MODELING THE EFFECT OF VENTILATION ON FIRE-INDUCED ENVIRONMENT IN A LARGE-SCALE RESIDENTIAL STRUCTURE

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ABSTRACT

Fire Dynamics Simulator (FDS 6.7.7) was used to simulate four gas burner fire experiments conducted in a purpose-built two-story residential structure. HVAC status (off vs. on) and door position (open vs. closed) were varied systematically as done in the experiments to understand their impact on fire-induced environment. Experimental data quantifying the airtightness of the building and flow rates from the HVAC ducts was used to set up and optimize the HVAC network. FDS qualitatively predicted the pressure development throughout the structure but under-predicted the steady-state pressures. FDS appropriately predicted the buoyancy-driven flow throughout the structure, and closed doors were found to severely inhibit gas transport. Steady-state temperatures in the closed rooms, however, were over-predicted. The prediction of steady-state temperatures in the closed rooms improved after consideration of heat loss from the duct to the ambient. FDS predicted temperature rise qualitatively well but the steady-state temperatures in FDS were under-predicted by about 10% on average.

INTRODUCTION

The U.S Fire Administration concluded that smoke inhalation alone is responsible for more fire-related deaths than thermal burns (USFA-FEMA 2021). The heating, ventilation, and air conditioning (HVAC) system is used to maintain local climate of the built environment and can participate in transport of smoke and hot combustion products through the duct network. Therefore, it is important to understand the impact of HVAC on the environment in a fire scenario experimentally to facilitate simulation of the built environment for performance-based designs (Ralph and Carvel 2018). Modeling the transport of gases through the HVAC duct network is challenging primarily due to the computational expense in computational fluid dynamics (CFD) based models of accurately describing and modeling the duct network of multi-compartment or multi-story buildings.

Previous experiments investigated the impact of airtightness of the building and the presence of an HVAC system on fire-induced pressure (Brohez and Caravita 2020; Hostikka et al. 2016) and transport of combustion products (Ghanekar et al. 2022). Hostikka et. al. found that increasing the airtightness of the built environment increases the peak over-pressures and soot production and reduces the visibility inside the environment. Open HVAC ducts act as leak paths and thereby participate in convective mass transport to different compartments via the duct network. A more detailed analysis of the ventilation pathways was completed by Ghanekar et. al. (Ghanekar et al. 2022) where a set of 18 experiments conducted in a residential structure were analyzed to quantify the effect of closed doors and HVAC system on gas transport. They concluded that the closed doors provided an effective ventilation barrier against the transport of combustion products.

A coupled-hybrid modeling approach employed in the computational fluid dynamics (CFD) based solver, Fire Dynamics Simulator (FDS), couples the CFD solver with an HVAC network model based on MELCOR (Floyd 2011). An update to the original coupled-hybrid approach was done in 2019 (Ralph, Carvel, and Floyd 2019) to allow for unsteady mass and energy transport in the FDS HVAC sub-model. Experiments conducted as a part of the OECD PRISME project (Audouin et al. 2013) were important to validate the updated HVAC network model where the mechanical ventilation from a tightly-sealed fire room was simulated to predict fire-induced pressure for a two-compartment scenario. However, further validation of the coupled-hybrid modeling approach used in FDS for the HVAC network is necessary, especially in a full-scale fire scenario. A preliminary FDS model was developed by Quiat (Quiat 2020) for the experiments conducted by Ghanekar et. al. (Ghanekar et al. 2022), but it did not evaluate the impact of ventilation on the fire-induced environment.

The purpose of this study was therefore to provide further validation of FDS by simulating a subset of experiments used in the study conducted by Ghanekar et. al. (Ghanekar et al. 2022). This paper focuses on the challenges involved in setting up such complex simulations in FDS and can hopefully serve as guidance for future modelers.

EXPERIMENTAL SETUP

Experiments were conducted in a purpose-built residential structure at Delaware County Services Training Center in Sharon Hill, PA. A total of 29 experiments were conducted using a gas burner located in the bedroom, living-room, or basement, with variation of the fire-room door position (open vs. closed) and HVAC status (off vs. on). HVAC status was either 'off' (passive – ducts open for transport) or 'on' (Cooling with a set temperature of 65 °C).

A subset of four experiments conducted with the gas burner in the basement, listed in Table 1 were selected for this specific study. These four experiments were most appropriate to study buoyancy-driven flow up the stairs onto the first-floor as well as ventilation-induced transport through the HVAC network. The test numbers shown here correspond to the numbers used in the entire test series. In these experiments, bedrooms 1 and 3 doors were always closed, and bedroom 2 door was always open. A brief description of the experimental structure, instrumentation, and HVAC network is provided here. The reader is encouraged to look for additional details in other publications (Weinschenk et al. 2022; Chaudhari, Weinschenk, and Floyd 2022).

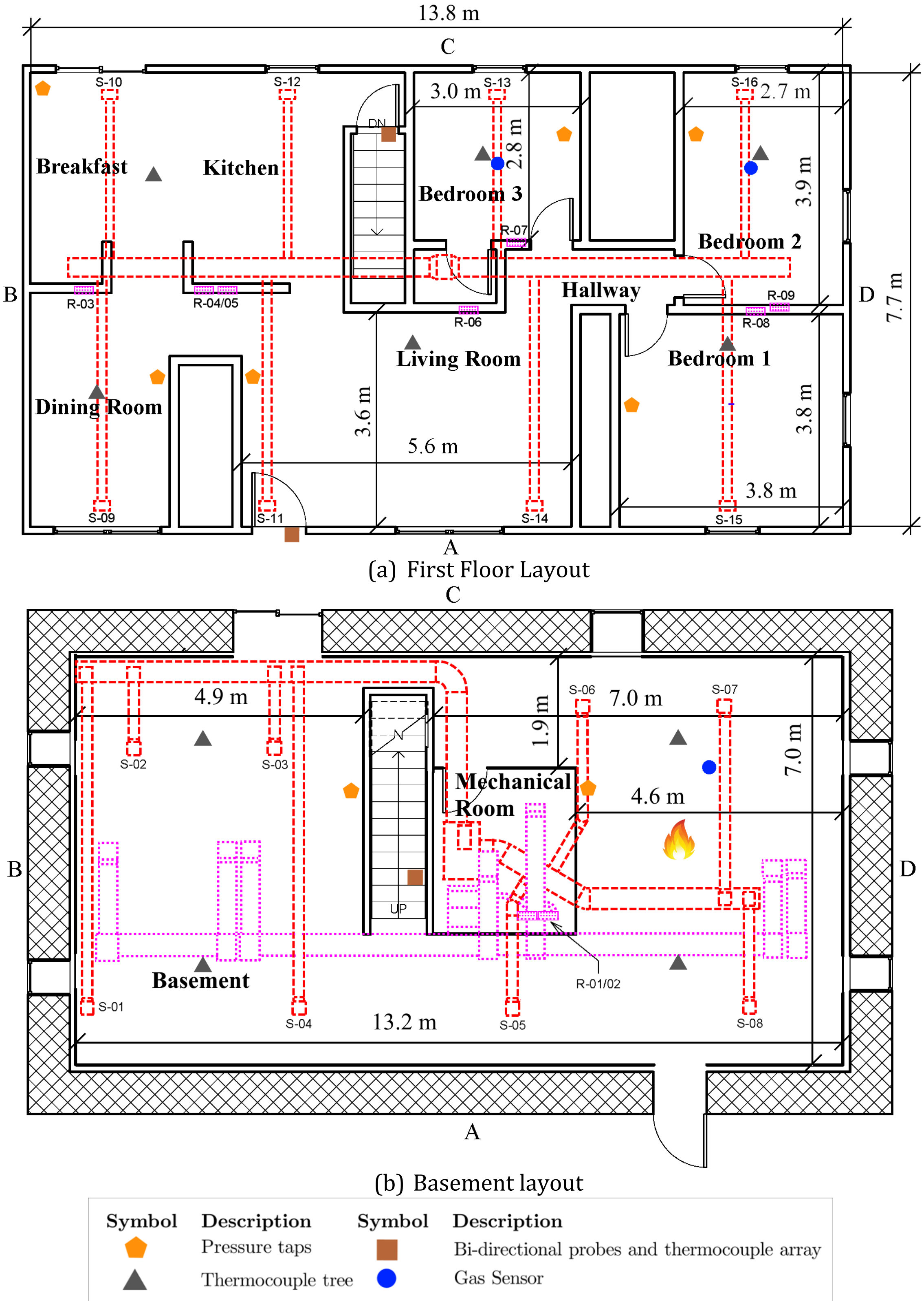
Table 1: Matrix of basement experiments studied here

Experiment label	HRR (kW)	HVAC status	Stairwell Door position	Test #
Ba1	300	Off	Open	23
Ba2	300	On	Open	24
Ba3	300	Off	Closed	25
Ba4	300	On	Closed	26

Instrumentation overview

The layout of the first floor and the basement, along with the HVAC network and instrumentation, is shown in Fig. 1. The first-floor exterior walls were comprised of cement-board, OSB, airgap and gypsum board, and the basement walls were comprised of 0.61 meter-thick concrete to simulate a below-ground-level floor. The burner used in the experiments had a surface area of 0.65 m × 0.65 m and was supplied with a fuel comprised of 92.5 vol.% propane, 5 vol.% propylene, and 2.5 vol.% butane. The heat release rate of the burner was nominally 300 kW for the basement fires. Temperatures were measured at every 0.30 m until 0.03 m below the ceiling using K-type thermocouples in an array at locations shown in Fig. 1. Gas species were measured by sampling gases at 1.22 m above the floor using Siemens OxyMat-6 paramagnetic oxygen sensors, Siemens

ULTRAMAT-23 non-dispersive infrared (NDIR) gas analyzers (for carbon dioxide), and infrared tunable diode laser absorption spectroscopy (IR-TDLAS) based sensor (for water vapor). Differential pressure was measured using pressure taps at 0.3 m, 1.22 m, and 2.13 m above the floor and 0.15 m away from the walls.



(a) First Floor Layout

(b) Basement layout

Figure 1: Layout of (a) First Floor and (b) Basement overlaid with HVAC duct network (supply network shown in red, and return network shown in pink).

All the data were collected at 1 Hz frequency including 120 seconds of baseline data prior to burner ignition. The experiments were conducted until it was no longer safe to do so and were stopped when oxygen concentration reached closer to 11.5% (LFL of propane) or when the HVAC filter clogged due to particulate matter accumulation.

HVAC network

The HVAC system included a 10.55 kW air compressor and a blower with a volumetric air flow rate capacity of up to 2400 $m^3\ h^{-1}$. The duct network was made of galvanized steel and was split into supply and return networks. The structure had a total of sixteen supply vents (labelled with prefix "S") and nine return vents (labelled with prefix "R") as seen in Fig. 1. External ventilation and leakage loss from the structure was characterized by performing leakage tests in accordance with ASTM E 779 (ASTM 2019). An equivalent leakage area was estimated as 0.137 m^2, defined as the area of a sharp-edged hole that would create the same leakage flowrate as the building would if both were subjected to a gauge pressure of 10 Pa. Flowrates from the HVAC vents without the fire were measured at each supply or return vent location before the first experiment and were verified to ensure consistency across subsequent experiments.

SIMULATION SETUP

Simulations were setup in FDS 6.7.7 with the default sub-grid turbulence model (Deardorff model) and single-step, mixing-controlled combustion of the fuel. The fuel was prescribed as the volumetric composition of 92.5% propane, 5% propylene, and 2.5% butane with a carbon monoxide yield of 0.02 and soot yield of 0.01. The geometry was created based on the available CAD drawings to replicate the experimental setup as closely as possible. The structural details of each wall used in the simulations can be found elsewhere (Chaudhari, Weinschenk, and Floyd 2022). All final simulations were conducted using a cubic mesh of cell size $\Delta x = 10\ cm$, which correspond to a $D^*/\Delta x$ ratio of 6.7.

HVAC network

The HVAC network in FDS, reliant on the specification of nodes, ducts, and vents, was designed to be as similar as possible to the actual HVAC network. Duct roughness for the galvanized steel was assumed to be 1×10^{-5} m for realistic losses. Each supply or return vent acted as a connection from the HVAC network to the FDS domain. Ducts were then laid from the vent to the adjacent intersection of another duct, creating a node in FDS. The ducts were assigned areas and lengths equivalent to that observed in the setup. The loss coefficients were initialized using the ASHRAE Fundamentals' Handbook (ASHRAE 2017) by considering the duct and the node geometries. The loss coefficients were then systematically changed until the predicted vent flowrates matched with the measured experimental cold-flow vent flowrates. The manufacturer-provided fan curve was fit with a second-order polynomial function such that flowrate at 0 Pa was 0.60 $m^3\ s^{-1}$, at 20 Pa was 0.59 $m^3\ s^{-1}$, at 100 Pa was 0.54 $m^3\ s^{-1}$, and at 600 Pa was 0 $m^3\ s^{-1}$.

The leaks from the residential structure to the ambient in the final simulations were prescribed by either using local leakage approach or zone leakage approach. The equivalent leakage area (0.137 m^2) in both approaches was distributed in proportion to the fraction of total leakage perimeter for each window/door or pressure zone, respectively. For the local leakage approach, half of the leakage area estimated for a window/door was prescribed at the top and the other half on the bottom of the window/door. For both approaches, the windows and door on the basement fire side (Side D) were sealed in the actual experiments and were therefore also simulated to be sealed. The perimeters of these openings were not considered for fractional leakage contributions.

Simulations were conducted by simulating a gas burner ramp of 1 s rise to the steady-state value of 300 kW. The objective of the study was to understand the FDS predictions of the steady-state conditions, and therefore the fire growth was not the focus of the simulations. The simulations were allowed to run until 60 s after the fuel supply to the gas burner in the experiments was shut off. This manuscript focuses on the setup of FDS simulations and preliminary results of temperature prediction. Detailed results of the simulations, including gas concentration predictions, can be found elsewhere (Chaudhari, Weinschenk, and Floyd 2022).

RESULTS

Here, the results of the process of HVAC network setup are discussed, followed by a discussion of temperature prediction and model validation results. Both zone and local leakage simulation approaches qualitatively provided reasonable pressure predictions right after burner ignition followed by slightly negative pressures in the basement and slightly positive pressures on the first floor. However, both approaches under-predicted the final steady-state pressure, but the local leakage approach provided better peak-pressure prediction away from the fire. All the simulation results discussed here were conducted using the local leakage approach.

HVAC network duct cold flowrates

The cold flowrates before and after the optimization of duct loss coefficients are shown in Fig.2. Loss coefficients initialized using the ASHRAE Fundamentals' Handbook (ASHRAE 2017) provided reasonable first approximations of cold-flow vent flowrates. Loss coefficients were optimized by increments/decrements of 0.5 units until the agreement of predicted vent flowrates with the experimental data improved. The loss coefficient of the duct connecting to a vent was increased if the flowrate was over-estimated or decreased if the flowrate was under-predicted. The impact of the changes in loss coefficients was somewhat dependent on the length and cross-sectional area of the duct, location of the node from the fan, and therefore the optimization process followed here was arbitrary. However, this optimization process could potentially be automated. Final flowrates from the supply vents after implementing the duct loss optimization have excellent agreement with the experimental data. In contrast, the predicted return flowrates are not within the uncertainty of the experimental data. This discrepancy can partly be attributed to the uncertainty of the device used for measurement of flowrates. The exact reason for higher discrepancy for the return vent flowrates is not known.

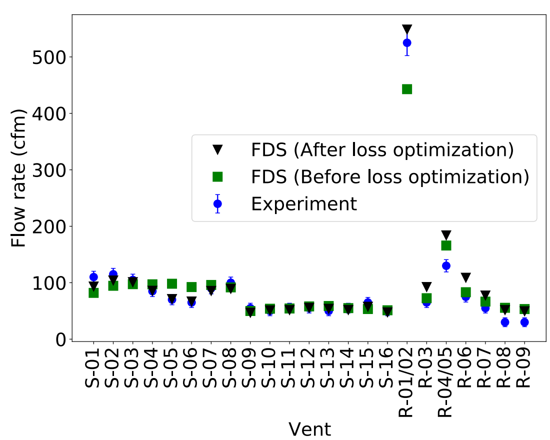
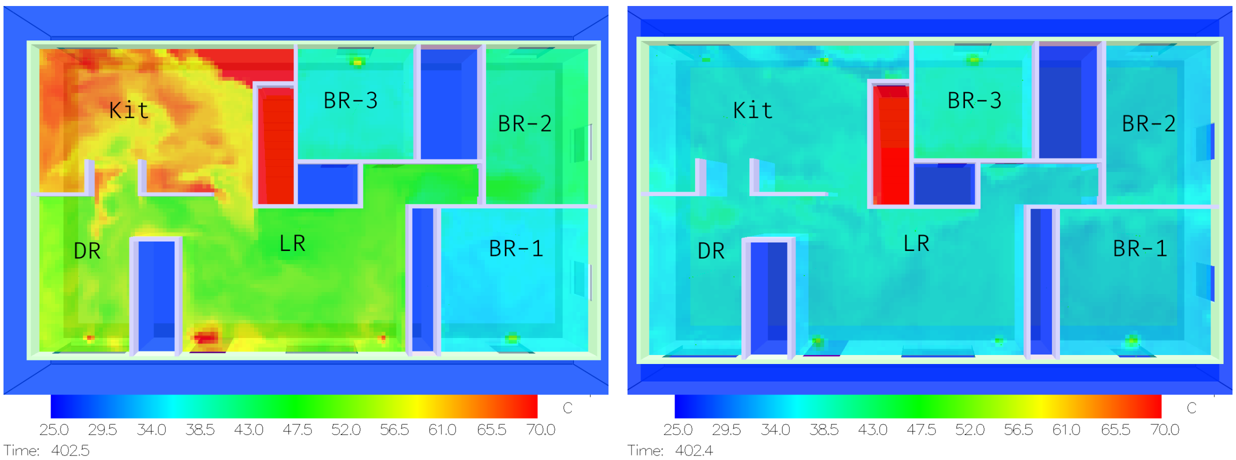


Figure 2: Cold flow-rates before and after optimization of duct loss coefficients.

Temperature distribution

The temperature distribution on the first floor at around 400 s after the burner ignition is shown in Fig. 3 for Tests Ba2 and Ba4. From this figure, it is evident that the closed stairwell door severely inhibits the ventilation pathway as indicated by the lower temperatures in the kitchen, living-room, and open bedroom (BR2). The transport of gases through the HVAC network can be visualized from the slightly higher temperature around the HVAC vents on this floor. Qualitatively, the temperatures in the closed bedroom (BR-3 and BR-1) are lower than the open bedroom (BR-2), again implying that the closed doors inhibit gas transport.



Test Ba2 simulation   Test Ba4 simulation

Figure 3: Temperature distribution on the first floor in test Ba2 (left) and test Ba4 (right). The annotations on the figures indicate the locations of the TC array in the respective rooms.

Temporal profiles

Comparison of predicted temperature profile with the experimental data for test Ba2 and Ba4 for the basement, BR-2, and BR-3 is shown below in Fig. 4. The steady-state temperature in the bottom left TC array in the basement is higher for the test Ba4 (closed stairwell door) than for test Ba2 (open stairwell door). FDS also predicts this qualitatively, but underpredicts the steady-state temperature in the basement. Temperature in the closed bedroom (BR-2) is lower when the stairwell door is closed (Test Ba4) compared to the open stairwell door (Test Ba2) case. FDS predicts that temperature in BR-2 for simulation of test Ba4 is lower than for test Ba2 but over-predicts the magnitude of temperature in BR-2 for test Ba4 simulation by about 10 °C. Similarly, temperature in the closed bedroom (BR-3), where the dominant mechanism for gas transport inside the room is through the HVAC duct, is over-predicted. The discrepancy in over-prediction of temperature in the closed rooms could be partially attributed to the lack of heat-loss considerations from the duct to the ambient. Although the duct network in the attic space was insulated, through which the duct network traversed to the supply vents, heat loss may occur for the vertical non-insulated HVAC duct which ran from the HVAC room through the bedroom 3 closet to the attic. This hypothesis was tested by including an Aircoil device in the duct that fed to bedroom 3 to continuously extract heat at a fixed rate. An estimated rate of 1.5 kW through duct (perimeter ~1 m) length of about 3 m to 4 m provided temperature rise comparable to the experimental data. Details of the implementation of the aircoil device and associated results can be found elsewhere (Chaudhari, Weinschenk, and Floyd 2022).

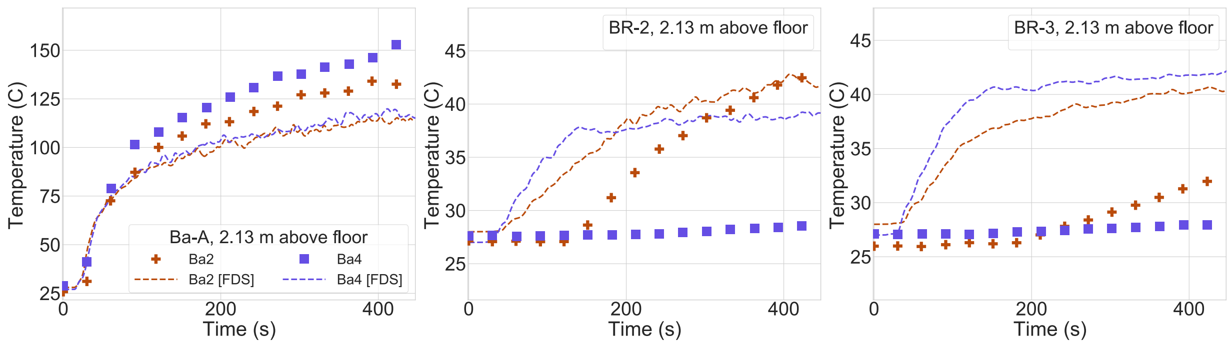


Figure 4: Predicted temperature profile in basement, open bedroom (BR-2), and closed bedroom (BR-4) compared with experimental data for test Ba2 and Ba4.

Model validation

Temperature rise, measured as the difference between the temperature before ignition for each thermocouple and the average temperature during the 60 s before the burner fuel shut-off, is compared for predicted and experimental data in the form of a scatter plot for each thermocouple for all the four basement fire experiments. The relative experimental uncertainty indicates the total expanded uncertainty (coverage factor of 2) for the thermocouples. The scatter in the predicted data is quantified by the relative model uncertainty. The model bias factor of 1 indicates the exact match with experimental data (ideal), and above or below 1 indicates over- or under-prediction, respectively. The solid red line passes through the distribution mean and indicates the bias factor multiplied by the expectation line (solid black line is a perfect match).

Overall, the steady-state temperatures predicted for the four basement fires are under-predicted, as indicated by the model bias factor of 0.9. The model relative uncertainty is 0.33, indicating that the temperature change was under-predicted by 10% $\pm$ 33% on average. Comparison of gas species concentrations (oxygen, water vapor, and carbon dioxide) can be found elsewhere (Chaudhari, Weinschenk, and Floyd 2022).

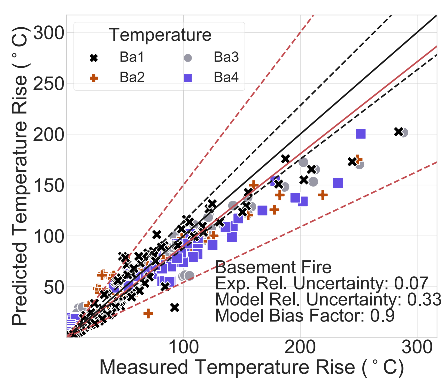


Figure 5: Validation result summary for temperature predictions.

DISCUSSION

This study shows that FDS provided reasonable predictions of the fire dynamics inside a two-story residential structure with an HVAC network. It is important to discuss the challenges encountered as well as important information found to be useful for simulation setup during this study. Setting up simulations for a large-scale setup is challenging and requires careful characterization of the scenario. Three parameters were found to be important for correctly predicting the pressure development and dynamics of the fire-induced environment in compartments equipped with an HVAC network - loss coefficients through the HVAC duct network, vent flowrates, and the fan curve.

Apart from this, the HVAC filter could potentially be important to accurately capture filter clogging. The airtightness of the building was also found to be important for describing the local or zone leakages from the compartment. The significance of some of these parameters was also discussed by earlier works (Janardhan and Hostikka 2017; Wahlqvist and Van Hees 2013). These parameters can be described by using experimental data and utilized in the simulation setup by following the practical guidance described below in Fig. 6.

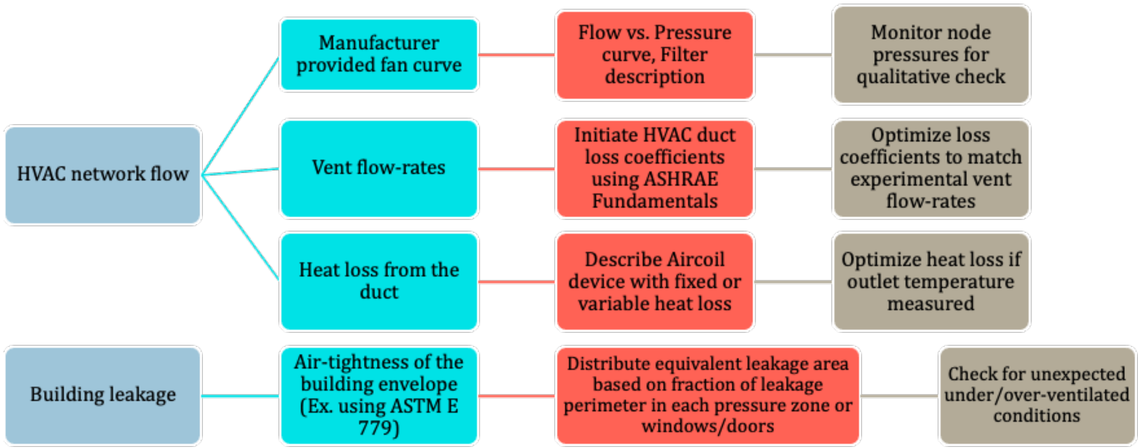


Figure 6: Practical guidance for simulating HVAC network and building leakages in FDS. Leftmost squares indicate the desired mechanism to be simulated in FDS, teal squares to the right highlight the phenomena that need to be characterized experimentally or empirically, red squares indicate the way the phenomena can be incorporated in FDS, and the rightmost grey squares indicate necessary checks/optimizations to verify the model.

Apart from characterization of the HVAC network, variables such as equivalent leakage area, Heat Release Rate (HRR), carbon monoxide and soot yield, and properties of wall components, could add to some uncertainty of the model described here. Sensitivity analysis of these parameters could be performed to better understand the significance of each parameter. Improving the accuracy of experimental measurements (such as HRR) and including additional measurements could help in improving simulations. Additional measurements of wall temperatures at a few locations, for example, could help initialize the simulations and explore the heat loss via conduction predicted through the walls.

CONCLUSIONS

Gas burner experiments conducted in a purpose-built two-story residential house equipped with an HVAC system were successfully simulated using FDS 6.7.7. Experimental data quantifying the airtightness of the building and cold-flow vent flowrates assisted in building and optimizing an HVAC network. FDS simulations replicating the experimental scenarios appropriately predicted the pressure development when compared with the experimental data. FDS predicted the impact of closed doors and HVAC ventilation pathways reasonably well compared to experimental data. However, the prediction of temperature in closed rooms away from the fire, where the gas transport primarily occurred through the HVAC network, was over-predicted. Consideration of heat loss from the HVAC duct to the ambient, a phenomenon not modeled directly in the HVAC sub-model, improved the temperature predictions in the closed rooms. Thus, in future simulations, heat loss from the duct to the ambient from non-insulated duct sections should be considered in FDS for improved predictions. Steady-state temperatures were under-predicted by approximately 10%, on average. Uncertainty in equivalent leakage areas, HRR, and properties of wall components, could explain some of the discrepancies in the model predictions, and sensitivity analysis can be performed to identify the most influential parameters.

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