VALIDATION OF FDS PREDICTIONS ON FIRE-INDUCED FLOW: A FOLLOW-UP TO PREVIOUS STUDY

Lei Wang[1*], Johnson Lim[2], James G. Quintiere[3]

[1] School of Safety Engineering, China University of Mining and Technology, Xuzhou, Jiangsu, 221116, China
[2] Defence Science & Technology Agency, Singapore 109679, Singapore
[3] University of Maryland, College Park, Maryland, 20742, USA
* Corresponding author, Email: windfloyd@gmail.com

ABSTRACT

In an attempt to investigate the accuracy of predictions of fire-induced flow into a compartment by FDS, a follow-up study was explored resting on the previous achievement. Simulations with more delicate configurations in multiple scenarios were performed. The results are compared with the Steckler's experimental data obtained at NIST in 1982. Improvements to the previous study include finer grids and an inclusion of radiative heat in the combustion model. The computational domain was increased such that it includes the space outside the doorway, not done in the previous study. In order to get a general application to different scenarios with varied door widths, the distance of the domain increase was scaled to the effective diameter D_d, the diameter of a circle with the same area as the doorway. To compensate for the reduced entrainment due to a rectangular burner adjoining a wall in the model instead of the round experimental burner, efforts are made by shifting the burner location for the modeling scenarios of fire at corner or against wall. It is found that $0.5D_d$ is the required computational domain extension to improve accuracy. The input and set up changes made to the FDS simulation allowed significant improvements to the prediction of mass flow rates for all three positions of the fire source. However, there is not much improvement for the remaining three parameters being compared: lower layer temperature, smoke layer height and neutral plane height.

INTRODUCTION

A set of full scale steady-state experiments of fire-induced flow in a single compartment was reported by Steckler *et al.* (1982). This benchmark compartment fire experiment was conducted at the National Bureau of Standards (NBS, former National Institute of Standards and Technology, NIST) in 1978. The compartment was 2.8 m by 2.8 m by 2.13 m high, with a single door of various widths, or a single window with various heights, as shown in Fig. 1. A fixed 30 cm diameter methane burner was used to generate fires with heat release rates of 31.6 kW, 62.9 kW, 105.3 kW and 158 kW. The experiment

consisted of 55 cases with different experimental configurations. The velocity and temperature profiles along the centerline of the door opening at steady state were recorded with vertical arrays of bi-directional probes and aspirated thermocouples.
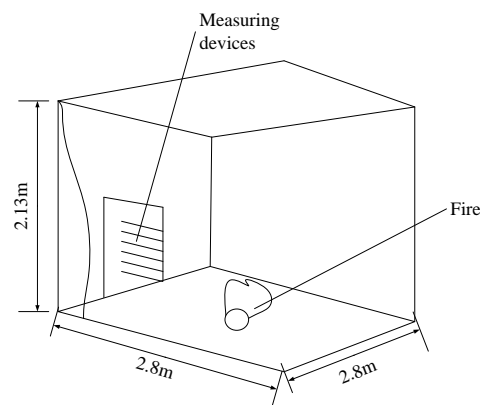

Fig. 1: Sketch of the Steckler's room fire. Source: Steckler et al., NBSIR 82-2520, 1982.

The measurement of fire-induced flow from various cases of the experiments gave very good results, and produced accurate full-scale values for the vent flow coefficient. It is reported that the mass flow balance was within 5%, velocity measurement error was estimated as up to 10 %, and temperature (aspirated probes) accurate to 2 % (Wang and Quintiere, 2009). Thus, the Steckler's experimental data (Steckler, et al., 1982) has been extensively used as a benchmark to validate various mathematical/computer fire models (Chung, et al., 2003; Cooper, 1984; Kerrison, et al., 1994; Lee, et al., 2004; McGrattan, et al., 1998; Morgan, 1986; Peacock, et al., 1993; Savilonis and Richards, 1988; Sinai; Suzuki, et al., 2003; Xue, et al., 2001; Yuen, et al., 2006).

In an earlier study (Wang and Quintiere, 2009), Steckler's experiments were modeled using FDS and compared to the predictions of a correlation derived from zone model theory. The thermal boundary wall condition was based on the experimental room construction material. The ambient temperatures over the course of the test series varied from 7 to 36 ℃, and were taken into accounts. The computation was allowed to reach a steady state. Also the vent

boundary condition was used as specified in the code. It was found that the FDS model lacked the ability to accurately predict all phenomena reported by the Steckler experiments. The fire-induced flows were off by up to a 50 % discrepancy.

This paper reports a further exploration of the FDS application to predict the data of the Steckler's experiment (Steckler, et al., 1982). In addition to stick adherence to the parameters and settings of the Steckler's experiment (Steckler, et al., 1982) and their representation in the FDS application, other considerations such as the grid size, domain boundary outside of the vent and fire location per burner shape are presented in the following section.

IMPROVEMENTS ON THE MODEL INPUTS

A finer gird resolution

Uniform grid size of 6 cm on each side was used in the previous work. It should be a natural response to check if the choice of the grid size has influenced the inaccuracy in the prediction. There are a few suggested rules to examine if the grid resolution is "fine enough". One of these, suggested in the User's Guide of FDS (McGrattan, et al., 2010b), is to evaluate the ratio of the characteristic fire diameter, D^*, to the nominal size of a mesh cell, δx. This value is thought of as the number of computational cells spanning the characteristic (not necessarily the physical) diameter of the fire. In the verification and validation study of different fire models sponsored by the US Nuclear Regulatory Commission (NRC) (Hill, et al., 2007), the value of $D^*/\delta x$ ranges from 4 to 16. According to this method, the previous uniform grid size of 6cm on each side gives a $D^*/\delta x$ value of 5.3 for the scenarios with a firepower of 62.9 kW. If the rule of the NRC rule is adopted here, the mesh size of 6 cm can be regarded coarse but acceptable.

The current study uses a uniform grid size of 5 cm ($D^*/\delta x$ = 6.3 with a fire power of a 62.9 kW), a minor improvement to the previous study. The same grid size is used in the FDS validation by NIST (McGrattan, et al., 2010a) for the prediction of the hot gas layer temperature and velocity profile at the doorway. However, in any case, the grid size is acceptable if it appears to be grid independent. Thus, an additional simulation with a smaller uniform size of 2.5cm in one of the fire scenarios was performed. The difference between the results for the two grid sizes is negligible; thus, the gird size of 5 cm is regarded as grid independent and therefore used in the all the following simulations.

A more reasonable radiative fraction

It is stated in the User's Guide of FDS (McGrattan, et al., 2010b) that the default settings for thermal radiation transport is appropriate for most FDS simulations. However, the fraction of energy released from the fire as thermal radiation, usually referred to as the radiative fraction, is by default 0.35 for a Large Eddy Simulation (LES) in FDS. Without a fundamental knowledge of combustion or further guidance in the User's Guide, an "average user" would not think of varying this parameter as one may not know the parameter could be fuel-dependent.

Tewarson (2002) tabulates in the SFPE Handbook data for chemical, convective, and radiative heats of combustion for well-ventilated fires with various fuels. These data were obtained from the measurement of steady state fires in well ventilated conditions, which resembles the Steckler experiments. In the case of the Steckler experiments, methane was used as the fuel. Thus, it is appropriate and reasonable to consider the radiative fraction for methane based on the ratio of the radiative heat over the total heat of combustion. According to the Tewarson's data, the value of the radiative heat and the chemical heat (total heat of combustion) for methane are 7.0 and 50.1 kJ/g, respectively, which gives a radiative fraction of 0.14. This value is used in the present simulations instead of the default 0.35 which was adapted in the previous study.

An extension of computational domain

In the previous study, the computational domain ended at the doorway and gives very poor results in comparison to the experimental data. By examining the pressure equations with the boundary condition at the vent, the authors in that study concluded that the exit boundary condition may not be accurate. Therefore, it was implied that the simulation discrepancy was due to error in the boundary condition. It is indeed admitted in the validation work of NIST (McGrattan, et al., 2010a) that relatively minor changes in the velocity boundary conditions at the edges and bottom of the door soffit can have a noticeable impact on the prediction of gas velocities at the vent. Although a sophisticated FDS user may choose to establish the domain of the computation away from the physical exit to avoid this possible error, as suggested in the FDS User's Guide (McGrattan, et al., 2010b), yet this change may be troublesome and misleading to an "average user".

In the present study, an attempt is made to study the effects of extending the computational domain beyond the vent, which is illustrated in Fig. 2. The potential improvement of this strategy is quantitatively assessed.
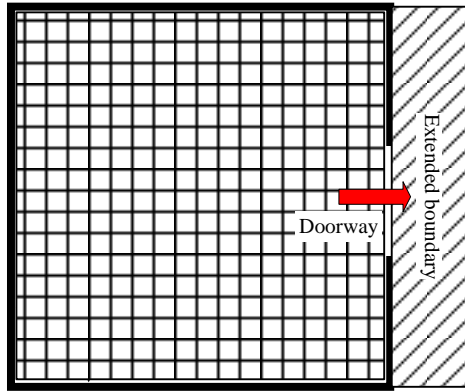
Fig. 2: Extension of computational domain in the present simulations.

In order to get a general application to different scenarios with varied door width, the distance that the domain was increased was scaled to the effective diameter, D_d of the doorway, where the effective diameter is defined as the diameter of a circle with the same area as the doorway.

Simulations of mass flow rate through the doorway with four different domain boundaries were performed: extensions of 1 m (fixed distance), $0.2D_d$, $0.33D_d$ and $0.5D_d$ from the doorway. The narrowest and widest doorway width of 0.24m and 0.99m, and a mid-sized doorway of 0.62m were used for this study. An additional simulation with the domain ending right at the doorway was also carried out as a reference. It is found from the results that there is significant improvement in the prediction of the mass flow rate when the computational domain is extended beyond the doorway. For large doorway widths, the FDS predictions are closer to the experimental data. This is possibly due to having more grid cells across the doorway and hence the flow phenomena are better resolved. In general, with the computational domain extended beyond the doorway by a distance equivalent to $0.5D_d$, the FDS predictions for mass flow rates are within 5% of the experimental data.

Hence, subsequent simulations are performed with this criterion.

A shift of fire location

Due to the restriction of rectangular grid modeling in FDS, the circular fire source could not be exactly represented. It converted to a square fire source with a similar surface area in the previous study. The square fire source was placed against the wall and hence entrainment was not possible along those sides at the wall. For the case of a circular fire source, some entrainment is still possible as a circular fire source is only in contact with the wall at a single point. As a result, the reduced entrainment may also have contributed to the discrepancy of FDS predictions in the previous study.

In the current study, an attempt is made to correct the entrainment for near wall fire sources by shifting the fire sources away from the walls. For position B and position C, where the fire source is placed at a corner and against the wall, respectively, the fire source is shifted such that the distance from each side of the fire source to the walls is similar. This is illustrated in Fig. 3. The distance is also scaled to the burner diameter, D_b in an attempt to investigate possible correlations.

From the results for position B (corner), at distances of 0.3 m ($1D_b$) to 0.7 m ($2.33D_b$) away from the wall, the FDS predictions are within 2% of the experimental data. For small doorway widths, the distance that the fire source needs to be shifted is smaller. There appears to be a linear relationship between the distance of the fire source from the wall and the mass flow rate, to the point where the predicted mass flow rate matches the experimental data. After which, the increase in mass flow rate is significantly reduced. Hence, for subsequent simulations, the fire source is placed at a distance of 0.7 m ($2.33D_b$) away from the walls. This would result in conservative predictions for the smaller doorway widths.
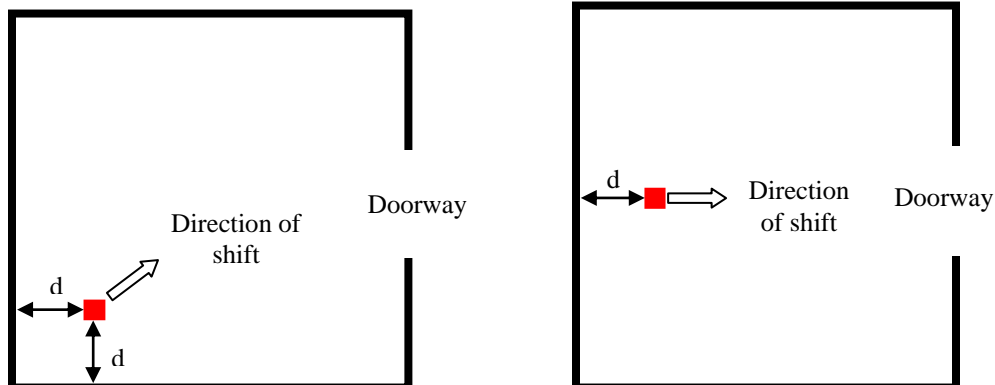

Fig. 3: Shift of fire locations in the present simulations for position B (corner) and C (against wall).

For position C (wall), at a distance of 0.5 m ($1.67D_b$) from the wall, the FDS predictions are within 1% of the experimental data. Similar to the fire source at position B, there appears to be a linear relationship between the distances of the fire source from the wall and the mass flow rate, to the point where the predicted mass flow rate matches the experimental data. For subsequent simulations, the fire source is placed at a distance of 0.5m ($1.67D_b$) away from the wall.

In an engineering perspective, a rule of thumb can be obtained that a distance of $2D_b$ away from the walls is sufficient to address the reduced entrainment in the rectangular burner settings for both the position B and C, which is proved by the simulation results within 5% of the experimental data.

It is surprising and interesting that a greater distance than expected needs to be shifted to compensate for

the loss of entrainment when a rectangular burner is simulated instead of a round one for near wall fire sources. It is usually thought that a shift of no more than $0.5D_b$ away from the wall is justified as this would be the tangent point distance for the round burner.

RESULTS AND DISCUSSIONS

Fire Source at Center (Position A)
The comparisons of the mass flow rate, neutral plane height, lower layer temperature and smoke layer height are shown in Fig. 4. The experimental data are plotted with the current and previous FDS predictions. There is a significant improvement to the prediction of mass flow rate with the average deviation from the experimental data less than 5 %. However, for the remaining three parameters, the predictions are slightly worse than the previous FDS work.
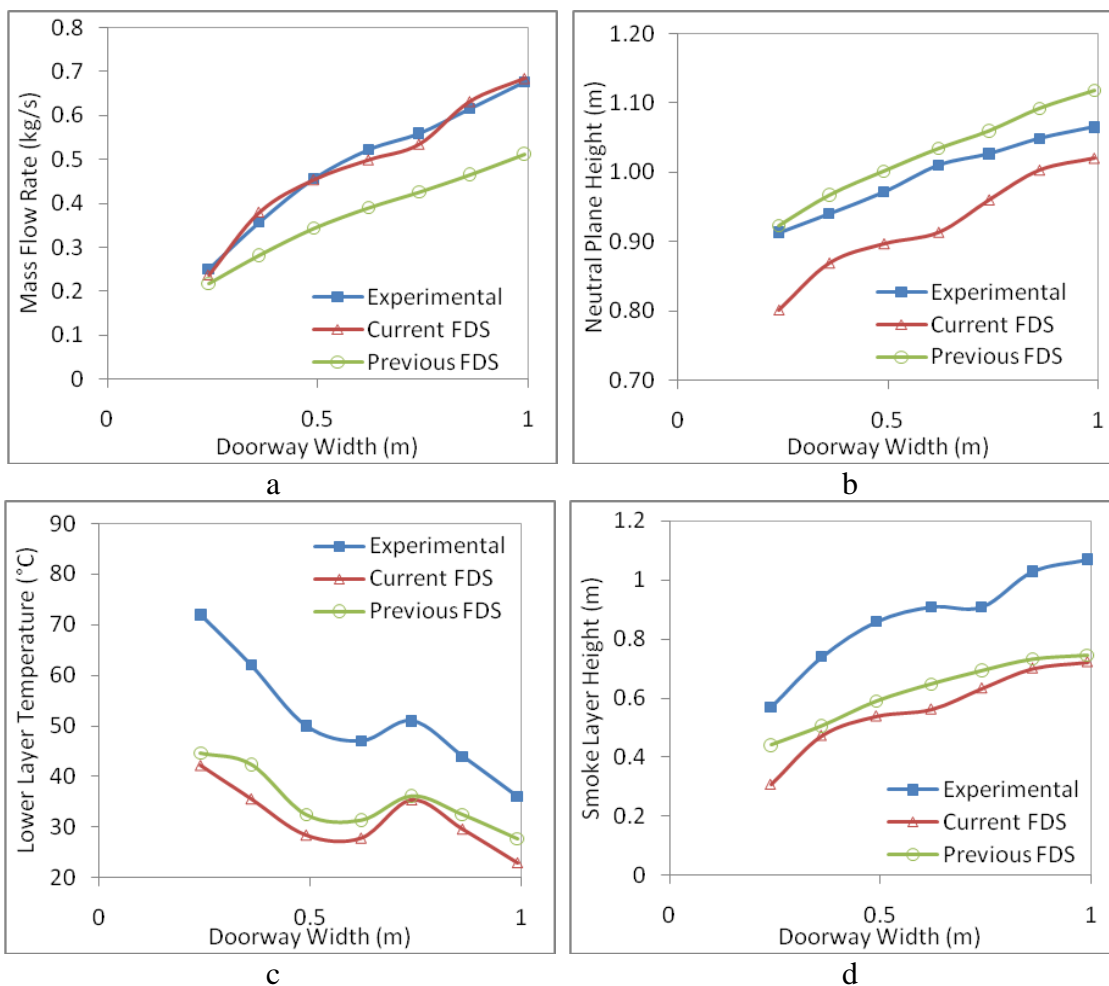

a

b

c

d

Fire Source at Corner (Position B)

With the fire source shifted 0.7 m ($2.33D_b$) away from the wall, all the FDS predictions give higher mass flow rate than the experimental data, as shown in Fig. 5. In most cases, they are within 10%, with the exception of the scenario with doorway width of 0.36 m, which is 16% higher. There is better agreement for neutral plane height, with the worse deviation of about 13%. The predictions of lower layer temperature and smoke layer height are very different from the experimental data.

Fire Source at Wall (Position C)

With the fire source shifted 0.5 m ($1.67D_b$) away from the wall, the FDS predictions for mass flow rates are in very good agreement with the experimental data, as shown in Fig. 6. Most predictions are within 4% of the experimental data, except for the scenario with doorway width of 0.36m, where the prediction is about 8.5% higher. There is reasonably good agreement for neutral plane height. However, similar to the previous case, the predictions of the other two parameters vary significantly from the experimental data.
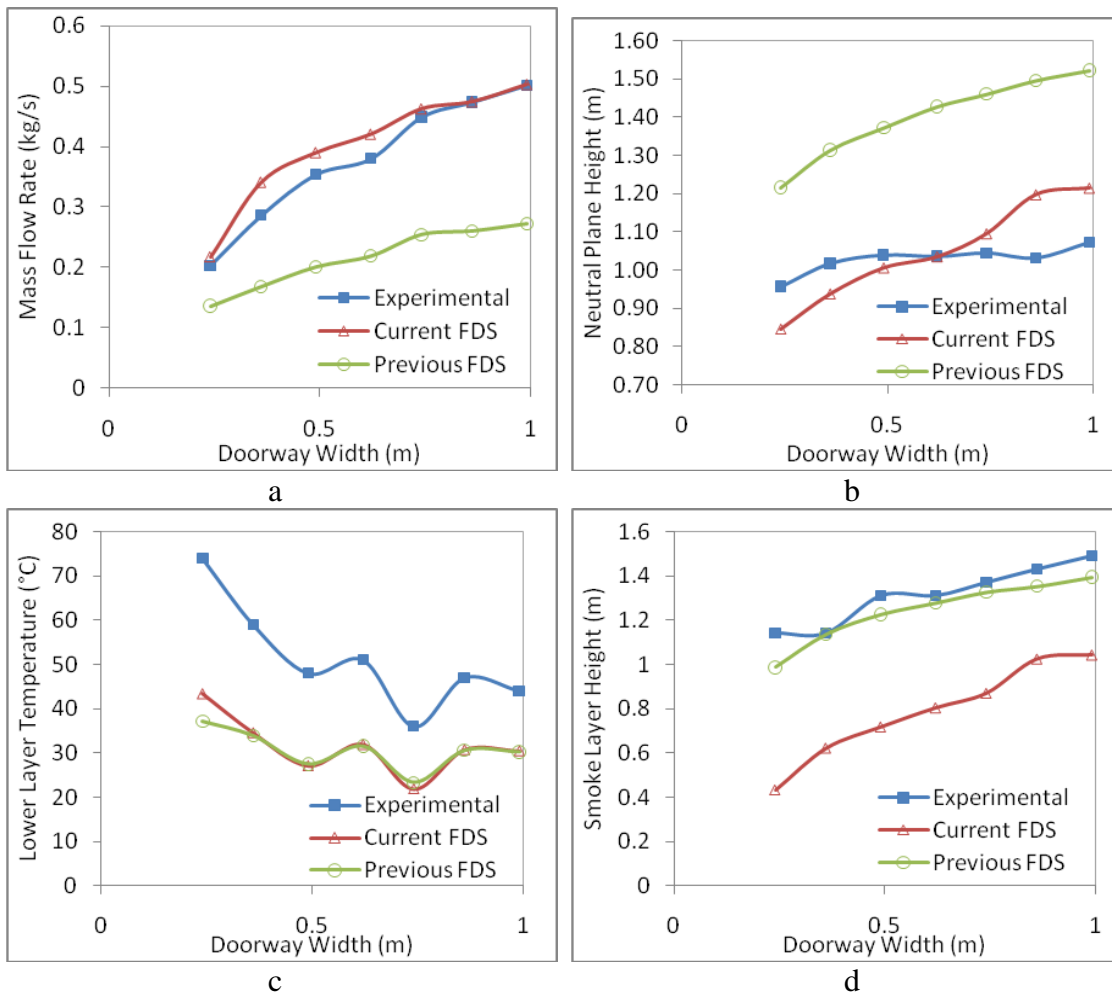

Fig. 5: Comparisons of the results from the current and the previous simulations by FDS in the presence of the experimental data for the scenarios with fire source at corner of the room. Four parameters, a. mass flow rate; b. neutral plane height; c. low layer temperature; and d. smoke layer temperature are compared with the doorway width increasing from 0.24 to 0.99m.
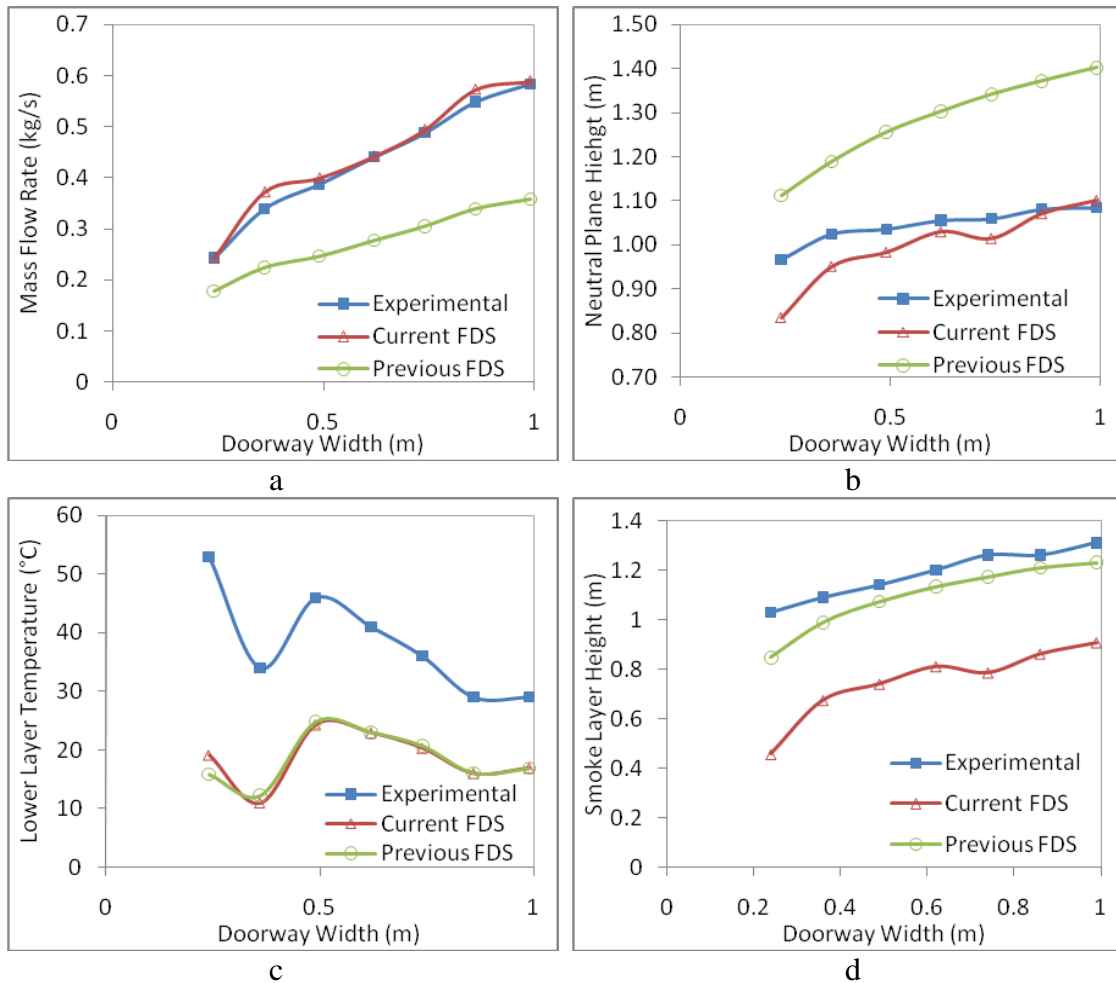
Fig. 6. Comparisons of the results from the current and the previous simulations by FDS in the presence of the experimental data for the scenarios with fire source against the wall. Four parameters, a. mass flow rate; b. neutral plane height; c. low layer temperature; and d. smoke layer temperature are compared with the doorway width increasing from 0.24 to 0.99m.

CONCLUSIONS

The improvements on model inputs made to the FDS simulation allowed significant improvements to the prediction of mass flow rates for all three positions of the fire source. It is found that the results achieve accuracy up to 96% of measured values, the error for which is within the measurement uncertainties.

Nevertheless, there is not much improvement for the remaining three parameters being compared. It is discouraging that after all of these efforts, FDS is still unable to give much better predictions of lower layer temperature, layer height and neutral plane height for this case. However, it might be understandable as these parameters are computed under a zone-model conception, and are calculated by an integral approximation in FDS (McGrattan, et al., 2010a). It is possible there is some inconsistency between these parameters computed by Steckler et al from their data and that computed in FDS. However, the observation

of the neutral plane should be distinct in the experiment and reproduced without ambiguity by FDS. For the neutral plane, FDS gives very good results for the fire locations near the wall and corner, but not the center. So overall improvement has been achieved for the flow rate, but not for all parameters.

Two rules of thumb were achieved on configuring simulations of mass flow rate through a veridical vent of a fire compartment: 1. a distance of $0.5D_d$ from the vent on the computational domain is needed to avoid the possible inaccurate boundary conditions (within 5%); and 2. for a fire located at the corner and against the wall, a shifted distance for the burner of $2D_b$ is needed to compensate the entrainment loss (within 5%).

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