Computational Fluid Dynamics (CFD) Modelling on Soot Yield for Fire Engineering Assessment

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1. Background

Computational Fluid Dynamic (CFD) Modelling is now widely used by fire safety engineers throughout the world as a tool for predicting smoke movement and tenability analysis. CFD model has often been used to justify the performance of the smoke control design as part of the performance based fire safety design in the current industry.

Typically the smoke extraction rate, number of smoke extraction point and the layout of smoke extraction point are designed using empirical equations from technical guidance such as NFPA 92B[i], NFPA 204[ii], CIBSE Guide E[iii], etc. All design parameters of the smoke control strategy and architectural design will be input in the CFD model for analysis. The below are examples of empirical equations extracted from NFPA 92Band NFPA 204.

$$D = \left(\frac{4Q}{\pi Q''}\right)^{1/2} \qquad \text{Eqt(1)}$$

$$z_l = -1.02D + 0.235 Q_c^{2/5} \qquad \text{Eqt(2)}$$

$$z_o = 0.083 Q^{2/5} - 1.02D \qquad \text{Eqt(3)}$$

$$T = T_o + \frac{Q}{1.5 m C_p} \qquad \text{Eqt(4)}$$

$$m = [0.071 Q_c^{1/3} (z-z_o)^{5/3}] + [1 + 0.027 Q_c^{2/3} (z-z_o)^{-5/3}] \quad (\text{If } z > z_l) \qquad \text{Eqt(5)}$$

$$m = 0.0056 Q_c \, (z / z_l) \quad (\text{If } z \leq z_l) \qquad \text{Eqt(6)}$$

$$V = \frac{m}{\rho_o} + \frac{Q}{1.5 \rho_o T_o C_p} \qquad \text{Eqt(7)}$$

where,

Q = *instantaneous heat release rate (kW);*

Q_c = *convective portion of heat release rate (kW);*

Q'' = *heat release rate per unit floor area (kW/m²);*

z_l = *mean flame height above the base of the fire (m);*

z = *height of the smoke layer boundary above the base of fire (m); (or desired smoke clear height)*

z_o = *height of the virtual origin above the base of the fire (if below the base of fire, z_o is negative) (m);*

D = *instantaneous fire diameter (m);*

T_o = *indoor temperature (°C);*

T_s = *average temperature of smoke layer (°C);*

m = *mass production rate of smoke when plume at height z (kg/sec);*

V = *volumetric smoke production rate (m³/sec);*

d =*smoke layer depth (m);*

Temperature and visibility are two critical criteria for tenability analysis for performance based assessments. In our project experience, the visibility results (i.e. smoke layer thickness for smoke with visibility of 10m or less) from CFD modelling are often more onerous than the results calculated using empirical equations. However, the temperature of smoke layer prediction from CFD matches well with smoke layer calculated from empirical equation. We have conducted a number of investigation and we have pinned this down to a number of reasons, we have chosen two elements, i.e. the weight-average method in developing soot yield and the soot yield deposit which is not currently included in the most CFD model.

2. Description of Issues

Based on our project experience in adopting CFD for predicting smoke spread in fire, we propose to conduct a further investigation into the issue of soot yield prediction and deposition in CFD modelling.

Firstly, the basic of visibility prediction by CFD model often follow the empirical equations.

For flaming combustion of wood or plastics:

$K = 7.6 \times 10^3\ ms$ *Eqt(8)*

For a fire burning at rate R ($kg \cdot s^{-1}$) *for a duration t (s), ms is given by:*

$ms = Y_{smoke}\ R\ t / Vs$ *Eqt(9)*

$S = 8\ Vs / (7.6 \times 103\ Y_{smoke}\ R\ t)$ *Eqt(10)*

where

K: *extinction coefficient* (m^{-1}) *and ms is the mass concentration of smoke aerosol* ($kg \cdot m^{-3}$).

Y_{smoke}: *the yield of smoke particles* ($kg \cdot kg^{-1}$) *and Vs is the volume of smoke (m3).*

C: *non dimensional constant characteristic of the type of object being viewed through the smoke, i.e. C = 8 for a light-emitting sign and C = 3 for a light-reflecting sign.*

S: *Relative Visibility (m)*

The above equations show that the yield of smoke particles (soot yield) is the major factor affecting the resulted visibility. Soot yield is one of the critical input data of CFD model. In general, most of the CFD software can only cater for single combustible reaction. The combustible considered in the analysis of our projects usually is a composition of several different materials.

A. Soot Yield Value Assessment Methodology for Composite of Combustible

In practice, the soot yield inputted to CFD model is usually calculated by the weight-averaging of the soot yield values of the involved materials. The more onerous visibility results shown in CFD model may be due to simplistic assumption of weight-averaging method, especially when the combustible contains synthetic fibre. Another calculation method of soot yield value as input to CFD model may be necessary. This will require derivation of equations or computer programme basing on mathematics and chemistry knowledge.

B. Soot Yield Deposition

Large numbers of validation tests for CFD softwares have been conducted by different organizations throughout the world, such as the VTT tests (iv). One of the common limitations of CFD softwares for predicting visibility is that soot loses due to deposition on affected surfaces (such as ceilings and walls) are not well quantified in the CFD model.

Development of numerical methodology for assess the soot loses due to deposition will be needed to improve the capacity of CFD modelling technique.

Reference

[i] NFPA 92B Guide for Smoke Management Systems in Malls, Atria, and Large Areas, 2009 edition, National Fire Protection Association, Quincy, MA, USA, 2009.

[ii] NFPA 204 Standard for Smoke and Heat Venting, 2007 edition, National Fire Protection Association, Quincy, MA, USA, 2007.

[iii] CIBSE Guide E, Fire Engineering, 2nd Edition, Chartered Institution of Building Services Engineers, London, UK. September 2005.

[iv] VTT Working Papers 66, Experimental Validation of the FDS Simulations of Smoke and Toxic Gas Concentrations, Tuomo Rinne, Jukka Hietaniemi and Simo Hostikka