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# Comparative study of FireFOAM and FDS in reduced scale well-ventilated compartment fire scenarios

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**Abstract.** The paper focuses on large eddy simulations of reduced scale well-ventilated compartment fire scenarios and aims to evaluate the performance of the current modelling capabilities of FireFOAM and FDS in terms of simulating the fire dynamics and smoke transport encountered in such circumstances. To this purpose, a qualitative and quantitative comparison of the two CFD codes as a function of grid size, considering different fire sizes under the same ventilation flow rate, is reported in the study. There are obvious differences between the predictions of the two CFD codes. More specifically, FireFOAM predicts better the fire plume dynamics with significantly lower grid dependency. On the other hand, FDS predicts slightly better the smoke layer temperatures for all the grid sizes considered. The observed deviations between the codes are mainly attributed to differences in the modelling options which affect the predicted flame temperature and structure, the radiation emission, as well as the predicted flow rates of fresh air inside the enclosure from the admission branch.

## 1 Introduction

Fires pose a serious risk in modern society, threatening both human lives and property, especially with the widespread use of combustible materials in buildings. More specifically, the study of compartment fires has received much attention in the past due to the great dangers associated with them (e.g., involving vitiated conditions, flame spread). Within this framework, the use of Computational Fluid Dynamics (CFD) for modelling fires has, nowadays, become an integral part of fire safety science and engineering. CFD-based modelling applied to fire research has made significant progress over the past decades [1]. Many of the physical processes that control fire dynamics can now be modelled using CFD with suitable accuracy, e.g., the turbulent flow, the pressure dynamics, the combustion process and the thermal radiation transport. Overall, there is a need for numerical models that can accurately simulate a plethora of fire-related scenarios (e.g., design of smoke control systems, fire detection, flame spread, fire suppression) over a wide range of time and length scales. A deeper understanding of the capabilities and limitations of the current CFD models is essential for providing the fire safety engineers with the appropriate guidelines to carefully design and perform their analysis when evaluating fire safety systems in buildings and industrial facilities. Within this context, there are still a number of remaining challenges that need to be overcome for CFD to reach its full potential for fire applications.



The main objective of the paper is to evaluate the performance and predictive capabilities of two of the most widely used CFD codes (i.e., FireFOAM and FDS) when it comes to simulating the fire dynamics in well-ventilated compartment scenarios with different fuel flow rates and mechanical smoke extraction (with natural air supply through an inlet branch). Focusing on range of grid sizes where flames can range from being fairly well-resolved to under-resolved, the paper will examine whether the CFD codes can accurately predict the flame and smoke temperatures (i.e., near the fire source and at the ceiling level) inside the enclosure. In addition, a qualitative comparison and analysis of the flame characteristics predicted by the two CFD codes will be made.

## 2 Modelling

Two different CFD codes are considered for the Large Eddy Simulations (LES) presented in the paper; FireFOAM [2], developed by FM Global, and the Fire Dynamics Simulator (FDS) [3], developed by the National Institute of Standards and Technology (NIST). Both CFD codes have been developed to simulate fire-related scenarios, e.g., involving smoke and heat transport, fire plumes, liquid pool fires, compartment fires, fire extinction, fire suppression, water sprays and flame spread among others. An overview of the main governing equations considered in FireFOAM and FDS can be found in [4] and [6], respectively. An outline of the main sub-models used in the numerical simulations with the two CFD codes is presented in Table 1. It should be noted that the intention is to evaluate how each code performs independently and not to have a direct comparison, hence, there was no attempt to use exactly the same sub-models. However, the same geometry and boundary conditions (i.e., considering 1D heat transfer through the enclosure walls and neglecting any leakages) were used in both codes. With FDS, the default models in LES mode were employed [3]. With FireFOAM the default model settings previously reported in [5] have been applied. The running and averaging times were 90 s and 60 s, respectively.

Table 1: Overview of the FireFOAM and FDS setup used in the simulations.

|                 | modified FireFOAM v1912  | FDS 6.9.1  |
|-----------------|--|--|
| Turbulence      | Dynamic Smagorinsky<br>$\mu_{sgs} = \max(\bar{\rho}(c_s \Delta)^2  \tilde{S} , -\mu)$<br>$k_{sgs} = c_I \Delta^2  \tilde{S} ^2$<br>$\epsilon_{sgs} = \frac{c_\epsilon k_{sgs}^{3/2}}{\Delta}$<br>$c_s, c_I, c_\epsilon, Pr_t$ : dynamic model  | Modified Deardorff<br>$\mu_{sgs} = \bar{\rho} C_v \Delta \sqrt{k_{sgs}}$<br>$k_{sgs} = \frac{1}{2} ((\bar{u} - \hat{u})^2 + (\bar{v} - \hat{v})^2 + (\bar{w} - \hat{w})^2)$<br>$C_v = 0.1, Pr_t = 0.5, Sc_t = 0.5$   |
| Combustion      | Eddy Dissipation Model (EDM)<br>$\bar{\omega}_F''' = -\bar{\rho} \frac{\min(\tilde{Y}_F, \tilde{Y}_{O_2}/s)}{\tau_{mix}}$<br>$\tau_{mix} = \min(\tau_{lam}, \tau_{turb})$<br>$\tau_{lam} = \frac{\Delta^2}{\alpha}$<br>$\tau_{turb} = \sqrt{\frac{\Delta}{(2k_{sgs}/3)^{1/2}} \left(\frac{\nu}{\epsilon_{sgs}}\right)^{1/2}}$ [5]  | Eddy Dissipation Model (EDM)<br>$\bar{\omega}_F''' = -\bar{\rho} \frac{\min(\tilde{Y}_F, \tilde{Y}_{O_2}/s)}{\tau_{mix}}$<br>$\tau_{mix} = \min(\tau_d, \tau_u, \tau_g)$<br>$\tau_d = \frac{\Delta^2}{D_F}$<br>$\tau_u = \frac{0.4\Delta}{\sqrt{(2/3)k_{sgs}}}, \tau_g = \sqrt{\frac{2\Delta}{g}}$ |
| Radiation       | Finite Volume Method (FVM)<br>Weighted Sum of Gray Gases (WSGG)<br>$\nabla \cdot \bar{q}_r'' = 4\sigma\kappa\tilde{T}^4 \left(1 + 6C_{TRI} \frac{\tilde{T}''^2}{\tilde{T}^2}\right) + E\bar{Q}_c''' - \kappa G$<br>$\kappa = -\frac{\ln(1-\epsilon)}{L} + C_{soot} f_v T$<br>$E = \max\left(\chi_r - \frac{\iiint_V (\text{emission} - \text{absorption}) dV}{\iiint_V \bar{Q}_c''' dV}, 0\right)$<br>$C_{TRI} = 2, C_{soot} = 1862 \text{ m}^{-1} \text{ K}^{-1}$ | Finite Volume Method (FVM)<br>Gray gas<br>$\nabla \cdot \bar{q}_r'' = \kappa(4\sigma C\tilde{T}^4 - G)$<br>$\kappa = \sum_i \min(\kappa_{i,Planck}, \kappa_{i,eff})$<br>$C = \frac{\sum(\chi_r \bar{q}_r''' + \kappa G)V}{\sum(4\kappa\sigma\tilde{T}^4)V}$  |
| Soot            | Prescribed soot yield ( $y_s = 0.024$ )  | Prescribed soot yield ( $y_s = 0.024$ )  |
| Convection      | Resolved by the grid   | Empirical model based on $Nu$  |
| Near-wall model | $\mu_{sgs}$ : dynamic model, $U$ : slip bc   | $\mu_{sgs}$ : WALE, $U$ : 'log law' wall model   |
| Schemes         | 2 <sup>nd</sup> order  | 2 <sup>nd</sup> order  |

### 3 Experimental case

Experiments performed by IRSN in NYX [7], a reduced scaled enclosure, are considered here. For brevity, only a limited number of experiments is considered for CFD model validation. The internal dimensions of the enclosure are (L x W x H) 1.5 m x 1.25 m x 1 m with the floor, side walls and ceiling consisting of a 23 mm thick layer of calcium silicate ( $\rho = 770 \text{ kg/m}^3$ ,  $k = 0.185 \text{ W/m/K}$ ,  $c_p = 970 \text{ J/kg/K}$ ). A square  $\text{C}_3\text{H}_8$  burner (i.e., 180 mm x 180 mm) with three fuel flow rates (i.e., 0.1 g/s, 0.2 g/s, 0.3 g/s), positioned in the center of the enclosure, is used as fire source. The radiative fractions,  $\chi_r$ , for the 0.1 g/s, 0.2 g/s and 0.3 g/s fire sources, measured in free-burn conditions, are on the order of 0.17, 0.21 and 0.23, respectively. Both the admission and extraction lines used for ventilation are positioned at the top of the enclosure. The admission line is open allowing for fresh air to enter the enclosure while the extraction line is connected to a fan, equipped with a variable speed drive, with an extraction rate of  $50 \text{ m}^3/\text{h}$  (i.e., value without fire). The extraction rates during steady-state conditions (i.e., values with fire) are higher and on the order of  $60 \text{ m}^3/\text{h}$ ,  $65 \text{ m}^3/\text{h}$  and  $75 \text{ m}^3/\text{h}$  for fuel flow rates of 0.1 g/s, 0.2 g/s and 0.3 g/s, respectively. The gas temperature above the fire and at other locations inside the enclosure is measured by 0.5 mm K type thermocouple trees. A schematic of the experimental setup, along with the position of the instrumentation, is presented in Figure 1.

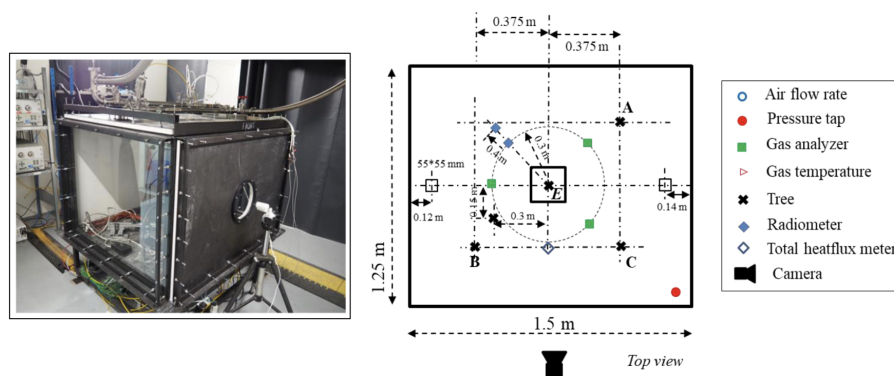


Figure 1: Schematic of the NYX facility and the instrumentation position. Figure reproduced from [7].

### 4 Results

A first qualitative overview of the simulations with FireFOAM and FDS, illustrating the average gas temperature and axial velocity on a 2D slice across the center of the burner with the finest grid size (i.e., 1 cm) and for different fuel flow rates, is presented in Figures 2 and 3, respectively. The considered grid resolution results in 18 cells across the burner diameter which is sufficient to resolve fairly well the fire plume dynamics. On the other hand, there is only reasonable resolution of the flow field inside the admission/extraction lines given the only 6 cells across the pipe diameters. Overall, consistently higher temperatures are predicted with FDS inside the enclosure, regardless of the fuel flow rate considered in the simulations. Some noticeable flame tilting towards the admission side, due to the incoming fresh air on this side of the enclosure, is predicted by both codes but the effect is more pronounced in the case of FireFOAM. This effect results in differences in the predicted centerline flame temperatures presented later in the paper. In general, the predicted temperatures in the flame region (i.e., near the burner surface) appear to be consistently higher with FDS, particularly for the lowest fuel flow rates, which is attributed to the differences in the modelling options considered in the two codes. Some oscillations are more distinctly evident with FDS at the position near the exit of the extraction branch. In the case of FireFOAM, the prescribed boundary condition for velocity at the walls (e.g., no slip versus slip) had a noticeable impact on the flame dynamics as well as on the resulting compartment temperatures and admission flow rates (results not shown here). This is a point of attention that will be investigated further in the future. The predicted radiative fractions from the FDS simulations were significantly higher (exact values are reported later) than those of FireFOAM, for all the scenarios. This higher emission is consistent and could also partially explain the higher compartment temperatures obtained with FDS. It is worth noting that the heat transfer through the enclosure walls was not correctly captured by the simulations with both codes (i.e., running time of 90 s) since the duration of the experiments was significantly longer (i.e., more than 1200 s) than what could be simulated within a reasonable amount of time.

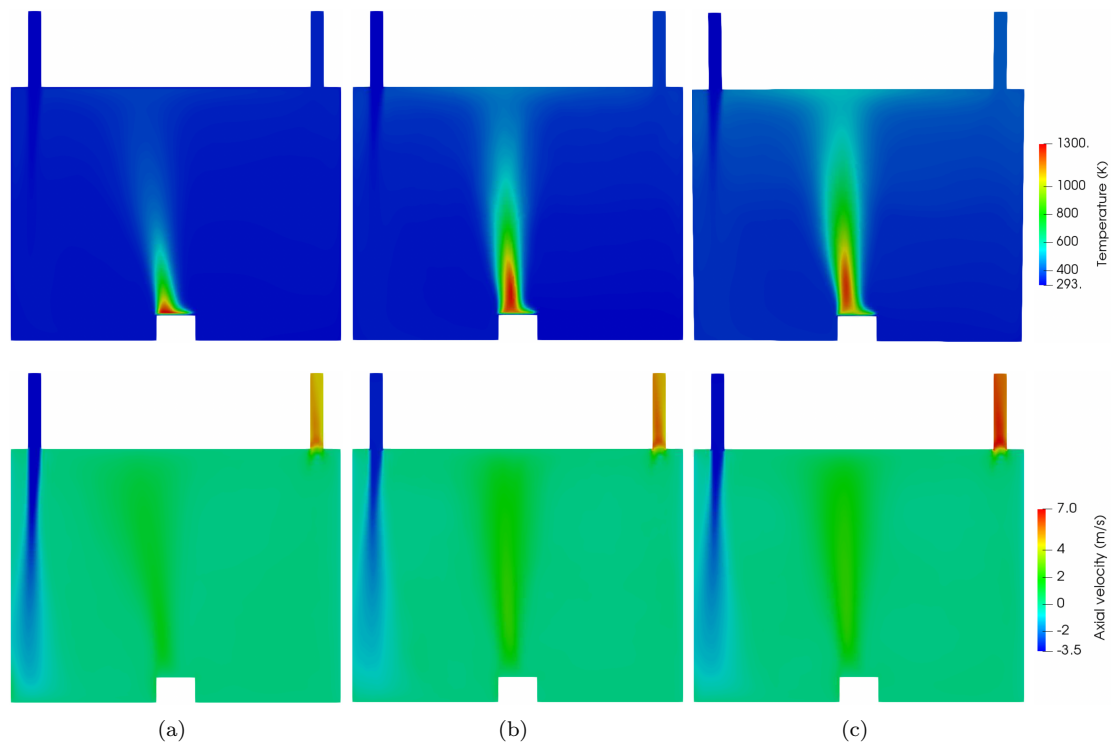


Figure 2: 2D slice of the average gas temperature (top) and axial velocity (bottom) with FireFOAM for a grid size of 1 cm and a fuel flow rate of (a) 0.1 g/s, (b) 0.2 g/s and (c) 0.3 g/s.

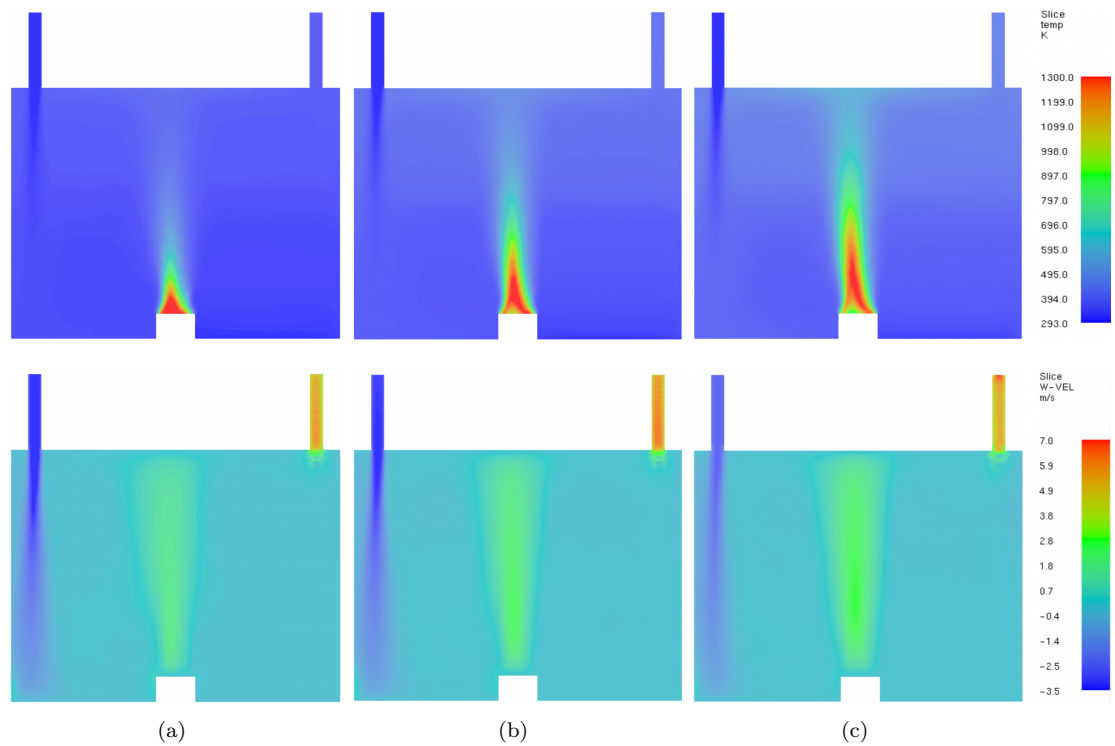


Figure 3: 2D slice of the average gas temperature (top) and axial velocity (bottom) with FDS for a grid size of 1 cm and a fuel flow rate of (a) 0.1 g/s, (b) 0.2 g/s and (c) 0.3 g/s.

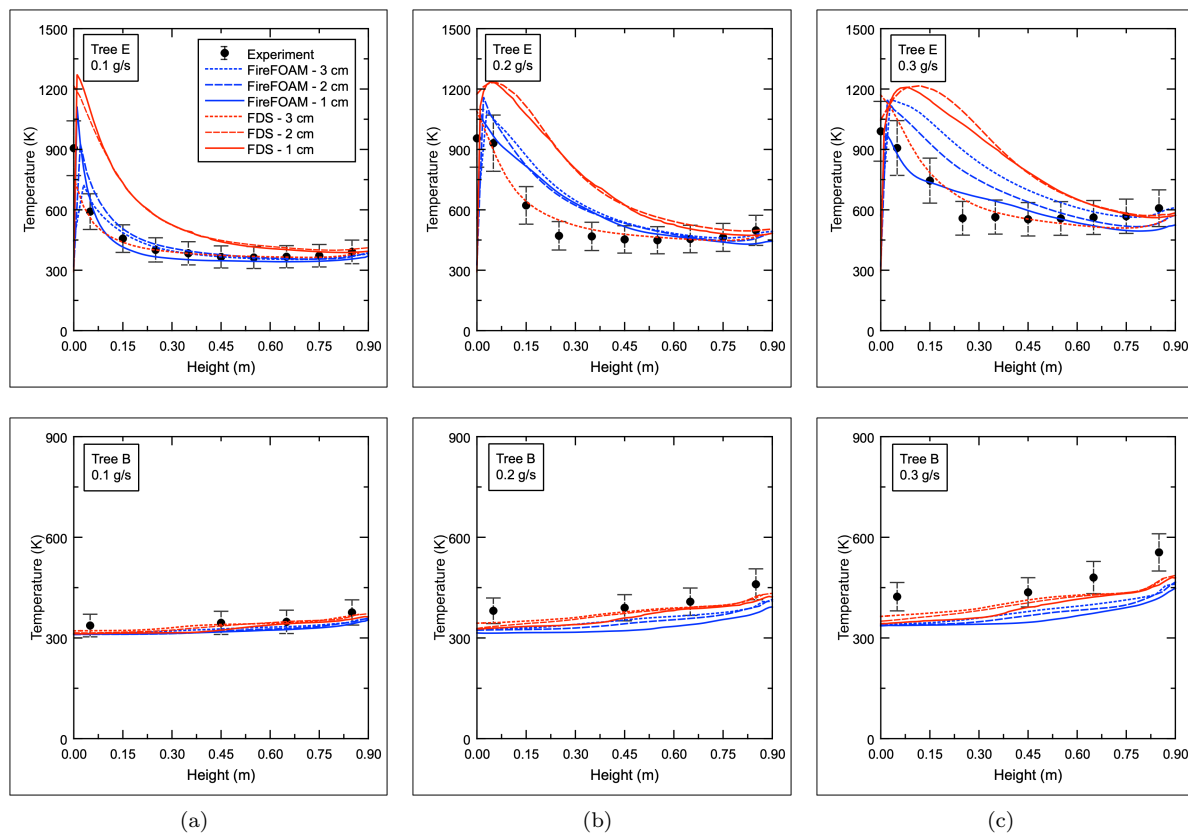


Figure 4: Average temperature with FireFOAM and FDS at thermocouple tree E (top) and B (bottom) for a fuel flow rate of (a) 0.1 g/s, (b) 0.2 g/s and (b) 0.3 g/s.

A more quantitative comparison between the predictions of FireFOAM and FDS is illustrated in Figure 4 presenting the temperatures at thermocouple tree E (i.e., indicative of the centerline flame temperature above the burner) and B (i.e., indicative of the temperature variation along the enclosure height). A 15% uncertainty (error bars) has been considered in the experimental measurements. Overall, the centerline temperatures (Tree E) are better predicted with FireFOAM and exhibit a reasonable grid dependency, particularly near the burner surface for the smallest fuel flow rate (as expected considering the  $D^*$  criterion). When compared to the experimental data, some discrepancies for the highest fuel flow rates are evident and the predicted maximum flame temperature is decreasing, due to better grid resolution and the fire becoming more turbulent. On the other hand, the FDS predictions reach grid independency for grid sizes of 1-2 cm but differ significantly when compared against the FDS predictions on the coarsest grid size (3 cm). In this case, the former predict a higher centreline temperature, compared to FireFOAM and the experiments, along the height of the enclosure (in line with what was previously observed qualitatively in Figure 3). The predicted temperatures along the height of the enclosure (Tree B) are in line with what was previously shown in Figures 2 and 3. The FDS predictions are consistently slightly higher than those of FireFOAM and are, in most cases, close to the experiments. In general, the discrepancies of the predictions with both codes increase with the fuel flow rate resulting in maximum deviations of up to 100 K for the 0.3 g/s case. It is worth noting that the same extraction flow rate is applied for both codes and that the admission line is open for fresh air to be entrained inside the enclosure. The predicted admission flow rates ( $\text{m}^3/\text{h}$ ) for different fuel flow rates with the two codes are reported in Table 2. The range of values reported is due to the influence of the grid size in the simulations. Overall, given the uncertainties, the CFD predictions are within a reasonable degree of accuracy from the experimental values (i.e.,  $\pm 10\%$ ). However, there are significant differences in the average predicted radiative fractions between FireFOAM (i.e., 0.17, 0.21, 0.23) and FDS (i.e., 0.27, 0.35, 0.41) for all the three test cases considered. The values predicted with FireFOAM are the ones prescribed, based on the available experimental data from free-burn experiments using the same burner, while the predicted

values with FDS are significantly higher (i.e., 60 - 80% depending on the case). The complex interaction between the different modelling options employed in each CFD code in this case does not make a direct comparison between FireFOAM and FDS straightforward. Eventually, the enclosure reaches a slightly different steady-state condition with each code, which is dependent on the predicted fire plume dynamics and the ventilation characteristics at the admission and the extraction lines. Further model validation, considering different ventilation flow rates (i.e., well-ventilated and under-ventilated cases), is required to further evaluate the predictive capabilities of the two CFD codes in the future.

Table 2: Comparison of predicted admission flow rates ( $\text{m}^3/\text{h}$ ) for various fuel flow rates.

|                   | 0.1 g/s | 0.2 g/s | 0.3 g/s |
|-------------------|---------|---------|---------|
| <b>FireFOAM</b>   | 45 - 48 | 39 - 43 | 40 - 44 |
| <b>FDS</b>        | 45 - 47 | 42 - 43 | 45 - 46 |
| <b>Experiment</b> | 45      | 43      | 41      |
| (meas. + leak.)   | (41+4)  | (39+4)  | (37+4)  |

## 5 Conclusions

The study evaluated the predictive capabilities of FireFOAM and FDS in simulating compartment fire scenarios using large eddy simulations. For this reason, experiments performed by IRSN on a reduced scaled well-ventilated enclosure with mechanical ventilation were considered. Overall, FireFOAM's predictions of the fire plume dynamics were closer to the experimental measurements while FDS predicted slightly better the smoke layer temperatures across different grid sizes. The resulting admission flow rates were comparable for both codes ( $\pm 10\%$  of the experimental values) but significant differences (i.e., 60 - 80% depending on the case) were evident in the predicted radiative fractions. Even though both codes over-predicted the centreline flame temperatures this did not have a significantly negative effect on the smoke layer temperature predictions. The CFD study illustrated the important coupling between fire plume dynamics inside the compartment and the ventilation characteristics when a mechanical ventilation system is in place and how they can be influenced by the modelling options employed in each CFD code. Within this context, the importance of the boundary conditions at the wall surfaces as well as of the transient conjugated heat transfer should also be further examined in the future.

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