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Experimental and numerical evaluation of the influence of the soot yield on the visibility in smoke in CFD analysis

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ABSTRACT

Experimental and numerical analysis have been performed to evaluate the influence of the soot yield parameter on the results of advanced engineering analysis, in regards to visibility. After identifying soot yield as the most influential factor on the results, fuels with various values of Ys have been analysed in a fire chamber and then compared to numerical data. The numerical analysis has been performed using two different CFD packages, ANSYS® Fluent®, and Fire Dynamics Simulator. The numerical analysis itself show an apparent hyperbolic trend of the visibility when changing the soot yield with clear consequences on the ASET (Available Safe Egress Time). Below a cut-off point, that exists at a soot yield value close to Ys =0,10 g/g, a small change in the parameter causes a substantial shift in the results (visibility or ASET time), while above this value an increase to soot yield does barely influence the results. Qualitative assessment of the results shows a need for use of conservative values of Ys in engineering analysis if detailed and precise material data is not available. Additionally to the full-scale experiments, a real case study has been included to show how this research can be translated into the Fire Safety Engineering design process. In this study, change of Ys value below 0,10 g/g caused a significant change of the qualitative assessment of the results of CFD.

1. Introduction

Many parameters exist that can be used to describe the smoke properties, e.g. temperature, mass density of products, obscuration density, transmittance, toxic gasses concentration, etc. Among these numerous variables, when conducting Fire Safety Engineering (FSE) analysis, one of the most important is the “visibility in smoke”. It is very common in FSE study, to see the visibility to be the first parameter that meets its critical value (tenability criteria). Visibility in numerical modeling is a result of modeling the transport of combustion products within the model, especially the soot aerosol. The soot is introduced into numerical domain through a source model, and its amount is directly affected by the effective heat of combustion of the fuel ($H_{c,eff}$) and the soot yield (Y_s). The visibility sub model is also dependent on the visibility factor (K) and the mass extinction coefficient of the smoke (σ). Previous research [1] has demonstrated, that among these parameters, the soot yield (Y_s) has the greatest influence on the value of visibility, while observation of engineering projects shown that is the one that is most liberally chosen.

The aim of this study was to further investigate the impact of soot yield on visibility. This goal was pursued through full-scale fire tests performed in the Building Research Institute (ITB) in Warsaw, Poland. Different fires have been examined, using fuels with a high diversity of soot yield values, varying from Ys =0.001 g/g to Ys =0.178 g/g. The density of the smoke layer has been measured with an optical densitometer.

The results have been compared to parametric numerical analysis, performed with ANSYS® Fluent® and Fire Dynamics Simulator. The numerical analysis shows a hyperbolic trend of the Visibility when increasing the soot yield with a cut-off point around 0.10 g/g, where a lower value can produce a relevant change, while a higher value a negligible change in the Visibility and therefore to the ASET (Available Safe Egress Time). Ultimately, a case study has been included to show how critical the soot yield is in the determination of the ASET in a real building.

2. Modeling visibility in smoke

2.1. Optical properties of smoke

The optical properties of smoke aerosol in the air are comparable with other dispersive systems. The intensity of light passing through

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Nomenclature

E	Illuminance [lx]
K	Visibility factor [-]
H_{ceff}	Effective heat of combustion [MJ/kg]
$\dot{Q}$	Heat Release Rate [kW]
K_m	Mass extinction coefficient [m^2]
m_s	mass flux of smoke [kg/s]
l	Length of light path [m]
c_p	Specific heat [kJ/kg K]
T	Temperature [°C or K]
I	Luminous intensity [cd]
Y_s	Soot yield [g/g]
z	Height in a fire plume [m]
D	Fire diameter [m]

Greek

ρ	density [kg/m^3]
λ	Wavelength [nm]
σ	Specific mass extinction coefficient [m^2/g]

subscripts

p	into the plume
0	ambient
fl	flame

the smoke depends on scattering, absorption, diffraction and other smaller effects, which are dependent on the parameters of the smoke and the light. Black smoke is highly absorbing, while white smoke is highly scattering the light. As smoke contains condensed water particles, additional light refraction is observed. As it is not possible to measure the absorption and scattering effects separately, their combined damping effect is measured. In engineering calculations, these effects are simplified even further, as the optical properties of smoke and their influence on the light are not modeled at all, but rather evaluated with simplified mathematical models of visibility within the smoke in function of the local smoke concentration.

Fig. 1 presents a typical method of displaying the results of visibility in smoke in a CFD analysis. Points (a), (b) and (c) are relatively close to each other but have radically different values of visibility. This does not mean that a subject in point (a) would see at 30 m distance, while one at (c) only at 5 m. The physical meaning is that an object would be visible from 30 m, 20 m or 5 m if a whole room was filled with a uniform smoke layer, as dense as in points respectively, (a), (b) or (c). To realistically determine the visibility through a non-uniform smoke, more advanced methods such as ray-tracing should be used.

2.2. Introduction of the smoke into the numerical model

In complex models, the fire is usually represented by one of three typical approaches, each of them can be implemented either as a 2D source (surface) or a 3D source (volume), depending on the solver:

a) fixed source of heat and smoke, which is described by its volume (area), and the amount of energy and mass of combustion products emitted within. The yields and their change in time are pre-defined, and chemistry models are not used. Complex phenomena such as pyrolysis, self-extinguishing or under-ventilated combustion are not explicitly modeled;
b) source term that emits fuel or a mixture of fuel and oxygen, which is further burned using simple chemistry models (e.g. 2-eq. Arrhenius models [2], or pre-mixed burning model [3]). The yields are dependent on the chemistry and local oxygen concentration, which allows the inclusion of self-extinguishing or under-ventilated burning phenomena, but due to predefined yield, time to burnout is not explicitly modeled;
c) model of materials that have a mass, and are the source of fuel through pyrolysis or evaporation. The chemistry of the combustion model is similar to model b). This approach allows modeling of the fuel depletion, the spread of the fire, but is the most computationally expensive and does not have sufficient validation for complex materials, thus is rarely used in practical engineering applications.

Models a) and b) are a prescript representation of a fire, which can be considered explanatory, but not predictive. Once the smoke is released into the model, to estimate the smoke density in particular control volumes (cells) of a CFD model, continuity, momentum, and mass transport equations, along with turbulent flow sub-model are solved. The smoke is generated within the source of fire, represented as soot particles introduced to the convective stream of air also produced by the source. This representation heavily relies on the main parameters relevant to the soot production – effective heat of combustion ($H_{c,eff}$), heat release rate (Q) and the soot yield parameter (Y_s). The mass of smoke introduced into the model can be presented as:

$$m_s = Y_s \frac{Q}{\Delta H_{c,eff}} \tag{1}$$

The amount of the soot often referred as the "mass smoke

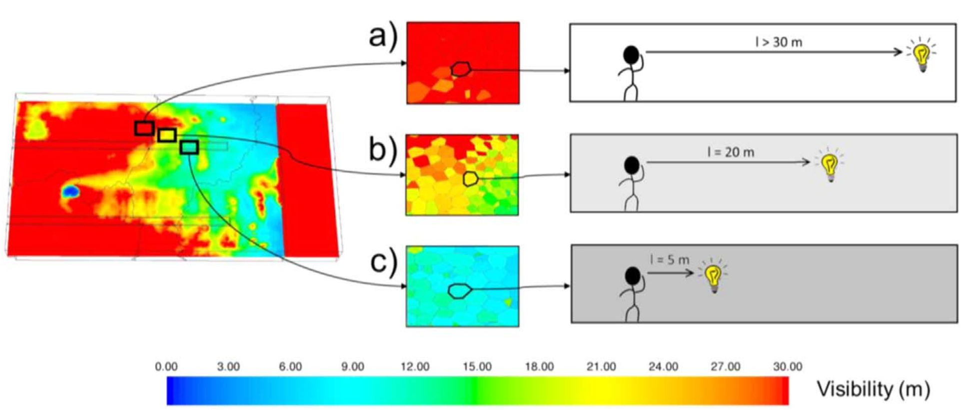

Fig. 1. The local visibility range plot (most left, range from 0 to 30 m and more, for K =3) is created as an array of visibility values from individual cells (middle clips). Value within each of the cells represents the distance, from which a certain object (eg. sign, light) would be seen, in a room (right side drawings) with uniform smoke corresponding to the mass concentration of the smoke within that cell.