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Modeling carbon black trace in building fire and its validation

Peizhong Yang [a,*], Guangyao Yao [a], Xun Tan [b]

[a] *School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China*
[b] *Fire Investigation Department, Shanghai Fire Bureau, Shanghai 200051, PR China*

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ABSTRACT

The carbon black trace is an important characteristic in a building fire accident and becomes crucial evidence in fire investigation. Based on the particle deposition theory, the mathematical model is established for the carbon black trace in a building fire. The numerical model of the carbon black trace is implemented into the Fire Dynamics Simulator (FDS) software. The total mass of the carbon black particle deposited on the wall surface can be calculated quantitatively and be simulated visually. The proposed model is applied into a fire accident as a validation. A numerical model is used to simulate the fire accident. In numerical simulations, the grid size resolution is analyzed. The accident reconnaissance data, accident interview record and accident scene photo/video are compared with the results of numerical simulations. It shows that the simulation results have a good agreement with those in the fire accident, which validates the mathematical model in this study. The proposed method can provide useful data for fire reconstruction and fire investigation.

1. Introduction

In fire investigation, various traces in the fire scene can be used as evidences to determine the fire starting time, fire location and fire spreading path. The carbon black trace is formed by the adhered carbon black particles on the wall surface. It is one of the most common trace characteristics in a fire accident and becomes the most important evidence in fire investigation.

1.1. Particle deposition research

Many investigators have contributed to the particle deposition research. Hall et al. (1998) studied the deposition of large particles from a small scale wind tunnel model of a chemical warehouse fire plume. The deposition of large particles from fire plumes has been modeled directly as an adjunct to earlier small scale wind tunnel experiment on gaseous plume dispersion using the same experimental conditions. The relative behavior of gas plume and heavy particle dispersion was compared. Sippola and Nazaroff (2002) reviewed published experimental and theoretical investigations of particle deposition from turbulent flows. They considered the applicability of this body of work to the specific case of particle deposition from flows in the ducts of heating, ventilating and air conditioning systems. Sippola and Nazaroff (2003) developed empirical equations to predict losses of 0.01–100 mm airborne particles making a single pass through 120 different ventilation duct runs typical of those found in mid-sized office buildings. Results suggested that duct losses were a minor influence for determining indoor concentrations for most particle sizes. Winkler et al. (2006) performed a parametric study of the effects of varying particle relaxation time on wall-deposition. They studied the deposition of dense solid particles in a fully developed turbulent square duct flow using large eddy simulations. Ten particle Stokes numbers, corresponding to two density ratios and five particle diameters were studied. Two particle number densities corresponding to initial particle numbers of 10^5 and 1.5×10^6 were examined. They presented variations in the probability distribution function of the particle deposition location with dimensionless particle response time, i.e. Stokes number. The deposition was seen to occur with greater probability near the center of the duct walls, than at the corners. The average streamwise and wall-normal deposition velocities of the particles increased with Stokes number, with their maxima occurring near the center of the duct wall. The computed deposition rates were compared to previously reported results for a circular pipe flow. It was observed that the deposition rates in a square duct were greater than those in a pipe flow, especially for the low Stokes number particles. Also, wall-deposition of the low Stokes number particles increased significantly by including the subgrid velocity fluctuations in computing the fluid forces on the particles. However, for small particles, the deposition rate in the square duct was two orders of magnitude

* Corresponding author. Tel./fax: +86 021 34206057.
E-mail address: pzyang@sjtu.edu.cn (P. Yang).

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higher than in a pipe. For large particles, the deposition rates in a square duct were closer to those in a circular pipe. Parker et al. (2008) predicted aerosol deposition rates from turbulent flow using Computational Fluid Dynamics simulations and compared them with experimental data. They assessed the influence of turbulence model choice. The use of isotropic turbulence models resulted in over-prediction of V_d^+ by more than 3 orders of magnitude for $\tau^+ < 0.2$, whilst the anisotropic Reynolds stress model gave results in good agreement with experiment. For $\tau^+ > 10$, there was little difference between the turbulence models. Simulations for both $R_e = 9894$ and 50,000 were carried out and good performance was seen for both. The effect of drag model was assessed and resulted in little difference in predicted deposition velocity. The influence of grid resolution was also studied and it showed that the cell center of the wall-adjacent cell should be at a distance of $y^+ = 2$ (y^+ is the dimensionless wall-normal distance) or less for quantitative prediction of deposition. Coarser grids resulted in over-prediction for low τ^+. Riahi (2010) studied the physics of smoke deposition from a hot layer to a wall in a hood apparatus based on thermophoresis experimentally and analytically. He used the optical density method to measure the amount of smoke deposited on the surface. He introduced solid phase mass specific extinction coefficient values for the first time for different fuels. The optical properties of the smoke deposited on the surface were determined and compared to the smoke properties in the gas phase. An analytical thermophoretic smoke deposition model was developed using the measured smoke properties. He also studied the physics of smoke deposition from a pan fire to the gypsum wall for different fire sizes and fuels. The optical density method was used for the wall tests. Solid phase mass specific extinction coefficients were determined for the wall tests. Fire size effect was also studied for the wall tests. The effect of fire size and change in the flow regime due to the fire size has been studied. It was noticed that the effect from turbulence changes the values for the solid phase mass specific extinction coefficient. The optical density measurement method was applied to the digital images taken from the smoke patterns against the wall. Results from the smoke pattern predictions for the wall tests showed a very good agreement between the digital images from the smoke deposition in the walls and the processed data. The analytical smoke deposition model based on thermophoresis was validated with the experimental data from the wall tests. There was good agreement between the experimental data and the results from the model. El-Zohri et al. (2013) presented a mathematical integrated model that simulated the coupled events causing flashover due to the deposition of soot particles on suspension insulators of high voltage transmission lines (HVTL). In the model, they considered non-steady three-dimensional multi-phase flow of agricultural fire producing the soot particles. The model described in detail the mechanism of the soot deposition combined with the developing of the electric field. They solved the model equations using an iterative finite-volume numerical technique together with the indirect boundary element and charge simulation methods. The model validity and accuracy were verified through the discussion of the results for a representative case study of a 15 kV cap-and-pin insulator string. The model formed a satisfactory tool in designing and dimensioning the insulators of high voltage transmission lines to avoid their expected fire-caused outages. Chen and Li (2014) carried out an experiment on particle dimensionless concentrations and size distributions above a near-wall heat source and in the indoor environment to investigate the effect of near-wall heat sources on the particle deposition. They measured and compared the suspended particles above the near-wall heat source and in the adjacent indoor air. The particles were collected under twenty-five different cases by using a Grimm 31-Channel Portable Aerosol Spectrometer. The results revealed that the particles above the near-wall heat source had larger deposition rate than that in the adjacent indoor air. Particles with 0.75–11.25 μm dimension stayed more in the air above the heat source than in the adjacent indoor air. They also found that the particle decay rate loss coefficient increased as the heat source surface temperature increased, and it reduced as the gap between the heat source and the wall increased. Guha and Samanta (2014) studied the aerosol particle transport and deposition onto an isothermal horizontal or vertical plate due to the combined effects of laminar natural convection, Brownian diffusion and thermophoresis. They considered four configurations: flow above a heated horizontal plate, flow beneath a cold horizontal plate, flow due to a heated vertical plate and that due to a cold vertical plate. Nano- to micro-sized particles (particle diameter in the range 1 nm to 5 μm) in air were considered. They found that the deposition velocity decreased with an increase in particle diameter, and increased with a decrease in the value of non-dimensional temperature difference. It was shown that the thermal drift may enhance the deposition rate by several orders of magnitude under certain circumstances. The profound role of using different expressions for the thermophoretic force coefficient was also assessed. Lecrivain et al. (2014) proposed a new three-dimensional approach to reproduce the growth of a multilayer deposit in a turbulent obstructed channel flow at Reynolds number Re = 10,000. They used Computational Fluid Dynamics and Computational Granular Dynamics to simulate 4 h of real deposition. A detached eddy simulation was employed to predict particle deposition while self-organized criticality was employed to reproduce the slow growth of the multilayer deposit. The three dimensional shape of the multilayer deposit matched remarkably well the experimental data.

1.2. Numerical simulations of fire accident

With the rapid development of computer technology and numerical method, numerical simulation plays an important role in fire research. The Fire Dynamics Simulator (FDS) (McGrattan et al., 2010a,b), developed by the U.S. National Institute of Standards and Technology (NIST), is based on the Large Eddy Simulation (LES) model and has high simulation accuracy and computation efficiency. Hence, it is widely used in fire simulations. The NIST used FDS to simulate several fire accidents including the Cherry Road fire (Madrzykowski and Vettori, 2000), the Cook County Administration Building Fire (Madrzykowski and Walton, 2004), the Station Nightclub Fire (Madrzykowski et al., 2006), and the World Trade Center disaster (NIST NCSTAR 1A, 2008). Xin et al. (2005) performed fire dynamics simulations of a 7.1 cm buoyant turbulent diffusion flame using a mixture fraction-based combustion model. Shen et al. (2008) also used FDS to reconstruct an arson fire scene in order to predict the development of heat, smoke and toxic gases at the fire scene, thereby supporting the work of fire scene investigation. Lin and Chuah (2008) used FDS to study the performance of different smoke extraction strategies for a long vehicle tunnel with a 100 MW fire scenario. The selection of single-point extraction (SPE) opening strategy versus multi-point extraction (MPE) opening strategy was analyzed. Jahn et al. (2008) studied the sensitivity of FDS modeling to a set of input parameters related to fire growth, such as fire size and location, convection, radiation and combustion parameters. It was identified that the simulations of fire growth were significantly sensitive to location or the heat release rate, fire area, flame radiative fraction and material thermal and ignition properties. Rein et al. (2009) conducted a round-robin study on the modeling prediction of the Dalmarnock Fire One Test. Comparison of the round-robin modeling results indicated large scatter and considerable disparity, both