Computation of a Compartment Fire with Smagorinsky Sub-Grid Scale Model

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Abstract. A fire tests using plywood crib as fire source was done in a cubical compartment to investigate the fire development and temperature distribution. The dimension of the experimental compartment was 4 m high, 4 m wide and 4 m length with a door opening of 2 m × 1 m wide located at one of the compartment wall. Several parameters were measured which includes fuel mass loss rate, compartment gas temperature, centerline doorway temperature, heat flux and wall surface temperature. Three-dimensional numerical simulations were performed using large eddy simulation with different values of Smagorinsky sub-grid scale constant. In order to accurately investigate the behavior of fire within the compartment by computational fluid dynamics (CFD), it is vital to study these Smagorinsky sub-grid scale constant. Numerically predicted results with various Smagorinsky sub-grid scale constant was compared with the physical results. It was found that the varying the Smagorinsky constant affect the numerical simulation results.

1. Introduction

Better knowledge of the improvement in compartment fire is vital for fire analysts and firefighters for foreseeing and assessing temperature, heating of adjacent structures and smoke creation [1]. The experimental data and the numerical simulation are two principal techniques used to explore the progress of compartment fires. No, doubt, progressively fire safety assurance concerns to utilize fire modeling software, including two-zone models and CFD models. As computational technologies are more accessible now at lower cost, CFD software’s are progressively being used for engineering applications [2]. Nonetheless, due less comprehensive information about material properties and incomplete demonstrates on the pyrolysis and fire behavior at different scenarios, there is still a requirement for development of numerical re-enactment strategies. Several turbulence models are present in literature for simulating the turbulent mixing phenomenon in various fire scenarios, such as Direct Numerical Simulation (DNS) model [3], Large Eddy Simulation (LES) model [4,5] and RANS [6]. The Sub-grid scale coefficient, (Cₔ) depends on flow and studied with the range from 0.1 to 0.25 by different flow applications as studied by different researchers [7,8]. While the simulation of indoor airflow under different conditions (i.e, Natural, forced and mixed convection) the value of 0.16 and 0.2 were found to be better agreement with experimental results [9,10]. The sub-grid scale turbulent Prandtl number (Pₚ) is derived by empirical correlation from the range from 0.2 to 0.9.

The physical results of compartment fire were studied and found that the effect of Cₛ, Pₚ and grid size (Δx) for weak buoyant plume there is no significant effect with the variation of model coefficient Cₛ and Pₚ. But for the case of the strong, buoyant plume, the (Cₛ) has an significant effect on the predicted temperature and heat flux [11]. The effect of Prandtl number was studied for enclosure fire and concluded that the (Pₚ) has no significant effect on Heat release rate (HRR), temperature and CO yield as compared to other coefficient, whereas, from Sₛ=0.1 higher value of CO yield was predicted with relative difference of 59 % than that of default value Sₛ= 0.5 [12].

It has been found that the effect of (Cₛ), on the simulation of compartment fire needs more investigations. Therefore, in the present study, the numerical simulations were performed using FDS
code for different SMG coefficients for two different mess sizes, i.e. 0.1 m and 0.14 m. In FDS a default value of $C_s$, $P_s$, $S_c$ are 0.2, 0.5 and 0.5 respectively [13].

2. Experimental Setup & Numerical Model

2.1. Compartment Configuration
The experimental compartment with dimension (4 m × 4 m × 4 m) was constructed to provide data from fire experiments. At center of the front wall of the compartment there was a door opening of dimension 1 m × 2 m. The experimental compartment walls were made up of normal bricks and plaster of 3 cm thickness on both sides of the wall. The ceiling was made up of Reinforced Cement Concrete (RCC). The schematic sketch of experimental fire compartment is presented in Figure 1. The ply board cribs were used as fuel for the experiment. The cribs were burned on insulated platform at the center, beneath which a digital load cell was provided to record the mass loss rate of the burning crib during experiment [14].

![Figure 1. Schematic view of experimental compartment](image)

2.2. Instrumentations
Several instrumentations were placed to measure various parameters such as, MLR, gas temperature and door gas velocity. The heat flux at different locations was measured using SBG01 heat flux guage of rating 0-20 kW/m². These gauges were installed in the experimental room to record the heat flux at floor and walls, as shown in Figure 1. HF1 and HF2 of working range 0-20 kW/m² were placed on the floor facing vertically upward and on back side of wall. Data logger was used to collect the readings of heat flux gauges with sampling rate of 5 sample per second. All heat flux gauges installed were having field view of 180°, emissivity > 0.95 and had error margin of ± 6%.

For measuring the gas temperature profile of compartment, one thermocouple array was placed at one of the back corner of the compartment. A total of 20 K-type thermocouples of 1 mm diameter were located with continuous vertical spacing of 200 mm throughout the tree. The K type thermocouple had the error of ± 1.5 °C. The bottom most thermocouple was located 50 mm above the floor and the top most thermocouple was located at 150 mm below the ceiling. An array of thermocouple array was installed to record the door temperature. A total of 9 thermocouples were installed stating from 150 mm height with a pitch of 150 mm upto 900 mm and thereafter a pitch of 300 mm up to 1800 mm height. All output readings heat flux gauges and thermocouples were collected using a data acquisition.

2.3. Description of FDS Model
The present transient numerical simulation was conducted with the FDS code Version 5.5.3 developed by NIST [15]. The dimension of the computational domain which encloses the compartment is 4.5 m ×
5.0 m × 4.5 m having a opening of dimension 1.0 m × 2.0 m located at the middle of front wall. At the center of the compartment a fire source was placed with a height of 0.2 m above the floor. To investigate the gas movement the computational domain has been extended 1 m from the doorway and the boundary conditions was set as open. The temperature sensors and heat flux gauges are defined in present simulation exactly at the same location as located in the experimental compartment. The detailed description of the location of instruments is as explained in Section 2.2. In the present study, the ambient temperature is was 20 °C and the relative humidity was 70 %. The default velocity and thermal wall boundary conditions as imposed in FDS, have been used for present numerical investigation.

2.4. Grid Sensitivity Analysis

As mentioned in the previous section, CFD tool FDS is used for present simulation. The size of the grid is an important parameter in CFD dictating its numerical accuracy. The size of the eddies which can be solved will mainly depend on the refinement of the numerical grid. Froude number was used to derive the characteristic diameter of the plumes, \( D^* \) and the grid size \( (\Delta x) \) was used to solve the flow field in buoyant plumes [16].

\[
D^* = \left( \frac{\dot{Q}}{\rho c_p T_c \sqrt{g}} \right)^{3/5}
\]  

(1)

Finer grid size may additionally provide extra correct solution; however, refinement of the accuracy of computation will be small after the variety of grid factors is expanded past a sure level. At the equal time, computational expense gets more prominent. In the present numerical simulation, five different grid size \( (\Delta x) \) has been chosen which ranges from 0.05 m to 0.14 m. It was found that for grid size of 0.05, 0.08 and 0.10 no significant deviation was found. The average percentage change for upper hot gas layer with reference to grid size 0.10 m for 0.08 and 0.05 m was 2.5 % and 2.1 % respectively. So for the present study the grid size of 0.10 m was adopted. The grid sensitivity analysis is illustrated in Figure 2. As the size of the cell increases, the computation time also increases which refines the predicted results. The initial time step for calculation is set to be 3 s. All calculations were carried out on a Dell-PC with a 3.60 GHz dual processor and 12 GB of RAM. It took approximately 12 h for a typical run.

![Figure 2. Grid sensitivity analysis](image)
3. Results and Discussions

The fire experiment was conducted using cribs made up of plywood as fire source. The compartment gas temperature, wall temperature and heat flux are measured at various locations and are validated with FDS code with varying SGS model coefficient are shown in Figure 3. To study the effect of turbulence model constant two grid size one of fine resolution of filter width 0.1m and coarse resolution of filter width of 0.14m have been taken. Figure 3 represents the comparison of experimental data with numerically predicted results by varying SGS constants in fine as well as coarse resolution. In Figure 3(a) the numerical results were obtained for different Smagorinsky sub-grid constant $C_s=0.13, 0.15, 0.17, 0.2, 0.23$ and compared with the measured values. In Figure 3(b) the Prandtl number ($P_r$) has been varied for value 0.1 to 0.9 and compared with the measured values, similarly the effect of turbulent Schmidt number ($S_c$) has been represented in Figure 3(c). With the default value of $C_s$, $P_r$ and $S_c$ (0.2, 0.5, 0.5) the result found to be in good agreement with experimental value. On further inspection it can be noticed that the effect of variation of $C_s$ and $S_c$ has less significant effect on the numerical results. Whereas, the numerical result obtained with the lesser value of Prandtl number, $P_r=0.1$ has significant effect on the predicted results. From Fig. 3(a,b,c) the thermal discontinuity height was predicted 0.95 m from the floor and when measured with the corner thermocouple is was found to be 1.05 m from the floor. However, no significant effect was seen when determined with different values of all SMG coefficients.

Temperature distributions at doorway centerline are illustrated in Figure 4. With default values for $C_s$, $P_r$ and $S_c$ the predicted results follow the similar trend to those of experimental values and found to be in good agreement. The percentage deviation between the predicted and experimental results are around 14 % for the cold layer temperature below the neutral plane and approximately 13 % for hot gas layer temperature above neutral plane. However, when experimental results were compared with different value of Prandtl number it was found to be under predicted with the percentage difference of about 36 % for $P_r = 0.1$ at the hot gas layer zone. On the other hand, no significant difference was found with the variation of Schmidt number, as shown in Figure 4(c). When the experimental results of doorway temperature profile were simulated with coarse grid the predicted centerline doorway temperature profile was found under predicted with deviation of 12 % with experimental values for default CFD turbulence model constants. However no significance change was noticed with the variation of $C_s$. With $P_r= 0.1$ the largest deviation was found about 32 % and a noticeable variation can be seen with different values of $P_r$ as shown in Figure 4(b). The deviation between numerical and experimental temperature profiles may be due to the fact that the temperature sensor absorbs the radiation coming from the heated surface boundaries such as wall, ceiling, and floor, or due to radiative heat transfer from hot gas layer to the cold layer which is present below the thermal discontinuity height and from the flames. Figure 5 presents the variation of heat flux on the floor of the compartment with different values of SGS constants. The location of the heat flux sensor HF1 is shown in Figure 1. The predicted peak heat flux prediction for HF1 was about 8 % when compared with measured heat flux. The variation of $C_s$ and $P_r$ has no significant effect on the predicted heat flux for both the heat flux sensors and found good agreement with the experimental results. Whereas with $P_r = 0.1$ the discrepancy in measurements is about 18 % for HF1. The simulation result was also found in good agreement with the experimental values when the grid size was coarse.
Figure 3. Comparison of compartment gas temperature profile. (a) Variation of $C_s$ for fine and coarse resolution. (b) Variation of $P_r$ for fine and coarse resolution. (c) Variation of $S_c$ for fine and coarse resolution.
Figure 4. Comparison of door temperature profile. (a) Variation of $C_s$ for fine and coarse resolution. (b) Variation of $P_r$ for fine and coarse resolution. (c) Variation of $S_c$ for fine and coarse resolution.
Figure 5. Comparison of heat flux on the compartment floor. (a) Variation of $C_s$ for fine and coarse resolution. (b) Variation of $P_r$ for fine and coarse resolution. (c) Variation of $S_c$ for fine and coarse resolution.

4. Conclusion
The present paper illustrates the comparison between experimental fire test data with numerical simulation in an enclosure under natural ventilation conditions. Twenty sets of simulation by large eddy simulation were carried out to investigate the effect of turbulence model constant on the
temperature profile and heat flux in compartment fires. And also to investigate the effect of turbulence model constants on grid resolution, simulation were performed for fine grid as well as coarse grid. The following observations were made:

- When simulations were performed with Δx of 0.1 m the simulation results has good agreement with the experimental values than that of coarse grid with filter width 0.14 m.
- The Smagorinsky sub-grid constant C_s on fine grid shows less significant effect on the predicted results as compared to coarse grid.
- Lower value of turbulent Prandtl number has large deviation with both fine and coarse grids as compared with higher turbulent Prandtl number. Whereas the effect of turbulent Schmidt number on both grid had less significant effect.
- The buoyant plume in present experiment is not very large therefore the predicted results show less dependency on the grid resolution. The effect of Smagorinsky sub-grid constant C_s has less influence due to weak buoyant plumes been as choice should be made for Prandtl number.

Nomenclature

| Symbol | Description |
|--------|-------------|
| Q      | Heat release rate, KW |
| T_∞    | Ambient Temperature, k |
| g      | Gravitational acceleration constant, m/s² |
| Δx     | Grid size, m |

Greek Symbols

| Symbol | Description |
|--------|-------------|
| c_p    | Specific heat capacity, kJ/kg-k |
| ρ_∞    | Air density, kg/m³ |

Non-dimensional Numbers

| Symbol | Description |
|--------|-------------|
| C_s    | Smagorinsky Constant |
| P_t    | Turbulent Prandtl number |
| S_c    | Turbulent Schidmt number |
| D*     | Characteristic fire length |

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