the feasibility of the concept and to review alternative rendering algorithms. PBRT is easily extendible through plug-ins and provides support for a variety of sampling and integration methods both for surface and volume regions.

Figures 1 and 2 present the results from a photorealistic render of a 5m long corridor with an illuminated 'EXIT' sign at the far end and a roof mounted illuminaire. The corridors was assumed to be filled with a homogenous soot concentration. In figure 1 very low absorption and scattering coefficients were specified, resulting in negligible attenuation of the illuminated sign. Figure 2 demonstrates the effect of increased absorption and scattering. Note how the scattered light from the ceiling illuminaire partially obscures that from the 'EXIT' sign. Indeed, it has been suggested that the intensity of ambient illumination should be reduced in the presence of smoke [33] to enhance visibility of exit signs.

The results from a time dependent CFD simulation of a 100kW fire in a 5m long corridor were taken as the basis for a demonstration with a non-homogenous soot concentration. The corridor was taken to be fully open at one end with an open doorway at the other end. The smoke was assumed to be a passive scalar, released at the fire source (1% by mass of the fuel mass flow rate) with constant specific absorption and scattering coefficients of 10 m^2/g and 5 m^2/g respectively.

A green illuminated 'EXIT' sign was placed above the open doorway. The corridor walls were assumed to be of a rough concrete texture. Alternative rendering techniques were then investigated together with alternative physical lighting arrangements, including ceiling lighting, ambient lighting and a directed spot light from the viewer (a torch !).

The series of images shown in figure 3 present a view of the corridor during the initial formation of the smoke layer over a period of approximately 1 minute. The viewer is looking from in front of the fire source towards the open doorway, when the corridor is illuminated by ceiling lights. The green illuminated 'EXIT' sign is clearly visible, though notice how the details of the individual letters are blurred by the relatively high intensity chosen for the lights. Rea et al. [34] commented that in their physical experiments an optimum brightness was found to exist for maximum clarity even in smoke free conditions.

In comparison, figure 4 presents a series of images for the same CFD simulation, but now rather than ceiling lights, a spotlight illuminates the scene from the position of the viewer, analogous to a hand held torch. An apparent shadow from the smoke plume is clearly visible in this case. Figures 3 and 4 clearly demonstrate the effect of light source on the final photorealistic image and the effect of light scattering from the corridor walls.

The above renderings appear to be realistic but remain to be validated. The quantitative nature of the numerical predictions will be assessed with reference to experimental data on light extinction taken in a laboratory scale multi-compartment smoke test cell [35]. A square cross-section duct, internally subdivided by a number of transparent partitions, will be each separately filled with smoke and both the individual section and overall path-length integrated extinction measured. Photo-detector intensity measurements at different laser light wavelengths will permit an estimate of 'local' turbidity and particle size to be inferred and comparisons made with the light intensity from a back-illuminated coded screen, analogous to an exit sign, viewed along the length of the cell. Rendered images from the visibility tool will be compared with both light intensity measurements and photographic imaging over a range of smoke densities.

CONCLUSION

This paper has introduced the methodology and presented initial results from the quantitative simulation of visibility through a smoke laden environment. The simulations have taken account of both direct illumination and scattered illumination from surfaces and smoke particulates. The underlying smoke movement was obtained from a prior time dependent CFD simulation and, with appropriate assumptions on soot particle properties, post-processed in a second phase to determine the visibility of an illuminated exit sign.

The principal aim of this project is to further advance the technical capability of performance based fire safety design, specifically related to the ability to simulate, a priori, perceived human visibility in smoke laden environments. This will be achieved through the development of a robust, and well validated, simulation tool, the Visibility Simulation Tool (VST). In order to be of maximum benefit to the fire community the VST will capitalise upon existing CFD based fire simulation packages currently available and by acting as a post-processing stage will be independent of the underlying flow solver itself. The tool will be made freely available to researchers and professional fire safety engineers.

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Figure 1: Photorealistic render of a corridor with an illuminate 'EXIT' sign

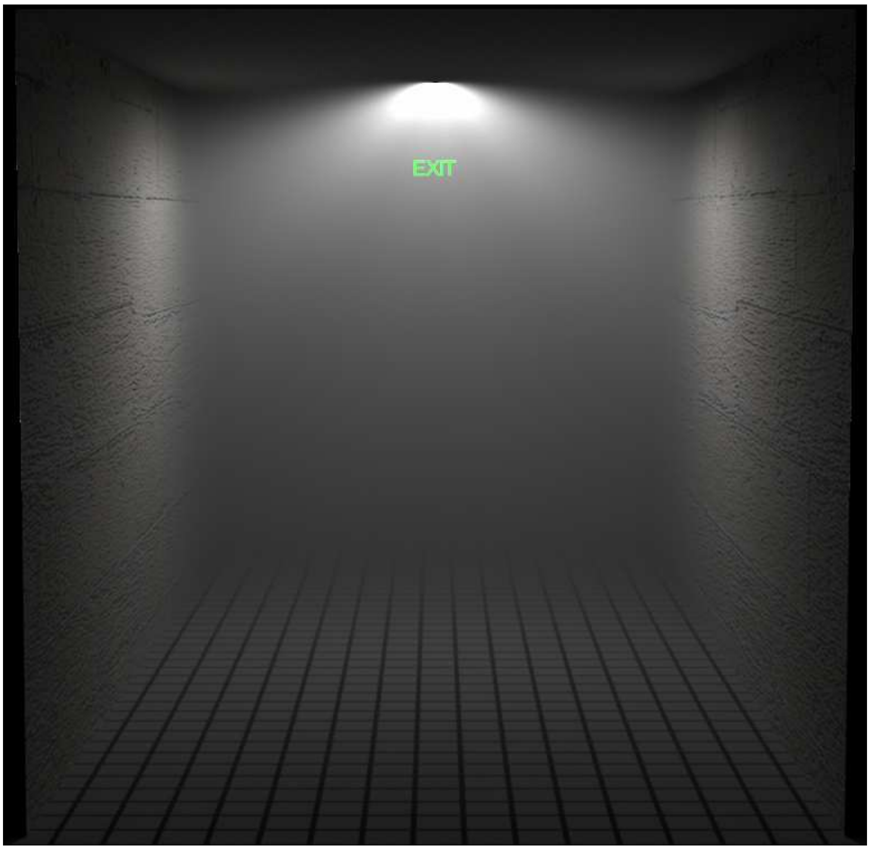

Figure 2: Photorealistic render of a corridor with an illuminate 'EXIT' sign in the presence of smoke

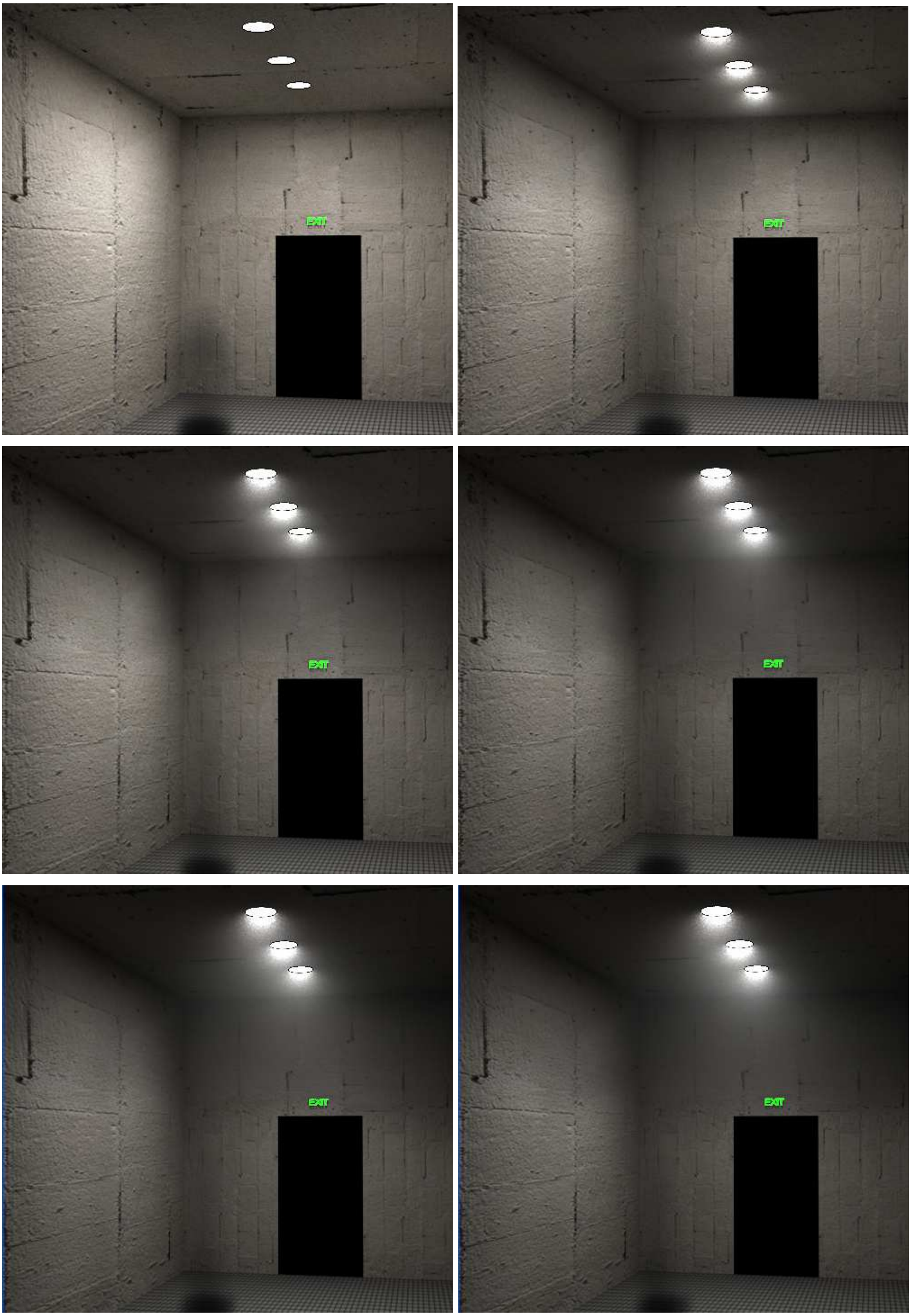

Figure 3. Photorealistic rendering from the results of a CFD simulation of a fire in a corridor, showing development of initial smoke layer of a period of 1 minute. Ceiling light illumination.

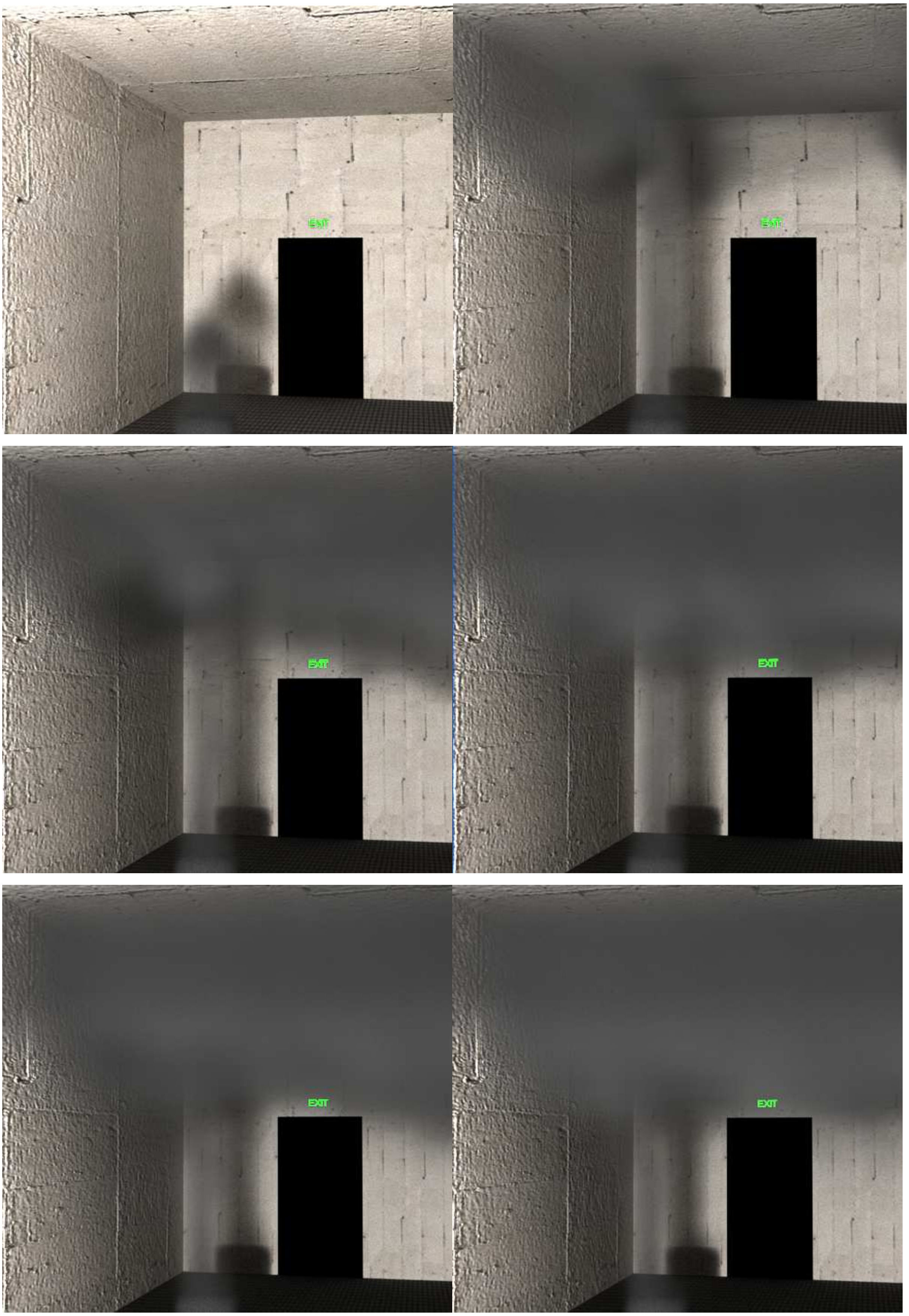

Figure 4. Photorealistic rendering from the results of a CFD simulation of a fire in a corridor, showing development of initial smoke layer of a period of 1 minute. Illumination by spot light (torch) from viewer.