CFD Analysis of Choices in the Design of Smoke Extraction Duct Systems (SEDS) for the Smoke Removal from a Compartment Fire

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Abstract

Large Eddy Simulations (LES) of smoke extraction duct system (SEDS) in single compartments of different volumes (i.e., 128 m^3, 512 m^3 and 2400 m^3) with FDS 6.5.3 are presented. The required grid resolution for accurate flow inside the duct systems is discussed and the influence of different SEDS design parameters (i.e., shape and position of duct system, number and position of extraction openings) on the smoke extraction efficiency of the system is analysed. The extraction rates applied to the SEDS are determined a-priori based on simplified calculations with these estimates compared against the predicted CFD results (i.e., in terms of predicted smoke free heights inside the compartments). Overall, the numerical predictions are satisfactory (i.e., within less than 5% errors) in most of the scenarios considered, apart from the 2400 m^3 compartments, where the smoke free heights are 20% lower than expected. The analysis of the numerical simulation results reveals some important aspects, including that the use of multiple extraction openings is not efficient, in terms of smoke extraction, in the same duct of the same compartment and that the local velocities, at the level of the extraction openings, can potentially exceed the maximum allowed design values. Among the SEDS design parameters, the position and shape of the duct (i.e., rectangular or flat) as well as the position of the extraction opening(s) do not have a significant influence in terms of predicted smoke free heights.

Keywords: smoke extraction, duct system, single compartment, FDS, LES

1 Introduction

Smoke management [1] inside buildings is essential for enhancing life safety, preventing asphyxiation of humans and increasing the visibility for people evacuating and for fire brigades or rescue teams accessing the fire. Smoke extraction duct systems (SEDS) are often used in utilitarian buildings. A typical environment for their application is (underground) car parks, airports, (large) production halls and storage areas. These can be assessed through modelling of such systems with the use of Computational Fluid Dynamics (CFD). The use of CFD is considered to be of great importance for modelling such scenarios for numerous reasons. First, it can provide a useful insight of the physics involved in a large number of different scenarios, also involving SEDS, which would not always be feasible through conducting experiments (i.e., in terms of both cost and execution time). Even though not always feasible to validate experimentally, the application of CFD can provide qualitative guidelines that could be useful for the design of SEDS. Furthermore, numerical simulations can provide a vast amount of flow field data for analysis purposes that would be impossible to obtain experimentally. The application of CFD, as opposed to the use of simplified models and correlations, can help towards a more accurate modelling of smoke transport [2] in complex geometries as well as towards designing more efficient and cost-effective SEDS. The advantage of CFD is that it can be applied to a wide range of scenarios where simplified models would either not be accurate and/or not fully applicable.

The paper focuses on contributing towards addressing the knowledge gap of detailed scientific studies on SEDS performance and design methods, at the level of the building by providing a proof-of-concept. The main objective of this work, relating to CFD modelling of SEDS in single compartments (i.e., office type of occupancy) with Large Eddy Simulations (LES), is to study the effect of various SEDS design parameters in order to determine the ideal design and the compromises on the performance when deviating from it. The choice of the different SEDS design parameters and their influence, when it comes to smoke extraction from single compartments, is analysed. In addition, a simplified method for calculating the necessary smoke extraction rate to achieve a pre-determined tenability criterion is presented. Comparisons between these simplified calculations and the results obtained from the CFD calculations is made in order to access the accuracy of the former. The numerical work aims to deliver a proof of concept for the design of an effective system of smoke ducts in buildings incorporated in an approach using Fire Safety Engineering (FSE).

To the authors' best knowledge, there are no similar CFD studies in the literature where a sensitivity study on the influence of different SEDS parameters has been investigated to this extent. Some numerical studies have modelled the SEDS as a simple vent on a wall without modelling the flow inside the duct (e.g., [3–5]) while other studies have considered already existing ducts in buildings without investigating the influence of different SEDS parameters (e.g., [6, 7]). In addition, the types of occupancies can also vary significantly ranging from e.g., atria to tunnels, which can pose different requirements with respect to the design of the SEDS when compared to our scenarios. With this in mind, the work presented in the present paper, intended to be a qualitative rather than a quantitative study, is considered novel.

2 Scenario determination

In order to study SEDS using CFD, certain choices have to be made when it comes to modelling. The main parameters that are important for consideration, relating to smoke generation from the fire and smoke extraction through the duct, include: the design fire (i.e., steady versus growing fire, fuel type, fire source dimensions), the compartment configuration (i.e., dimensions), the duct design parameters (i.e., dimensions, extraction rate, maximum allowed velocity), as well as the tenability criteria [8] (e.g., based on gas temperatures ($T \leq 60^oC$), radiative fluxes ($\dot{q}_r^{''} \leq 2.5$ kW/m^2), visibility (≥ 10 m) or toxicity ($CO < 1000$ ppm)). It is worth noting that the choice of the various modelling parameters strongly relates to the design criteria (i.e., protection of means of escape, assisting fire-fighting operations, protection of property) of the smoke extraction ducts and type of occupancy (e.g., office, industrial warehouse, residential building, etc.) involved in the scenario. In addition, evaluation of the performance of SEDS could be made by considering different tenability criteria depending on the type of design objective.

2.1 Type of occupancy

The type of occupancy considered here is *offices*. The dimensions and volume of the considered compartments, comprising of 20 cm thick brick walls, are given on Table 1. A sensitivity study involving different duct configurations and lengths, number and position of extraction openings has been considered. An overview of the different cases considered is presented in Figure 1. The compartment configuration, not fully enclosed but considering a 2 m downstand, can be seen as a smaller volume inside a large compartment. This configuration allows for smoke accumulation, but does not affect the fresh air entrainment towards the fire (i.e., no flow blockage caused by nearby walls), nor does it create any intricate flow field due to the considered geometries (e.g., closed compartment with a single ventilation opening). This way, the influence of the individual SEDS design parameter can be studied independently, without the added complexity caused by the compartment geometry. Outside the compartment, the boundaries (i.e., white sides in Figure 1) are set to open for fresh air to be freely entrained into the computational domain.

Table 1 Overview of the compartment (i.e., office) dimensions used in the simulations.

Compartment	Dimensions (L x W x H)	Volume
Medium	8 m x 4 m x 4 m	128 m^3
Large	16 m x 8 m x 4 m	512 m^3
Extra-Large	30 m x 20 m x 4 m	2400 m^3

2.2 Design fire

The selection of a suitable fire, representative of a considered scenario, typically referred to as a design fire [14], is an important step in the evaluation of the performance of SEDS. A design fire is considered to be a quantitative description and representation of the fire that would be encountered in a real-life scenario depending on the type of occupancy considered. In the current study a *steady fire* is used. An overview of heat release rate (HRR) per unit area (HRRPUA) (kW/m^2) values reported in literature for fuel-bed controlled office fires is given in Table 2. The assumption of a steady fire allows the smoke extraction duct system to account for all possible fires up to the design fire size (i.e., no fire can develop faster than the one immediately going to steady state). The current study uses CFD to study the effect of various SEDS design parameters in order to determine the ideal design, hence the consideration of a steady (i.e., not growing) fire has been explicitly made.

Table 2 Suggested HRRPUA (kW/m^2) values for fuel-bed controlled office fires.

Reference	HRRPUA (kW/m^2)
BRE [9]	270
CEN [10]	255
Hopkin et al. [11]	150 - 650 (maximum)
BSI [12]	290
Eurocode [13]	250

It has been reported, based on real-life experiments, that the HRR values for office fires were approximately 500 kW before any fire suppression occurred [15]. In other real-life experiments involving office type of occupancies, it was reported that a design fire with a steady-state HRR of 500 kW would provide a conservative estimate for open-plan offices. In other office fire cases, peak heat release rates in the order of approximately 1 MW have been reported/considered [17–19]. Another aspect that could potentially be important, particularly if toxicity and visibility is of importance, is the amount of soot

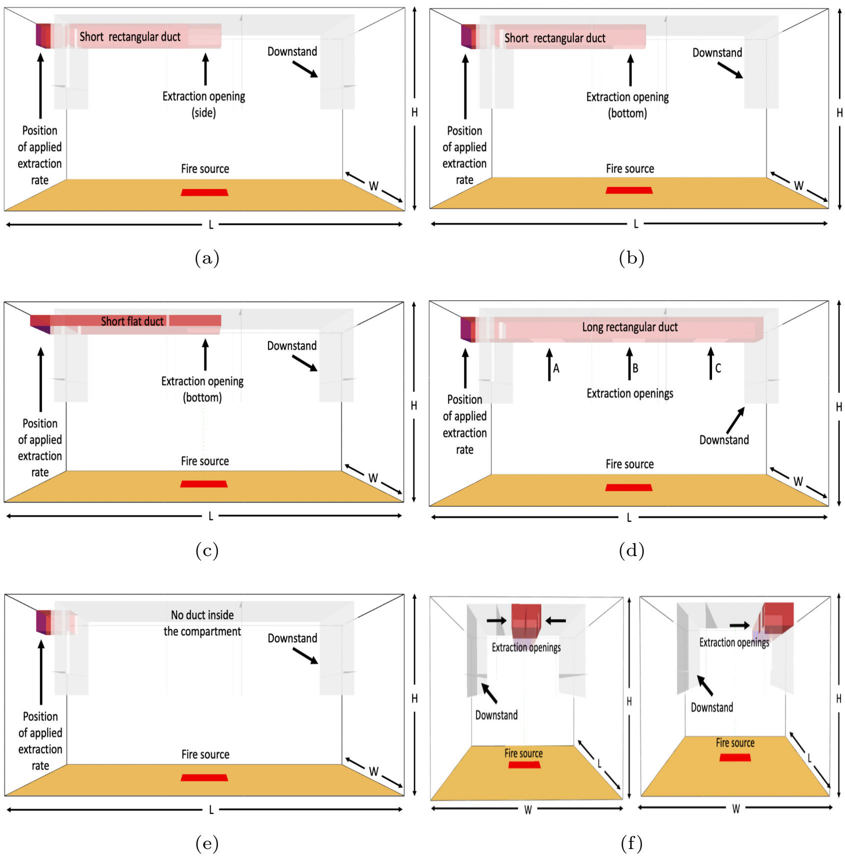


Fig. 1 Schematic of the compartment geometry, position of the applied extraction rate, downstand, fire source and different duct configurations considered in the simulations. Acronyms: short rectangular duct (SRD), long rectangular duct (LRD), short flat duct (SFD), no duct inside the compartment (ND), extraction from the bottom of the duct (B), extraction from the side of the duct (S), duct positioned in the center of the compartment (center), duct positioned against a compartment (wall). Configuration example of (a) 'SRD-S-center', (b) 'SRD-B-center', (c) 'SFD-B-center', (d) 'LRD-B-center', (e) 'ND-center' and (f) 'LRD-S-center' / 'LRD-S-wall'.

and CO released from fires inside occupancies. Some representative values that have been reported in literature in the past for office fires are 0.03 and 0.01 for soot and CO yields [16], respectively. Based on what has been reported above, the choice of a steady 500 kW fire (i.e., 255 kW/m^2) involving a sooty fuel (i.e., n-heptane) was made in the numerical simulations. An overview of the considered fire source characteristics is given in Table 3.

Table 3 Overview of the fire source characteristics [30] used in the simulations.

Fire source	**Value**
Fuel	n-Heptane (n-C_7H_{16})
HRR	500 kW
HRRPUA	255 kW/m^2
Dimensions (L x W)	1.4 m x 1.4 m
Radiative fraction	0.33
Soot yield	0.037
CO yield	0.01

2.3 Smoke extraction duct system

2.3.1 Design criterion

The design criterion for the SEDS in this case is the *protection of means of escape*. The objective is to obtain a desired smoke-free height inside the compartment in the areas where evacuation of people takes place. The minimum clear height above escape routes for non-public buildings (e.g., offices) is taken to be 2.5 m [9]. The SEDS should be able to fulfil this requirement during the entire duration of the considered design fire [9].

2.3.2 Duct configurations

The sensitivity study on different SEDS parameters includes the number (i.e., one versus multiple), position (i.e., at the bottom versus at the side of the duct) and size (i.e., one opening of 1 m x 1 m (bottom) versus two openings of 0.5 m x 1 m (side)) of the extraction openings. The value of the applied smoke extraction rate is based on simplified calculations, presented in section 3. A simplified approach is employed in this case, considering a constant extraction rate value that is independent of pressure losses inside the duct (i.e., no extraction fan characteristics have been considered). The maximum allowed velocities inside ducts are typically in the order of 10 m/s (i.e., low pressure systems) - 40 m/s (i.e., high pressure systems) [20]. The considered value here is taken to be approximately 15 m/s. An overview of the considered duct system characteristics employed in the simulations is given in Table 4.

3 Estimation of SEDS extraction rate

The calculation of the required smoke extraction rate, required to maintain the desirable smoke free height of 2.5 m, is based on simplified calculations, similarly to what is reported by Merci et al. [21]. Such simplified methods rely on the assumption of ‘steady state’ conditions, considering average and uniform smoke layer properties, and neglect heat transfer from the hot smoke layer to the structure (which for large compartments might not be negligible, though). Additionally, the size of the compartment is only indirectly accounted for through the coefficient in the entrainment correlation, the choice of the design fire and the fire area, as well as the selected smoke free height. These simplified methods are in principle only valid for configurations for which the

Table 4 Overview of the duct system parameters used for the simulations in this section.

Duct system	**Value**
Dimensions	length^a x 1 m x 0.5 m
Material type	PROMATECT-LS ^{b}
Material thickness	0.035 m
Location	Below the ceiling and along the L side
Extraction rate	7 m^3/s (see section 3)
Maximum allowed velocity	$\approx$ 15 m/s
Number of extraction openings	Variable
Extraction opening position	Bottom / Side^c of duct
Extraction opening size	1 x (1 m x 1 m) - Bottom 2 x (1 m x 0.5 m) - Side^c

^{a}The length of the duct system varies, depending on the scenarios considered.
^{b}PROMATECT-LS is a non-combustible low density calcium silicate board which is used for the construction of fire-resistant ducts. The thermal material properties have been provided by Etex/PROMAT.
^{c}When the extraction is from the side, the duct is split into 2 smaller ones, each with dimensions length^a x 0.5 m x 0.5 m, with the use of a separator. In this case, each smaller duct extracts 3.5 m^3/s.

Table 5 Overview of the simplified calculations.

	Value	**Comment**
Input		
Fire side length - D (m)	1.4	Steady for of 500 kW
$HRRPUA$ (kW/m^2)	255	Office fire
Radiative fraction - χ_r (-)	0.33	Heptane
Specific heat - c_p (kJ/kg/K)	1	Ambient air
Ambient temperature - T (K)	293	20^oC
Smoke free height - z (m)	2.5	For office
Output		
Fire area - A_{fire} (m^2)	1.96	Square fire geometry
Fire perimeter - p (m)	5.6	Square fire geometry
Total HRR - $\dot{Q}$ (kW)	500	$\dot{Q} = A_{fire} \cdot HRRPUA$
Convective HRR - $\dot{Q}_{conv}$ (kW)	355	$\dot{Q}_{conv} = (1 - \chi_r) \cdot \dot{Q}$
Entrainment rate - $\dot{m}$ (kg/s)	7.46	Thomas correlation: $\dot{m} = 0.337 \cdot p \cdot z^{3/2}$ valid when $z \leq 10\sqrt{A_{fire}}$
Smoke layer temperature - T_{layer} (K)	338	$T_{layer} = T_{amb} + \frac{\dot{Q}_{conv}}{\dot{m} \cdot c_p}$
Smoke layer density - ρ_{layer} (K)	1.04	Ideal gas law: $\rho_{layer} = (p \cdot M_w)/(R \cdot T_{layer})$ with $p = 101325$ Pa, $M_w = 28.96$ kg/mol, $R = 8.314$ J/(mol $\cdot$ K)
Volumetric extraction rate - $\dot{V}$ (m^3/s)	7.14	$\dot{V} = \dot{m}/\rho_{layer}$
Maximum duct velocity - V_{max} (m/s)	15	Duct type specific
Cross-sectional area of duct - A_{duct} (m^2)	0.48	-

empirical formulae considered (i.e., entrainment correlations) are applicable [21]. In particular, it cannot be expected that such simplified methods are applicable to complex geometries (e.g., spaces with complex air entrainment patterns). An example of a simplified calculation for the calculation of the required smoke extraction rate is presented in Table 5. Initially, the required input data (i.e., fire source, ambient air properties, smoke free height) of the calculations are given, together with any assumptions employed. Finally, the output data (i.e., smoke layer temperature, volumetric extraction rate, cross section area of the duct) from the calculations are presented.

4 Numerical modelling

The CFD code used for modelling is the Fire Dynamics Simulator (FDS 6.5.3), developed by the National Institute of Standards and Technology (NIST). FDS is a low-Mach number, LES code which solves conservation equations for mass, momentum, chemical species and sensible enthalpy. It is a second order accurate, finite difference code with explicit time marching on structured grids. Turbulence is modelled using Deadorff's model [22] while the sub-grid scale kinetic energy is calculated based on the scale-similarity model of Bardina et al. [24]. The combustion model employs a one-step, infinitely fast, irreversible chemical reaction for the fuel combined with a modified Eddy Dissipation Concept (EDC) model [25] for turbulence-chemistry interactions while the mixing time scale model is calculated based on the work by McDermott et al. [26]. Soot and CO are modelled through a simple approach of defining a-priori yields for the fuel. With respect to radiation modelling, the radiative intensity is treated as a function of both spatial location and angular direction and is obtained by solving the radiative transfer equation (RTE) by the finite volume discrete ordinates model (fvDOM) accounting for attenuation and augmentation of radiation by absorption and emission, respectively. The mean Planck absorption coefficients for the chemical species are dependent on temperature and calculated by the RADCAL model. The number of solid angles used for the RTE discretisation is set to 100 [27]. The near-wall modelling is based on the law of the wall for smooth surfaces [23]. The validity and accuracy of wall functions depends on the near-wall grid resolution which should fall within a certain range of y^+, the non-dimensional distance from the wall expressed in viscous units. A general guideline is that the first grid size should fall within the log layer with values of $y^+ = 30$ corresponding to highly resolved flows. The upper limit of the log layer for statistically stationary boundary layers will depend on the Reynolds number, hence no specific values can be easily given. Several recommended values that exist in literature provide some rough estimates (i.e., $y^+ = 300 - 500$ [29] and $y^+ < 1000$ [27]). FDS employs the constant coefficient Smagorinsky turbulence model with a Van Driest damping function for the subgrid scale viscosity in the first off-wall grid cell.

5 Results

The results from the numerical simulations with FDS for the different compartment geometries considered in the study are reported in this section. The run times for the 'Medium', 'Large' and 'Extra-Large' compartments were set to 60 s, 90 s and 300 s, respectively, ensuring that a sufficient number of flow-through times were considered for steady state conditions to be reached.

5.1 Medium compartment

The numerical prediction for the medium compartment (i.e., 128 m^3) are presented here. Initially, a grid sensitivity study is presented followed by a numerical study on various duct system parameters.

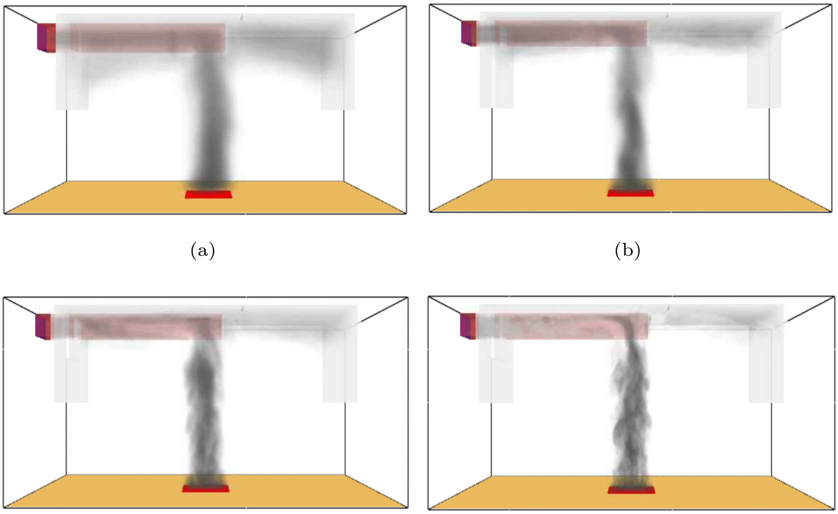
5.1.1 Mesh sensitivity study

Emphasis is initially given on the mesh sensitivity of the predictions in order to determine the minimum required grid size for accurate numerical modelling of the fire plume and of the flow inside the duct. An a-priori choice of the grid sizes used in the simulations is made by considering the ratio of the characteristic fire diameter, D^*, and the grid size, Δx. The characteristic fire diameter is defined as:

$$\Delta^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{2/5} \approx 0.73\ m \tag{1}$$

where $\dot{Q}$ (i.e., 500 kW) is the heat release rate, ρ_∞ (i.e., 1.2 kg/m^3) is the ambient density, c_p (i.e., 1 kJ/(kg·K)) is the specific heat, T_∞ (i.e., 293 K) is the ambient temperature and g (i.e., 9.81 m/s^2) is the gravitational acceleration. The quantity $D^*/\Delta x$ can be thought of as the number of computational cells spanning the characteristic (not necessarily the physical) diameter of the fire. The higher the $D^*/\Delta x$ values the more 'resolved' is the fire dynamics in the simulations. Nevertheless, the $D^*/\Delta x$ ratio should only be used as an indicator of the quality of the mesh of a given numerical study and it is not intended as a replacement of a grid sensitivity study. Such a grid sensitivity study is presented in this section. In literature, $D^*/\Delta x$ values ranging between 5-20 have proven to give satisfactory accuracy with an acceptable computational time for many fire scenarios [28] while values up to 16 were required for simulating fire plume scenarios [31]. Based on the above, a maximum ratio of $D^*/\Delta x = 30$ has been considered for the choice of the different grid sizes in the numerical simulations. Hence, four different grid sizes, Δx, have been considered, i.e., 20 cm ($D^*/\Delta x \approx 3.5$), 10 cm ($D^*/\Delta x \approx 7$), 5 cm ($D^*/\Delta x \approx 15$) and 2.5 cm ($D^*/\Delta x \approx 30$). The compartment geometry considered for the grid sensitivity study was previously presented in Figure 1 while the main duct system parameters are given in Table 4.

As expected, refining the grid size from 20 cm to 2.5 cm results in more turbulent structures in the fire plume region. This is portrayed in Figure 2 which presents the smoke inside the compartment for different grid sizes. The smoke extraction efficiency is somewhat affected in the coarsest grid size cases (i.e., 20 cm and 10 cm) with some smoke accumulation occurring below the ceiling. Smoke extraction is more complete on the finest grid size case (i.e., 5 cm and 2.5 cm) with significantly less smoke accumulation below the ceiling compared to the coarsest meshes. The choice of grid size has an effect on the

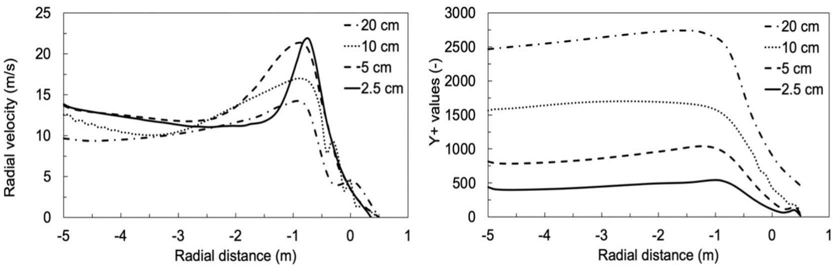


(a) (b)

(c) (d)

Fig. 2 Schematic of the instantaneous smoke inside the medium compartment for an 'SRD-B-Center' configuration with grid sizes of (a) 20 cm, (b) 10 cm, (c) 5 cm and (d) 2.5 cm.

smoke extraction efficiency because a finer grid size implies more cells across the extraction opening and better resolution of the turbulent flow.



(a) (b)

Fig. 3 Time-averaged (a) centreline radial velocity (m/s) and (c) y+ values (-) at the top surface inside the duct as a function of grid size. The fire source is located underneath the duct at 0 m radial distance.

The numerical predictions regarding the radial velocity on the centreline and the y+ values inside the duct system are presented in Figure 3. The fire is positioned underneath the duct at radial distance 0 m. A sudden increase in the radial velocities is observed at the extraction opening, due to the bending of the flow, with maximum values in the order of 22 m/s, approximately 50% higher than the maximum velocities of 15 m/s considered in the design of the duct system. Subsequently, the velocities decrease and approach the maximum limit of 15 m/s considered, however, the duct is not long enough to have a fully developed flow. It is worth noting that the bending of the flow at the level of the extraction opening creates a non-uniformity in the flow inside the duct. The time-averaged y^+ values obtained at the top surface of the duct system further confirm that the grid sizes of 5 cm and 2.5 cm are most appropriate for accurately simulating the flow inside the duct system (i.e., $y^+ \approx 500 - 1000$). The observations for the time-averaged centreline temperature and axial velocity profiles in the fire plume region (not shown here) are similar. The differences in the predictions between the 5 cm and 2.5 cm cases were in the order of approximately 10-20% depending on the location and quantity examined. Additionally, no qualitative/quantitative differences were observed on the smoke extraction efficiency between the 5 cm and 2.5 grid size cases. Given the grid sensitivity study presented here, the choice to use a grid size of 5 cm for the remainder of the numerical simulations was made. This choice is essentially a compromise between numerical accuracy and affordable computational cost, particularly considering simulations involving big compartments and/or multiple compartments connected with a duct system.

5.1.2 Number of extraction openings

A sensitivity study on the influence of the number of extraction openings (i.e., 1, 2, 3), mainly focusing on the SEDS extraction efficiency, for an 'LRD-B-Center' configuration (i.e., see Figure 1(d)), is initially presented. An overview of the the main duct system parameters is given in Table 4.

The numerical results regarding the smoke inside the compartment are presented in Figure 4(a). Regardless of the number of extraction openings, it is clear that the applied extraction rate of 7 m^3/s is sufficient to maintain a smoke free height of 2.5 m. There are no significant qualitative differences between the use of either 2 or 3 extraction openings for the duct system, however, a thicker smoke layer is observed in the case where only 1 extraction opening is used. A more quantitative analysis is shown in Figure 4(b), reporting the extraction rates (kg/s) at each opening. It is clear that the most efficient opening is the one closest to the left boundary, where the extraction rate is applied, accounting for approximately 75% of the extraction when more than one opening is considered. It is worth noting that opening C in the case with 3 extraction openings (i.e., Figure 4 - top right) is not efficient at all as it does not extract smoke but rather blows smoke already within the duct system back in the compartment (i.e., negative extraction rate). Overall, the numerical results suggest that the use of a single extraction opening (e.g., placed in the center of the compartment) would be sufficient for effective smoke extraction and for maintaining the desired smoke free height inside the compartment. This was confirmed by additional simulations (results not shown here) regardless of the fire source location.

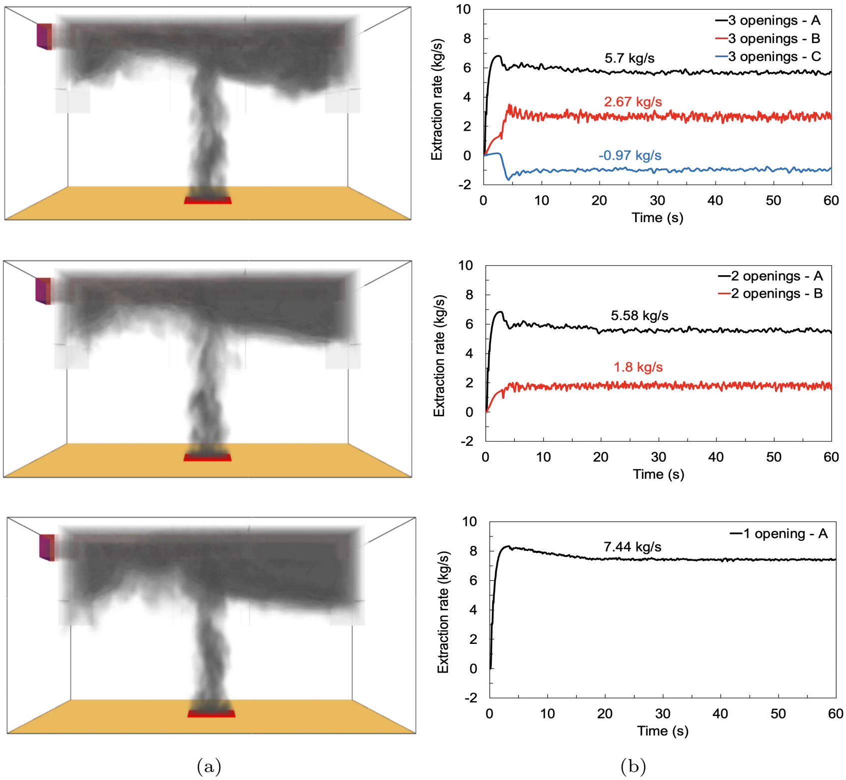


Fig. 4 Schematic of the (a) smoke inside the medium compartment and (b) time evolution of the extraction rates for an 'LRD-B-Center' configuration. Top: 3 openings (A, B, C), middle: 2 openings (A, B), bottom: 1 opening (A).

5.1.3 Position of the duct system and its openings

A set of numerical simulations placing the extraction openings on the side of the duct system are considered in this section corresponding to 'LRD-S-center' and 'LRD-S-wall' configurations (see Figure 1(f)). The objective is to compare the smoke extraction efficiency compared to the previous cases, where the extraction openings were placed at the bottom of the duct system. Placing the extraction openings at the side of the duct system will potentially be a better approach if plug-holing (i.e., extraction of fresh air in the smoke exhaust if the extraction rate is too high) is expected to be an issue. Nevertheless, given the applied extraction rate in the duct system this is not the case in the scenarios considered here.

The simulations here consider two different scenarios which involve the placement of the duct system in the center of the compartment (Figure 5(b)) and the placement of the duct system against the wall (Figure 5(a)). In the former case extraction occurs from both sides of the duct system while in the latter case extraction occurs from a single side. Note that in these scenarios, where the duct system is placed in the center of the compartment, a separator is considered inside the centre of the duct system which separates the main duct into two smaller ones. The main reason for such a consideration (i.e., which is not necessarily representative of current real-life practice) is that any smoke which is extracted from one side of the duct system does not potentially go back into the compartment from the opposite extraction opening of the duct system.

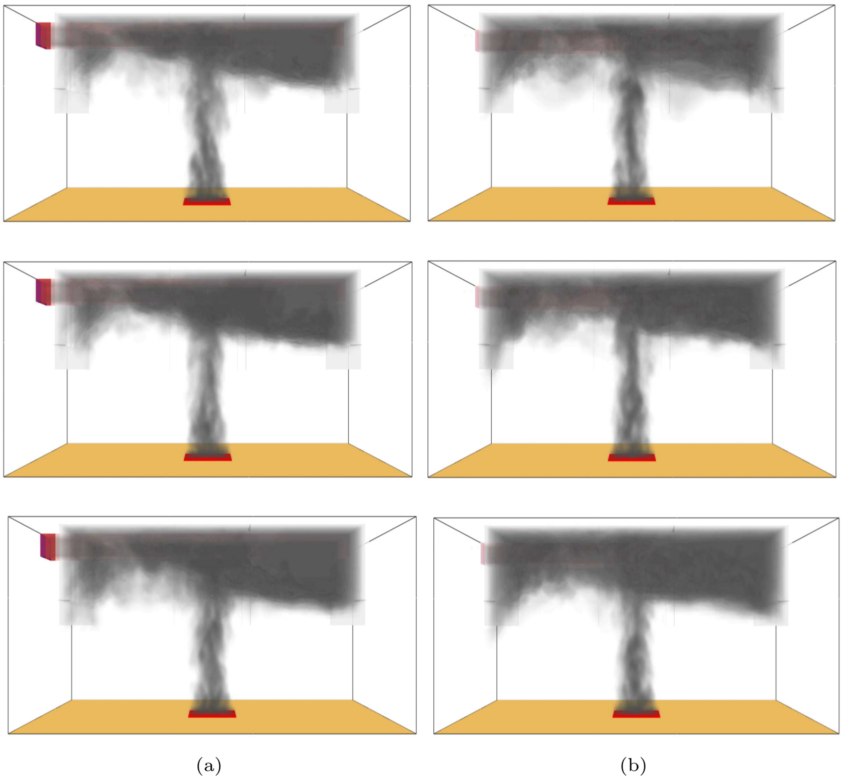


Fig. 5 Schematic of the smoke inside the medium compartment for an (a) 'LRD-S-center' and (b) 'LRD-S-wall' configuration. Top: 3 openings (A, B, C), middle: 2 openings (A, B), bottom: 1 opening (A).

It can be observed qualitatively from the results presented in Figure 5 that the differences in the predicted smoke layer heights inside the compartment between the two cases are not significant, both maintaining the desired smoke free height. The relative differences between the two cases are similar, regardless of the number of extraction openings in the duct system.

5.1.4 Position of extraction opening

The smoke extraction efficiency when considering only one position along the length of the duct system is further evaluated here considering the 'SRD-S-Center' and 'SRD-B-Center' configurations (see Figures 1(a) and 1(b), respectively). The aim is to further support the conclusions drawn from the previous sections, i.e., that limiting the number of extraction openings is possible without significantly affecting the smoke extraction efficiency. In this case, a shorter length for the duct system is considered, placing the extraction opening in the centre of the compartment. The motivation of this design is to have a more cost-effective duct system, compared to the previously cases, as the other part of the duct is not necessary used for smoke extraction in the single room. A sensitivity study on the influence of the extraction position of opening (i.e., from the bottom or the side of the duct system) and of the fire location (i.e., placed in the centre and off-centre of the compartment) is presented here.

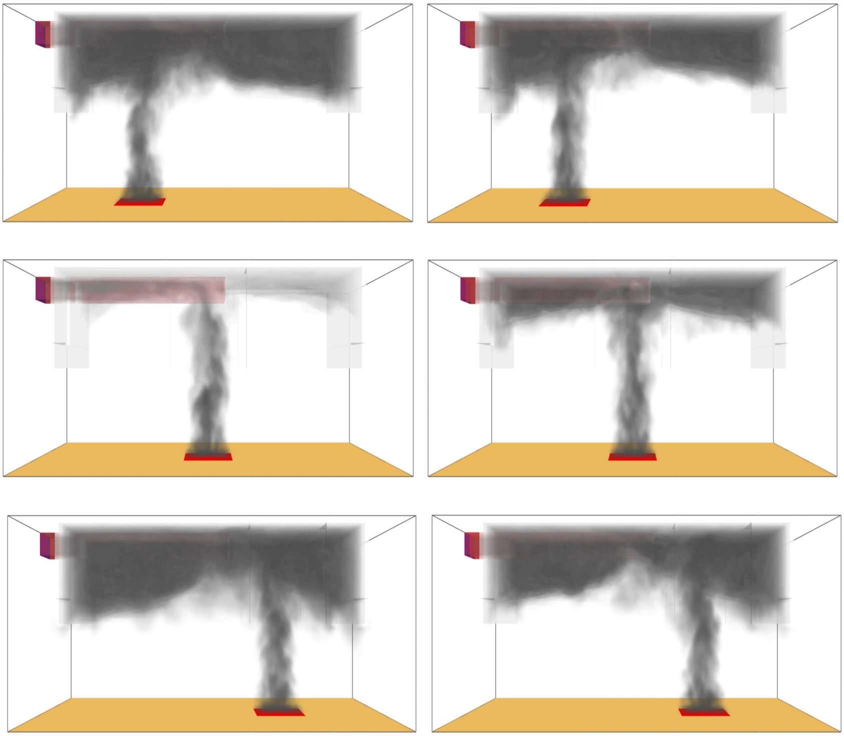
The smoke inside the compartment when extracting from the bottom (i.e., Figure 6(a)) and from the side (i.e., Figure 6(b)) of the duct system for different fire source locations is presented. Between the two cases, extraction from the side appears to be more efficient as thinner smoke layers are evident in this case. Exception to this observation are the cases with the fire located in the centre of the compartment where, as expected, smoke is much easier extracted when the opening is placed at the bottom of the duct system. Even in this case, however, smoke extraction from the side performs well and maintains the desired smoke free height. Since these scenarios have a relatively small probability to occur, they are not considered the most representative cases for evaluating the duct system performance. Furthermore, smoke extraction from the side is expected to be a better approach in terms of possible plug-holing problems (not evident in the case at hand). Regardless of the smoke extraction position, however, the duct design as presented here is essentially more cost-effective when compared to the previous designs considered, given its shorter length.

5.2 Large compartment

The numerical predictions for the large compartment (i.e., 512 m^3) are presented here. Initially, an evaluation of the predicted pressure losses inside the duct is presented, followed by a numerical study on various SEDS parameters. The main SEDS parameters, i.e., duct height and width, extraction rate, as well as the maximum velocity allowed inside the duct system, have been kept the same.

5.2.1 Pressure losses

As a first step, a set of numerical simulations with different grid sizes are performed in order to investigate whether accurate predictions of pressure losses are obtained inside a long duct in which the flow is fully developed. The purpose here is to further verify that the chosen grid size of 5 cm is



(a) (b)

Fig. 6 Schematic sketch of the smoke inside the medium compartment for an (a) 'SRD-B-Center' and (b) 'SRD-S-Center' configuration. Top: fire on the left side, middle: fire in the centre, bottom: fire on the right side.

sufficiently small to accurately simulate the flow inside the duct system. This configuration is more suitable for evaluating the pressure losses because the duct is sufficiently long to have a fully developed flow, not disturbed by the presence of multiple extraction openings. In this case, a large compartment is used with an 'LRD-B-Center' configuration with only one extraction opening at the right end of the duct (see Figure 1(d) considering only opening C).

The theoretical pressure losses inside the duct system are estimated based on the Moody diagram [32]. A smooth pipe solution has been considered as this corresponds to the setup of the numerical simulations (i.e., law of the wall modelling for smooth surfaces with no material roughness considered). The air properties (i.e., density and kinematic viscosity) considered in the calculations below are based on the average temperature (i.e., approximately 50^{o}C) inside the duct obtained from the simulations. The estimation of the smoke temperature could have also been made from the simplified calculations presented in Table 5 (i.e., the smoke layer temperature is taken as 338 K or 65^{o}C) assuming that the smoke does not cool down as it flows inside the duct. The assumption is considered less reasonable, because some cooling will take place. Either way, however, the difference between the kinematic viscosity at 50^{o}C and 65^{o}C is very small and would not significantly alter the resulting Reynolds number and the resulting friction factor obtained from Moody's diagram.

The equivalent diameter for a rectangular duct, D_e, is calculated as [33]:

$$D_e = \frac{1.3(ab)^{0.625}}{(a+b)^{0.25}} = 0.762\ m \tag{2}$$

where $a = 0.5\ m$ and $b = 1\ m$ are the two sides of the rectangular duct.

The Reynolds number inside the duct system considering a maximum velocity of $V = 15\ m/s$ is:

$$Re_{D_e} = \frac{V \cdot D_e}{\nu} = \frac{15\ m/s \cdot 0.762\ m}{17.98 \cdot 10^{-6}\ m/s^2} = 635706 \tag{3}$$

From the Moody diagram, considering a smooth pipe solution, the friction factor for $Re = 635706$ is $f_D \approx 0.0125$. Finally, the calculated pressure losses, calculated over a $L = 10\ m$ duct length, are approximately:

$$\Delta P_{loss} = f_D \frac{\rho V^2}{2} \frac{L}{D_e} = 0.0125 \frac{1.09\ kg/m^3 \cdot (15\ m/s)^2}{2} \frac{10\ m}{0.762\ m} \approx 20.11\ Pa \tag{4}$$

The predicted pressures losses (i.e., calculated as the difference in pressures between positions $r = -8\ m$ and $r = 2\ m$ inside the duct) for the 5 cm and 10 grid size cases (i.e., 21 Pa), presented in Figure 7 and Table 6, are reasonably close to the theoretical pressure losses, i.e., 20.11 Pa (±4%) obtained from the Moody diagram. Furthermore, the predicted values are close to the suggested uncertainties associated from the use of the Moody diagrams as suggested in literature (i.e., expected errors up to 10% [34]). Together with the grid sensitivity study previously presented for the small compartment, this further justifies that a grid size of 5 cm is sufficiently small for accurate simulation of both the fire plume and the flow inside the duct system in these scenarios.

Table 6 Calculated pressure losses (i.e., in Pa/m and Pa) inside the duct with CFD.

Grid size (cm)	**Pressure (Pa) r=-8 m**	**Pressure (Pa) r=2 m**	**Pressure loss (Pa/m) / (Pa)**
20	-121	-110	1.1 / 11
10	-215	-194	2.1 / 21
5	-257	-236	2.1 / 21
Theoretical	-	-	2.01 / 20.11

5.2.2 Sensitivity study

Having established that a shorter (i.e., half compartment in length) duct system is sufficient in the previous section, the influence of the extraction position

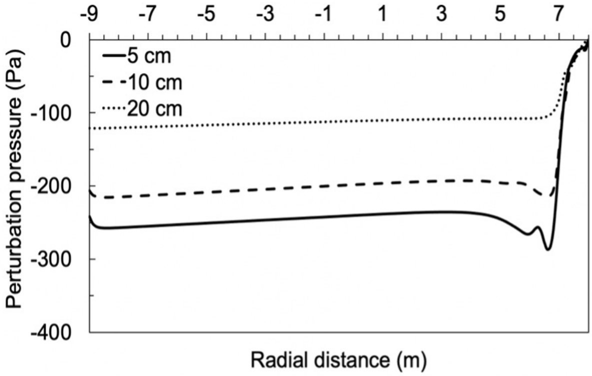
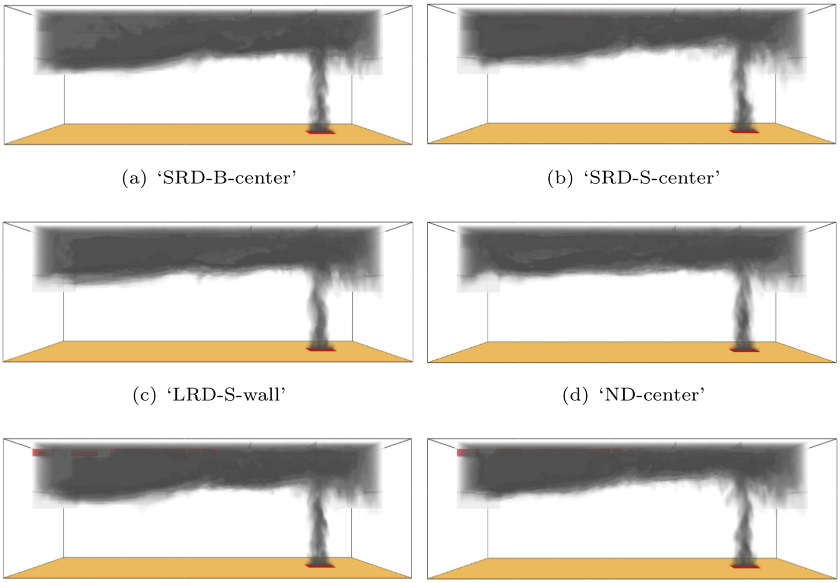


Fig. 7 Average centreline perturbation pressure inside the duct as a function of grid size predicted with CFD.

(i.e., bottom versus side), the position (i.e., in the center of the compartment versus against the wall) as well as shape (i.e., rectangular: 0.5 m x 1 m versus flat: 0.25 m x 2 m) of the duct system is examined here. The fire is placed near a wall, located the furthest away from the extraction opening, but still considered as free standing (i.e., maximum air entrainment and produced smoke volume), as this can be identified as the worst-case scenario in order to study the efficiency of smoke extraction.

The numerical results for the smoke inside the compartment from the different cases considered are presented in Figure 8. The numerical predictions reveal that smoke extraction from the side (i.e., Figure 8(b)) is slightly more efficient than extraction from the bottom (i.e., Figure 8(a)) of the duct system as, in the former case, thinner smoke layer heights are obtained inside the compartment (i.e., approximately 2.5 m versus 2.2 m smoke free height for the two cases, respectively, at the locations furthest away from the fire). On the other hand, the position of the duct system, placed against the wall (i.e., Figure 8(c)), does not lead to significant differences on the smoke extraction efficiency and predicted smoke layer heights (i.e., less than 5%). An even shorter duct system (i.e., Figure 8(d)), which only extends between the boundary where the extraction rate is applied to the compartment wall itself (i.e., length of 1 m), was also considered. The main motivation for using such a configuration is to determine whether the smoke extraction opening needs to be placed within the interior of the compartment (i.e., close to the centre of the compartment) or not. The duct system with a shorter length in this case (i.e., effectively not behaving as a smoke reservoir like in the previous cases) performs equally well and is able to maintain the desirable smoke free height. It should be noted that this design will potentially have added savings, compared to the previous cases, on the fan due to reduction in pressure losses that need to be overcome. For compartments of this size and volume, the length of the duct inside the compartment does not seem to have a significant influence on the smoke extraction efficiency of the system. This observation further supports the previous conclusions that, in the present simulations, the applied extraction rate is the main controlling parameter when it comes to the performance of a smoke extraction duct system with a given cross section for compartments of this size (i.e., maintaining a desired smoke free height) and not any other duct-related parameters (e.g., number and size of extraction openings, position of the duct system, etc.). This is particularly the case as the smoke extraction rate in the simulations is not calculated based a fan curve, rather it is constant regardless of the pressure losses inside the duct.



(a) 'SRD-B-center' (b) 'SRD-S-center'

(c) 'LRD-S-wall' (d) 'ND-center'

(e) 'SFD-B-center' (f) 'SFD-S-center'

Fig. 8 Schematic of the smoke inside the large compartment for the different cases considered. See Figure 1 for the different configurations considered.

Finally, a flat duct system is considered aiming at evaluating whether there is a significant influence of the duct geometry on the smoke extraction efficiency. Two cases, namely extracting from the bottom (i.e., Figure 8(e)) and the side (i.e., Figure 8(f)) of the duct system, are considered with the duct system placed in the center of the compartment (i.e., along the long side). In this case, the height of the duct system is halved (i.e., 0.25 m) while its width is doubled (i.e., 2 m) in order to maintain the same cross-sectional area (i.e., 0.5 m2) with the previous examined cases. This means an increase of the flatness ratio from 1:2 to 1:8. The predicted smoke inside the compartment reveals that there are no significant qualitative differences between the two scenarios considered and both maintain the desired smoke free height. In fact, the results are quite similar to the ones previously obtained with the rectangular duct in terms on predicted smoke layer height. Overall, extraction from the side of the duct system again seems to be slightly more efficient. It is worth noting that even though the smoke extraction efficiency with a flat duct in this case, was equally good compared with the use of a rectangular duct, it does not also imply that the chosen grid resolution (i.e., 5 cm) is sufficient for accurate simulation of the flow inside the duct. In this case, there are only 5 cells across the height (i.e., 25 cm) of the flat duct, hence no accurate prediction of the velocity and pressure drop inside the duct should be expected. When the flatness ratio of the duct increases, the grid size will have to become smaller so that there are sufficient number of cells across the height to accurately simulate the flow inside the duct. Nevertheless, the fact that the smoke extraction efficiency is not significantly affected is an important conclusion.

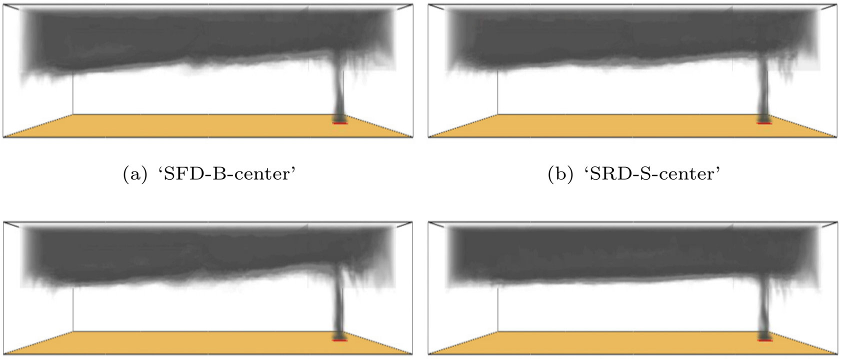
5.3 Extra-large compartment

Results from the numerical simulations for the extra-large compartment (i.e., 2400 m^3) are presented in this section. The main objective is to examine the influence of the extraction position (i.e., bottom and side), as well as the length of the duct system, and to further verify the validity of the conclusions drawn in the previous scenarios (i.e., for the 128 m^3 and 512 m^3 compartments).

The numerical results for the predicted smoke inside the compartment are presented in Figure 9. For all cases, regardless of the location and position of the smoke extraction, the predicted smoke free height is slightly less than the desired value (i.e., approximately 2 m) on the left side of the compartment (i.e., location furthest away from the fire). The case presented in Figure **??**, depicting a worst-case scenario with the fire located as far away from the extraction location as possible, performs similarly to the cases where the extraction location is closer to the fire. It is worth noting that the simplified calculations neglect heat transfer from the hot smoke layer to the structure (which for large compartments might not be negligible) when determining the required smoke extraction rate. Nevertheless, the simulation using a higher extraction rate (i.e., Case 3 with 10 m^3/s) did not significantly improve the predicted smoke free height. Given the big dimensions of the compartment in this case, a possible reason for this observation could be the gradual cooling down of the smoke as it travels away from the fire which reduces the buoyancy forces. Additionally, multiple openings could potentially be required in order to maintain the desired smoke free height in large-size compartments if smoke is far away from the extraction opening. On the other hand, the smoke layer height is still maintained at acceptable levels for all scenarios at locations close to the fire (i.e., right side of the compartment).

6 Conclusions

The paper presented Large Eddy Simulations (LES) focusing on smoke extraction in single compartments of different volumes (i.e., 128 m^3, 512 m^3 and 2400 m^3) with the CFD code FDS 6.5.3. A sensitivity study on multiple smoke extraction duct system (SEDS) design parameters (i.e., shape and position of



(a) 'SFD-B-center'

(b) 'SRD-S-center'

(c) 'SRD-S-center' - 10 m^3/s

(d) 'ND-center'

Fig. 9 Schematic of the smoke inside the extra-large compartment for the different cases considered. See Figure 1 for the different configurations considered.

duct as well as the number and position of extraction openings) has been conducted. The applied extraction rate for the duct system has been determined a-priori based on simplified calculations. The major conclusions drawn from this numerical study are summarised as follows:

- Based on the grid sensitivity study (i.e., 20 cm, 10 cm, 5 cm, 2.5 cm), focusing on the fire plume characteristics, as well as on the predicted flow inside the duct system (i.e., pressure loss, velocity, y^+ values), a grid size of 5 cm is considered a good compromise between accuracy and acceptable computational cost for SEDS of this size (i.e., CFD engineering of SEDS at building level).
- The openings closest to where the extraction rate is applied, are the most efficient. Hence it is not very efficient to have multiple openings on a single duct system inside a compartment. The use of few (i.e., one or two) extraction openings placed close to the centre of a small / medium size compartment is the most efficient strategy in terms of smoke extraction. In fact, the use of multiple extraction openings can result in smoke being recirculated back into the compartment through the duct system. However, for very large compartments multiple openings could have a benefit, but this is not yet demonstrated in this study.
- The velocity inside the duct system can locally exceed the maximum, based on simplified calculation methods, design value, e.g., near the position of the extraction opening due to the bending of the flow. The extent of this effect will also depend on the relative sizes of the extraction opening and the duct system. For the cases considered in the paper, an increase of up to 30% in the maximum velocities considered in the design phase were observed inside the duct system.
- The length (i.e., covering half or whole length of the compartment) and height (i.e., 0.25 m or 0.5 m) of the duct system, as well as the number and

the position (i.e., in the centre of the compartment or against a wall), did not have a substantial influence in the smoke extraction efficiency for the cases considered for which the desired free smoke height was obtained.
- The desired smoke free height was maintained in most of the cases considered (i.e., discrepancies of less than 5%), apart from the extra-large compartment cases, where values of 2 m instead of 2.5 m were obtained (i.e., 20% discrepancies). This aspect indicates that caution is required when big compartments are considered, because the suggested simplified methodology for determining the required extraction rate might become less accurate. In this case, multiple extraction openings could also be required.

Finally, it should be noted that the applied extraction rate is an important input parameter that will influence the duct system efficiency (i.e., in terms of maintaining a desired smoke free height). The applied extraction rate often relies on the estimation of the entrainment rate from experimental correlations which can include errors / uncertainties. Overall, this study proofs that a SEDS system can be designed for the required purpose of maintaining a free smoke height by using simplified calculation methods.

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- Code availability: Software application. The FDS 6.5.3 code used in the paper is open-source and freely available through https://github.com/firemodels/fds.
- Authors' contributions
  Conceptualization: Georgios Maragkos, Karim Van Maele, Emmanuel Annerel, Bart Merci; Methodology: Georgios Maragkos; Formal analysis and investigation: Georgios Maragkos; Writing - original draft preparation: Georgios Maragkos; Writing - review and editing: Karim Van Maele, Wilfried Piontkowski, Emmanuel Annerel, Bart Merci; Funding acquisition: Emmanuel Annerel, Bart Merci; Supervision: Emmanuel Annerel, Bart Merci.
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