Evaluating Visibility Using FDS Modelling Result

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ABSTRACT

The issue of evaluating visibility in inhomogeneous smoke conditions for fire safety engineering assessment is addressed in this study. The limitations of the simple correlation method adopted in Fire Dynamic Simulator are investigated. This method is then extended to incorporate non-homogeneity into the evaluation of visibility. The new method is applied to a simple example to demonstrate the differences between the resulting visibilities and to highlight the potential problems in the simple correlation method. The use of the methods for tenability analysis is also discussed.

KEY WORDS: critical contrast, extinction coefficient, inhomogeneous, optical path length, virtual visibility.

NOMENCLATURE

E	visibility factor	P_L	optical path length
I	luminance, lux	S	visibility, m
I_B	luminance of background, lux	S_{aL}	virtual visibility along line of sight, m
I_o	initial luminance, lux	s	distance along a path, m
K	light extinction coefficient, m^{-1}	t	time after ignition, s
K_{aL}	average extinction coefficient along line of sight, m^{-1}	V	volume, m^3
K_m	mass specific extinction coefficient, m^2/kg	V_r	visibility ratio
L	path length, m	x, y, z	coordinates, m
M	mass, kg	ρ	density kg/m^3

INTRODUCTION

Loss of visibility is one of the criteria for attainment of untenable conditions in risk assessment. A study carried out by Bryan [1] showed that visibility of exit signs, doors and windows is of great importance to building occupants attempting to evacuate a building. The objectives of building fire safety design and assessment are concerned with maintaining a tenable condition with adequate visibility to allow safe evacuation by building occupants in the event of a fire, and to facilitate fire brigade intervention.

Computer fire models are commonly used in support of fire safety engineering design and assessments. Most computational fluid dynamics models predict thermodynamic and fluid flow properties, such as temperature, pressure, velocity, species concentrations and soot aerosol density by solving the governing equations. Some convert these properties into the parameters, such as visibility, that can be used for engineering design and assessment purpose [2]. This conversion process, though not critical to CFD models themselves, is an important step to practical use of the models.

Fire Dynamics Simulator (FDS) [3] together with the display package, SmokeView [4], developed at the National Institute of Standards and Technology (NIST) is arguably the most popular field fire model [5] adopted by fire research and engineering communities. FDS has the capability of the predicting temperatures, toxic species concentrations, extinction coefficient, visibility and so forth. FDS uses the predicted local parameter of smoke extinction coefficient and Jin's equation [6] to evaluate visibility at given location conditions. Visibility is an extensive parameter which depends on the dimension of the domain or the conditions along the line of sight between a subject (building occupant) and an object (exit sign). Jin's equation correlates visibility with smoke (light) extinction coefficient which is an intensive parameter. This correlation is valid only under the circumstance of uniform or homogeneous distribution of the extinction coefficient, but may not give appropriate estimates of visibility generally. The issue of visibility being path-dependent and its ramifications to smoke visualization in graphic presentation of computer simulation results was highlighted by Kang [7].

The objective of this study is to examine further the problems associated with the approach adopted by FDS and to propose an alternative approach to predicting visibility conditions.

Visibility Through Smoke

Visibility is defined as the maximum distance at which an object of defined size can be seen and recognized [8]. In case of fire emergencies, what matters the most is the visibility of exit signs. The visibility of exit signs became the focus of some fire safety scientists in the second half of the last century. It was found that the visibility condition depends on many factors, including smoke obscuration, room illumination level, light emitting or light reflecting signs, wavelength of the light, individual's visual acuity and smoke irritant content.

In a study carried out by Schooley and Reagan [9], the influence of sign contrast, observer visual acuity, exposure time and threshold illumination on exit sign visibility was investigated. The variation in detectable contrast as a function of exposure time was revealed in their study. They also concluded that with sufficiently illuminated background the contrast of sign for the intended ambient illumination, observer to sign distance and optical transmittance along the distance are the main factors to assess the legibility of an exit sign.

An extensive study to evaluate the visibility of exit signs in clear and smoky conditions was performed at National Research Council (NRC) Canada, by Clark *et al* [10] who evaluated the effect of exit sign type, threshold visibility criterion and ambient smoke chamber illumination on the visibility of a range of exit signs. Sixteen observers sat in a viewing booth from the sign and indicated if they could see or read the sign. Smoke was added to the chamber until the sign was obscured and the critical optical density was obtained. The data analysis indicated generally that greater smoke density was required to mask the visibility of signs with higher luminance. When ambient luminance was provided in the test chamber, sign visibility was reduced. Removing supplementary ambient illumination reduced scattered light and enabled the signs to be more visible.

The most important and widely referenced work is, perhaps, that by Jin in 1978 [6]. In his study the effect of smoke irritant was eliminated by positioning the subjects outside the smoke filled chamber. The visibility of light reflecting and light emitting exit signs inside the chamber were observed from outside through a glass window. The visibility measurement through smoke relied on the test subjects to determine the distance at which the object was no longer visible. The smoke condition in the smoke chamber can be assumed more or less uniform, that is, a constant extinction coefficient throughout. It was found that the product of the visibility S and the smoke extinction coefficient K is almost constant for given types of smoke and sign:

$$SK = E$$

or

$$S = \frac{E}{K} \tag{1}$$

where E is visibility factor or non-dimensional constant. The value of E depends on the threshold contrast, optical properties of smoke and optical/optometry properties of signs (Jin, 1978). It varies between 5 and 10 for light emitting signs, and between 2 and 4 for light reflecting signs [11]. Further delineation of the theoretical background of Eq.(1), or its connection with the threshold contrast theory, can be found in [12]. This equation establishes a relationship between an extensive parameter (S) and an intensive parameter (K) in a very much similar way as that between volume, mass and density. However, as we know it, the relationship

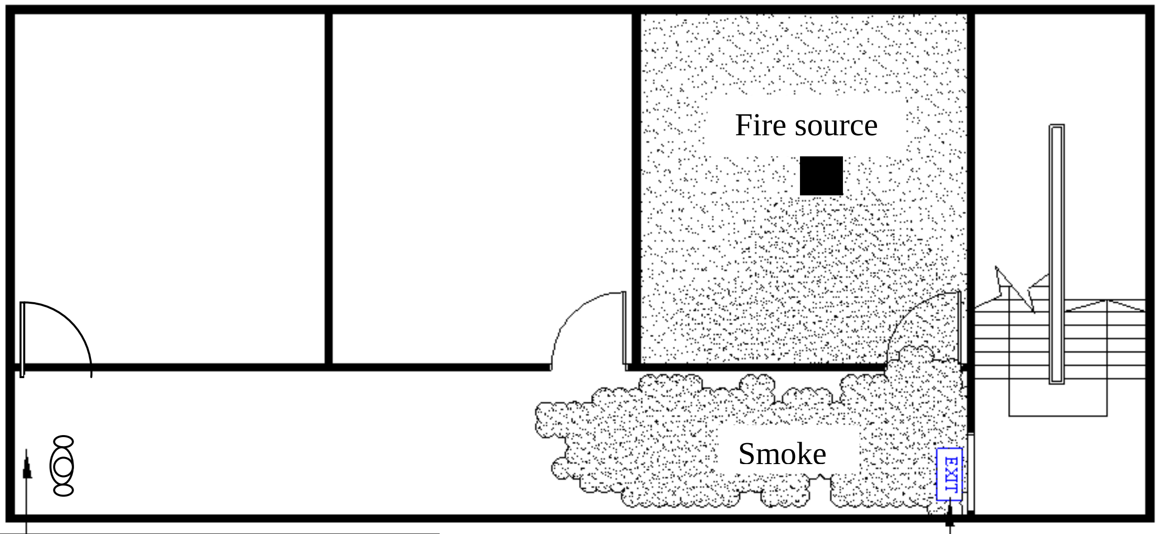
$$V = \frac{M}{\rho} \tag{2}$$

holds only if density ρ is constant throughout the volume domain V. Likewise, Eq.(1) is valid when K is constant along the line of sight.

FDS Model and Visibility Evaluation

FDS uses large eddy simulation technique to solve numerically a form of the Navier-Stokes equations appropriate for low-speed, buoyancy-driven flow with an emphasis on smoke and heat transport from fires. The model solves the fundamental equations for conservation of energy, mass and momentum, and calculates the heat and fluid flow throughout the computation domain. The distributions of various parameters such as visibility, gas velocity, gas temperature and species concentrations, are predicted by the model. Smoke particles are tracked along with all major products of combustion. The quantity for assessing visibility in a space is the light extinction coefficient, K, which is related to density of smoke particulate, smoke yield and mass specific extinction coefficient [3].

Estimates of visibility through fire smoke in FDS model is obtained according to Jin's correlation as in Eq.(1), i.e., visibility is calculated from the predicted local extinction coefficient K. Such an approach is valid only if smoke property is uniform or homogeneous in the range of concern and may not give reasonable result when the extinction coefficient varies along the line of sight. A situation where discrepancy exists between the evaluated visibility based on the local extinction coefficient and the reality is illustrated in Figure 1. The exit sign at one end of the corridor is submerged in smoke layer and may not be seen by a subject at the other end. However, the local condition at the other end is clear of smoke. An evaluation of visibility using Eq.(1) and the local extinction coefficient may yield a visibility of greater than the length of the corridor. Therefore, the current method of estimating visibility in FDS as a function of local measurement may not be appropriate.



Equation (1) indicates a good visibility at this location.

Exit sign is submerged in the smoke layer and may not be visible by the subject at the other end.

Figure 1. Illustration of non-uniform smoke condition affecting actual visibility.

Recognising the limitations of Eq.(1) and the potential problem in its direct use to interpret the results of CFD models, Husted, *et al* [13] and Kang [7, 14] suggested the direct light attenuation calculation method to estimate visibility and the computer graphic presentation of smoke visual effect. A ray tracing technique was employed to carry out the integration of extinction coefficient (or its variable component) along the lines of sight. The luminance attenuation, or light obscuration, was calculated. The visibility was then quantitatively determined by a graphic method in which the visual appearances of objects at given locations were used as referencing background. The graphic approach established the connection between the intensive parameter K and the extensive parameter S, and is largely based on the evaluation of light attenuation or smoke obscuration rather than on the evaluation of variation in contrast. This approach is similar to that adopted in FDS5 [3] for evaluation of beam detector activation. The latter is a valid approach since, unlike human eye, beam detectors are sensitive to absolute change in light intensity. The relationship between smoke obscuration and contrast, or between obscuration and visibility, may not be straightforward. In addition, the existing method still awaits to be tested, or experimentally verified. It is worthwhile noting that Eq.(1) is suited to zone model [15] applications.

AN ALTERNATIVE APPROACH TO VISIBILITY EVALUATION

Since Jin's correlation has been empirically tested under special homogeneous smoke conditions, it would be plausible to extend it to inhomogeneous conditions taking into account the variability of extinction coefficient along the line of sight. It is, therefore, proposed to use the average extinction coefficient along the line of sight instead of the local extinction coefficient in Jin's equation to evaluate visibilities of a sign at distance and visible distance in general. To this end, the concept of virtual visibility is introduced:

$$S_{aL} = \frac{E}{K_{aL}} \tag{3}$$

where K_{aL} is the average extinction coefficient along line of sight (m^{-1})

$$K_{aL} = \frac{1}{L}\int_0^L K(s)ds \tag{4}$$

and L is the distance between the eye of the subject and the sign. In words, virtual visibility is the visible distance that is evaluated from the average extinction coefficient along the line of sight of given distance L. If the virtual visibility S_{aL} is greater than the distance L, then the sign is visible and otherwise, invisible.

Tenability based on visibility can be estimated in a similar way. In this case, L represents the tenability limit. If the virtual visibility S_{aL} along the direction of egress is greater than the tenability limit L, then the condition at the location is deemed tenable. Otherwise, it is not. Define the ratio of virtual visibility to tenability limit as the visibility ratio:

$$V_r = \frac{S_{aL}}{L} \tag{5}$$

The smoke condition is tenable when $V_r \geq 1$ and untenable otherwise.

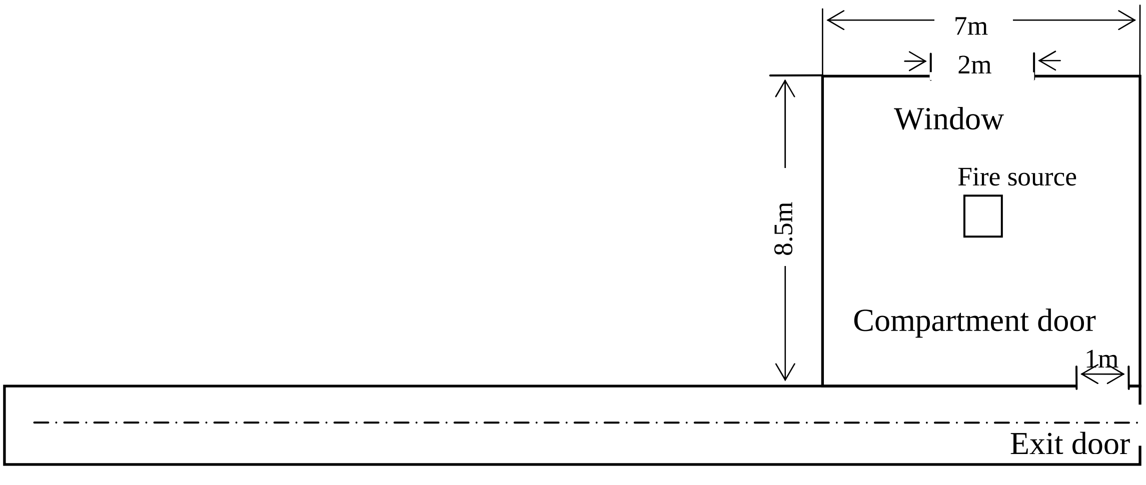
The theoretical foundation of the above discussion is delineated in Appendix.

APPLICATION

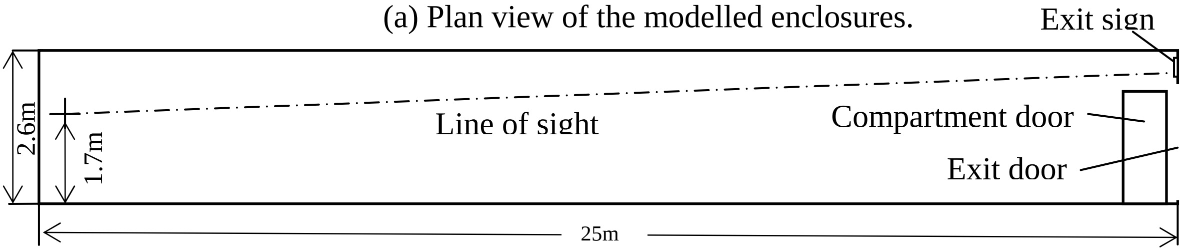
The application of the proposed approach to evaluation of visibility using field modeling results is illustrated through the study of a simple case as presented in Figure 1. Firstly, a simulation model is established and executed using FDS. Secondly, a simple ray tracing technique is employed to the predicted distribution of extinction coefficient along the line of sight to an exit sign to obtain the average extinction coefficient.

FDS Simulation

The model representation of the building layout is simplified and includes a compartment of 8.5m deep and 7m high with a door opening into an elongated corridor of 25m long and 1.5m wide. See Figure 2. There is an exit door from the corridor to the out side. All doors are 1.0m in width and 2.1m in height and are fully open in the simulation. Another door of similar dimensions (denotes as "B" in) is located at one end of the corridor and is open to external ambient. The height of the enclosures is 2.6m. A fully open window (denotes as "C") of 2.0m in length and 0.8m in height is located at the centre of the north wall with the sill height of 1.0m above the floor.



(a) Plan view of the modelled enclosures.



(b) Section view of the corridor.

Figure 2. Building layout for fire modelling.

Two meshes shown as in Figure 3 were employed in the simulation. Mesh-1 represented the corridor and Mesh-2 represented the fire compartment. The grid sizes for these two meshes were notionally 0.10×0.10×0.05m and 0.10×0.10×0.10m respectively. The grid size for the fire compartment (Mesh-2) corresponded to less than one-ninth of the characteristic fire diameter. Mesh-1 grid underwent piecewise linear transformation in z-direction to increase grid density at upper part of the corridor. The grid z-size above 2.1 m was reduced to 0.02 m. Note that the x-axis is brought to front in Figure 3 for legibility.

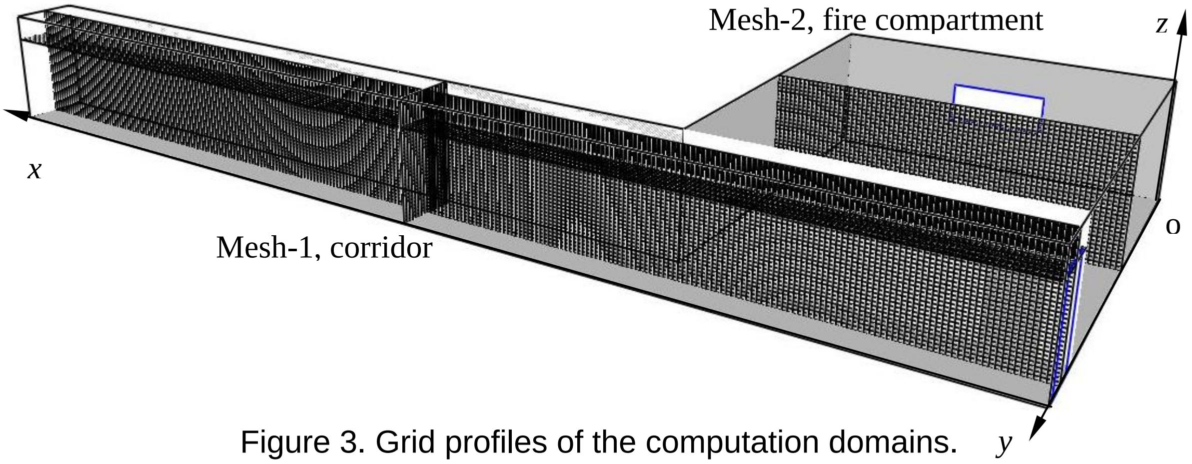


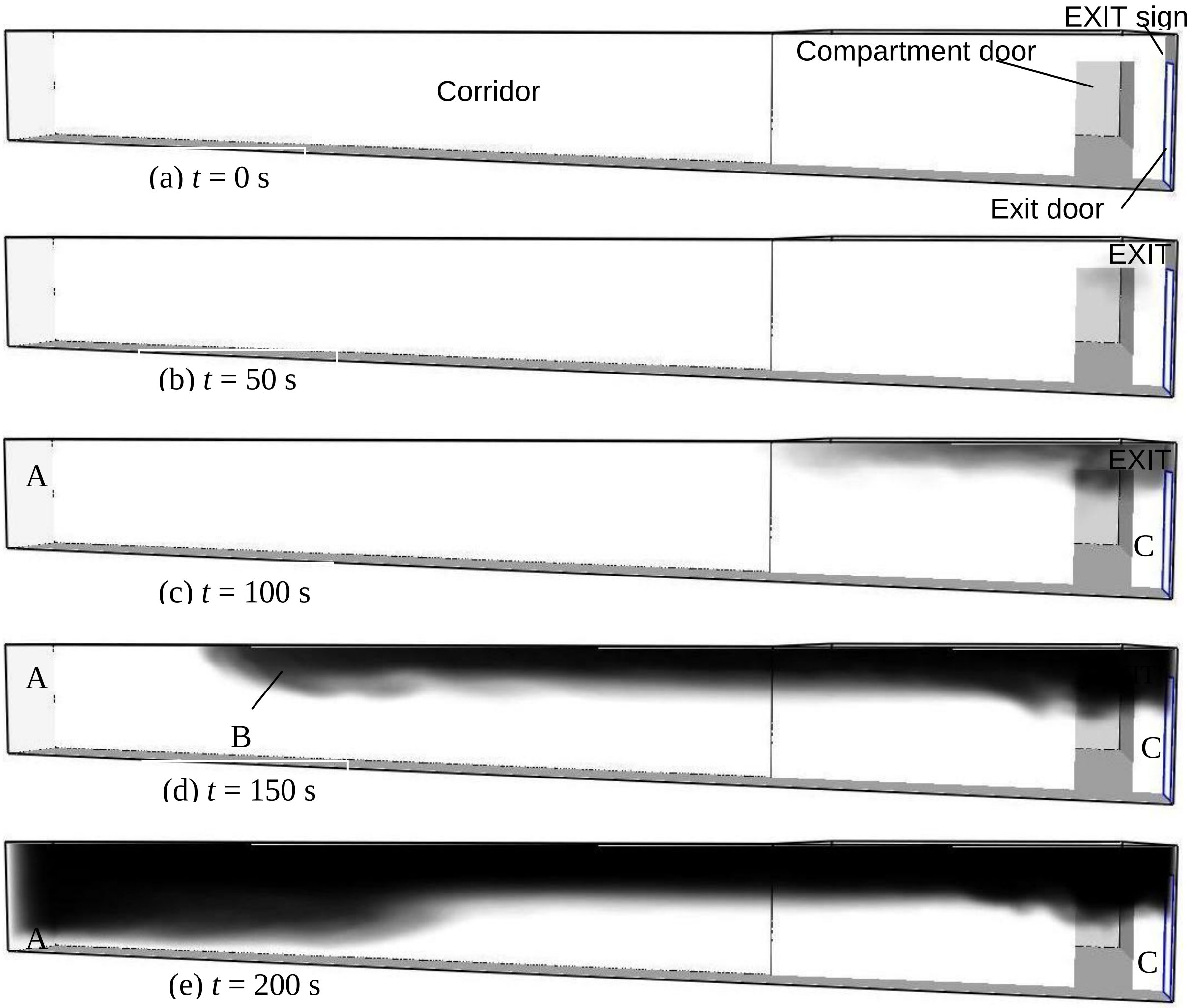
Figure 3. Grid profiles of the computation domains.

The walls of the compartment and the corridor were constructed of concrete and the ceiling and floor were assumed inert and adiabatic in the modeling. The initial and ambient temperature was 30 °C. The fire source was assumed to be an upholstered chair with a peak heat release rate of 900 kW and a medium t^2 growth rate [16]. The heat release rate maintained at the peak level after it was attained. The fire source was approximated as a rectangular fire object of 1.0 m wide by 1.0 m long located at the centre of the compartment. The fuel is represented by the reaction of polyurethane with soot yield of 0.1 kg/kg [17].

A total numbers of 25 evenly spaced sensors measuring local extinction coefficient and visibility are positioned along the centre line of the corridor and along the line of sight (see Figure 2) from an observer at the far end of the corridor to the exit sign at the other end above the exit door. The horizontal distance between consecutive sensors was 1.0m. The height of human eye level was assumed to be 1.7m above floor level and the height of the exit sign 2.2m.

Predicted Visual Effect of Smoke and Visibility by FDS

The SmokeView [4] snapshots of 3D qualitative smoke visual effect in the corridor at a number of time instances are presented in Figure 4. The corresponding quantified colour slices of visibility profiles across the central vertical plane of the corridor as predicted by FDS are shown in Figure 5.



(a) *t* = 0 s

(b) *t* = 50 s

(c) *t* = 100 s

(d) *t* = 150 s

(e) *t* = 200 s

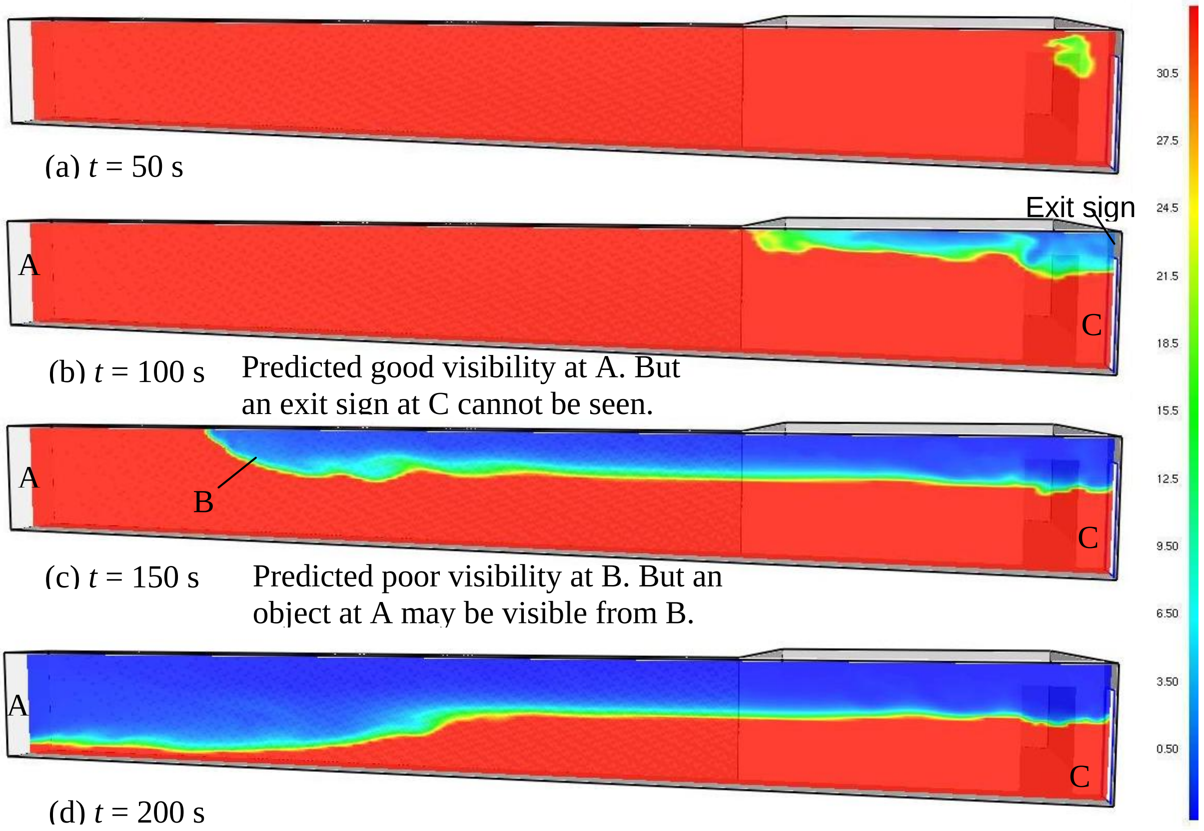
Figure 4. Visual effect of smoke infiltration into the corridor.

It can be observed from Figure 4 that smoke spilled into the corridor at approximately 50s after the start of the fire. As the fire continued to grow, more smoke spilled into the corridor and the visibility of an exit sign above the exit door at location C would be affected at *t*=100s. This exit sign may not be visible to a subject at location A. However, FDS visibility output based on the predicted local extinction coefficient may indicate otherwise [see Figure 5(b)].

At *t*=150 s, smoke front is about 3 m away from the far end of the corridor. The predicted visibility at point B in Figure 5(c) was less than 3 m. Yet, it might be possible for someone at point B to have a vision of an object at point A.

It can be discerned from Figure 5 that the smoke concentration along the line of sight of a subject varied as a function of time and location in a transient flow field. The graph shows a constant visibility of 30 m for *x*>9 m at time 100 seconds. A visibility of 30 m was also observed at *x*=25 m and at *t*=150 s. This prediction can be misleading since the exit sign may not be visible at this location and time.

At *t*=200 s, the predicted result at location C, 1.6m above the floor near the exit door, indicated a good visibility of greater than 30 m for a potential rescuer. However, a potential victim at location A would not be seen by the rescuer. See Figure 4(e) and Figure 5(d).



(a) *t* = 50 s

(b) *t* = 100 s Predicted good visibility at A. But an exit sign at C cannot be seen.

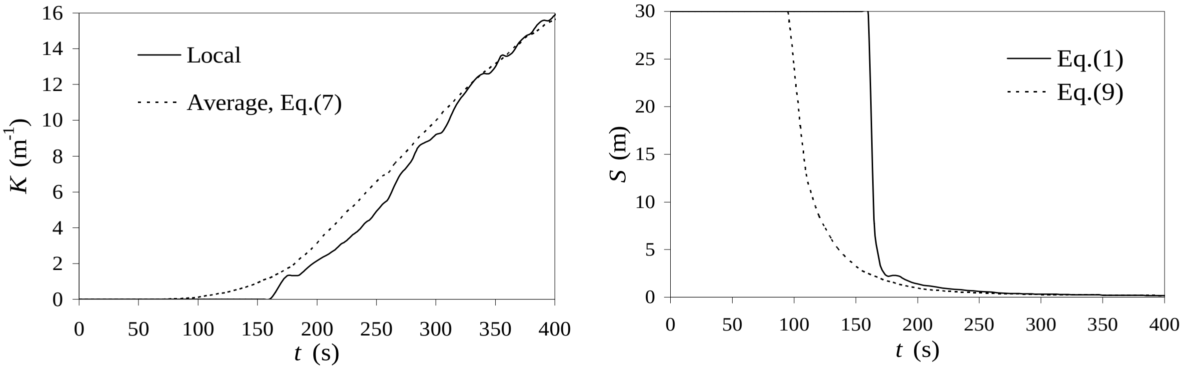
(c) *t* = 150 s Predicted poor visibility at B. But an object at A may be visible from B.

(d) *t* = 200 s

Figure 5. Snapshots of visibility profiles at various times.

Quantitative Estimates of Visibility and Comparison

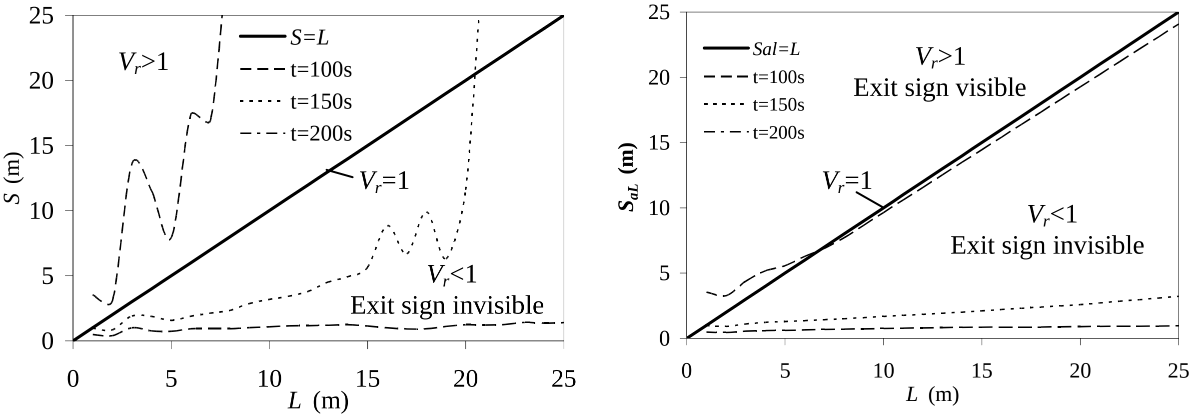
The local extinction coefficient predicted by FDS at the given point A in Figure 5 is compared with the extinction coefficient averaged along the line of sight between A and C in Figure 6(a). It can be discerned from Figure 6(a) that the predicted extinction coefficient K based on local measurement is lower than that based on average K value at x=25 m. This resulted in an overestimation of the visible distance by FDS model [Eq.(1)] when compared with the alternative average extinction coefficient K_{aL} method [Eq.(12)], as shown in Figure 6(b). The default value of 3 was assigned to the visibility factor, *E*, in Eqs.(1) and (12).



(a) Extinction coefficient (b) Estimated visibility

Figure 6. Comparison of extinction coefficients and the corresponding visibilities as functions of time at *x*=25 m.

Presented in Figure 7 is a comparison of local visibility estimated using Eq.(1) against virtual visibility estimated using Eq.(12) as a functions of distance L along the line of sight at given times. The S=L line in Figure 7(a) divides the corresponding graph into two regions. The predicted curves of visibility in the upper region imply that the exit sign is visible to a subject at a given distance. Otherwise in the lower region, the sign is not visible. The same applies to Figure 7(b).



(a) Local visibility (b) Virtual visibility

Figure 7. Comparison of local visibility and virtual visibility as functions of distance *L* along line of sight at given times.

A substantial difference can be discerned between the predicted visibility using local measurement and that using the proposed average extinction coefficient method. For example, at t=150s, FDS predicted a visibility of more than 25m for a subject positioned at 25 m away from the exit sign. However, the virtual visibility was only 3.2 m which is much less than the distance between the observer and the sign, indicating that the sign is not visible to the observer. It would be impossible for an observer at this time and location to have a vision of the exit sign. The predicted visibility based on the local extinction coefficient can be misleading to an untrained interpreter. The alternative virtual visibility method is seen to give more appropriate predictions.

CONCLUSION

Visibility is an extensive parameter. It depends on the obscuration along the line of sight. It is generally non-isotropic. The approach of using an intensive parameter to evaluate an extensive parameter directly without considering the spatial variation is generally inappropriate and could lead to misinterpretation by uninformed users.

The alternative method of using the average extinction coefficient over the line of sight provides more appropriate estimate of visibility than the method based on the local extinction coefficient. The proposed method is an extension of the exiting Jin's correlation which has empirical as well as theoretical foundations.

The application of the average extinction coefficient method in a simple example demonstrated both the qualitative and quantitative differences to the simple local extinction coefficient method.

The discussion of visibility through smoke in the current study is on the ground of optical properties of smoke. The discussion did not consider the irritant effects to the eyes of human subjects, nor the variability in the visual abilities of human subjects. It would be desirable to experimentally verify the average extinction coefficient method presented in this paper.

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APPENDIX

The integral form of Bougur's law which describes the attenuation of light rough a medium reads:

$$I_L = I_0 \exp\left[-\int_0^L K(s)ds\right] \qquad (6)$$

where s is the distance from a reference point, L is path length and $K(s)$ is the local extinction coefficient at s. The integral on the right hand side of the above equation

$$P_L = \int_0^L K(s)ds \qquad (7)$$

is referred as the dimensionless optical path length.

For a special case of homogeneous smoke condition and constant extinction coefficient K,

$$P_L = KL \qquad (8)$$

and

$$I_L = I_0 \exp(-KL) \tag{9}$$

An average extinction coefficient over the path length L can be defined as

$$K_{aL} = \frac{1}{L}\int_0^L K(s)ds \tag{10}$$

Or

$$P_L = K_{aL}L = \int_0^L K(s)ds \tag{11}$$

In other words, the optical path length over a distance L can be expressed as a product of an average extinction coefficient value and the path length. Equation (11) indicates that light attenuation along the physical path length with variable extinction coefficient can be treated as equivalent to that along the same path with a constant average extinction coefficient. Assume that this average extinction coefficient is equivalent to the constant value of a homogeneous system such as the one used in Jin's [6] experimental study. Using this average extinction coefficient and Jin's correlation as in Eq.(1), a virtual visibility can be defined

$$S_{aL} = \frac{E}{K_{aL}} \tag{12}$$

The virtual visibility is the visible distance of a sign along a path where the extinction coefficient is averaged over a given path length. The virtual visibility equals to the actual visibility if

1. the smoke condition is homogeneous, i.e., K=constant along the line of sight; or
2. numerically, S_{aL} determined from Eq.(12) is equal to the path length L over which the average extinction coefficient is evaluated as in Eq.(10).

Or notionally

$$S_{aL} = S \text{ if } \begin{cases} K_{aL} = K = \text{constant along } L\text{; or} \\ S_{aL} = L \end{cases} \tag{13}$$

The second condition for Eq.(13) leads to a way to evaluate visibility along a given direction in an inhomogeneous smoke environment. Substitute Eqs.(10) and (12) into the second condition of Eq.(13). The solution S of the resulting integral equation

$$\int_0^S K(l)dl = E \tag{14}$$

is visibility, or visible distance along a given line of sight.