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Adapted FLASHCAT methodology to model horizontal cable tray fires using computational fluid dynamics

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ABSTRACT

Nuclear power plants (NPPs) have an extensive network of electrical cables and associated trays to support daily operations. As electrical cables have combustible mass, their presence adds to the fire load in such plants. Thermal stress from cable fires can cause cable failures and spread fire to other redundant cables or other equipment, jeopardizing the safe operation of NPPs. Assessing the heat release rates (HRR) of cable fires is critical for the nuclear industry as HRR regulates the thermal stress in the surrounding of a fire and other fire products that can damage the facility. This paper presents a computational fluid dynamics-based method to model the HRR of such cable fire. The method is partly based on the FLASHCAT model (modiﬁed and adapted here) and the surface temperature ignition model of the Fire Dynamics Simulator (FDS) software. The simulation set up with validation objective replicates an experiment of OECD PRISME 3 program in which cables arranged over two horizontal trays are burnt. HRR obtained from the simulation had peak HRR underestimated by 4%, and the time to reach peak HRR overestimated by 5%. The result is encouraging as it provides conﬁdence in using the method outlined in the paper.

1. Introduction

Cable tray fires in nuclear power plants (NPPs) may endanger the safe operation of NPPs if proper measures are not taken to limit their effects [1]. To understand fire behavior in a nuclear facility – like compartments, PRISME (French phrase propagation d’incendie pour des scénarios multi-locaux élémentaires) and PRISME 2 experimental campaigns were carried out, including experiments with cable trays [2,3]. Specific experiments have been done to increase knowledge and to improve the predictive method for cable fires in an open atmosphere and mechanically ventilated compartments [4]. Under the OECD (Organisation for Economic Co-operation and Development) PRISME 3 program, IRSN (Institut de Radioprotection et de Sûreté Nucléaire) conducted an experiment named PRF BCM-S2 in which two cable trays were burnt in an open atmosphere under a large-scale calorimetric hood to understand their fire behavior. The cables were PE/PVC (Polyethylene/Poly Vinyl Chloride) insulated and loosely packed on two horizontal cable trays. Data relevant (discussed later) to the requirement of numerical modelling of such fire was made available to the participants of the PRISME 3 program. Participants were asked to carry out simulations targeting the experimental results, which included the prediction of HRR and gas temperatures above cable trays based on existing knowledge and research. Research has been an integral part of such work as it is still very challenging to model cable fire due to complex arrangement of cables on trays and its adaptation in the simulation model, complex burning properties, complex internal cable structure etc.

There are many approaches available to model fire on cable trays. Among them, the three most popular approaches are based on pyrolysis modelling, surface temperature ignition model, FLASHCAT model. Matala et al. in Ref. [5] demonstrated the pyrolysis model’s success in simulating PVC cables using small-scale and bench-scale data against the experimental results. Beji et al. has used the surface temperature ignition model based on experiments carried out under Cable Heat Release, Ignition, and Spread in Tray Installations during FIRE (CHRISTIFIRE) project and demonstrated its successful applicability for cable fires in an open atmosphere with some stipulated conditions. Modified versions of FLASHCAT are also available, for example, as proposed by Zavaleta et al. in Ref. [1]. In this paper, the surface temperature ignition model of

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Fire dynamics simulator (FDS) software has been jointly used with the modified and adapted version of the FLASHCAT model to simulate the PRF BCM-S2 cable tray fire experiment.

2. Experimental setup

In the PRF BCM-S2 experiment, two horizontal cable trays (ladder-type cable trays, open on the bottom side with 25 mm rungs at every 300 mm) with PE/PVC insulated cables were set against an insulated side wall in an open atmosphere (Fig. 1). Cables were ignited using blowtorches located near the center of the trays adjacent to the insulated side wall. The flame from the blowtorch touched the lower and the upper cable surfaces to ensure ignition. Related experimental data is covered in this section. Unless mentioned otherwise, such data has been provided either by IRSN or taken from related publications [8,9]. Due to the confidentiality of the project, only selected details/data are stated.

Cable trays were 3 m long, 0.9 m wide, and 0.15 m in height. The distance between the trays was 0.45 m. Each tray had 112 loosely arranged 2.4 m-long cable samples filling approximately half the height of the trays. The insulated side wall was 2.6 m long, 2.2 m high, and 0.04 m thick. The insulated side wall had a 350 kg/m³ density, and specific heat was considered 1 kJ/kg K. Thermal conductivity was considered to vary with temperature as 0.06 W/m.K, 0.11 W/m.K, 0.15 W/m.K at 200 C, 600 C, 800 C respectively. Thermal conductivity at intermediate temperatures was automatically interpolated in the simulation. Details were also provided about the cable composition and physical measurements, relevant thermo-physical properties, chemical reaction, and bench-scale average heat release rate per unit area (HRRPUA) based on cone-calorimeter tests.

Values related to the cable composition and physical measurements are mentioned in Table 1. Such values are used in FLASHCAT model primarily to calculate the effective combustible mass per unit area of the cable surfaces created in FDS.

PE and PVC were involved in the combustion. A single-step mixing controlled gas phase chemical reaction based on emission factors and other variables that best fitted the values estimated during the large-scale experiment was formulated by IRSN as:

$$
0.32 \text{C}_2\text{H}_4\text{Cl} + 0.68 \text{C}_2\text{H}_6 + 2.213 \text{O}_2 \rightarrow 1.53 \text{CO}_2 + 1.26 \text{H}_2\text{O} + 0.32 \text{HCl} + 0.107 \text{C} + 0.153 \text{CO} + 0.211 \text{CH}_4
$$

It is to be noted here that, in above chemical reaction, methane is included in the reaction products to account for the unburnt gases obtained during the experiment (thus, in FDS simulations methane does not participate in combustion). The details regarding such formulation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
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<tr>
<td>PE (Polyethylene)</td>
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<table>
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<tr>
<th>Symbol</th>
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<th>Jacket material</th>
<th>Linear mass density (kg/mm)</th>
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<tr>
<td>εs</td>
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**Table 3**

Combustion characteristics of the chemical reaction [8].

<table>
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<th>Symbol</th>
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<td>Ysoot</td>
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<tr>
<td>ΔHc</td>
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</tr>
<tr>
<td>χr</td>
<td>0.35</td>
</tr>
</tbody>
</table>

* 0.9 is the default value of emissivity in FDS which is close to emissivity of PVC mentioned in Ref. [10].
and various emission factors are given in an IRSN report [11].

Combustion characteristics of the chemical reaction were also measured during the large-scale experiment and are provided in Table 3. The chemical reaction and its combustion characteristics were used in FDS to enforce yields of incomplete combustion products, heat of combustion, and the radiative fraction of combustion heat release.

Moreover, bench-scale average HRRPUA based on cone calorimeter tests were also provided for two different irradiance values (HRRPUA 245 kW/m² and 314 kW/m² at an irradiance of 50 kW/m² and 75 kW/m², respectively). Such average HRRPUA are the mean values of HRRPUA obtained during the time interval in which the mass loss percentage ranged from 10% to 90% during cone-calorimeter tests. Based on the values of average HRRPUA, mass flux from cable surface computational cells was fixed in FDS. Such mass flux, together with the heat of combustion, governs the time evolution of heat release rates (HRR) in simulations.

3. Methodology

3.1. Numerical modelling

Numerical simulations in this work have been done with CFD code, FDS (6.7.7 version). FDS uses Large Eddy Simulation (LES) based code for thermally driven low-Mach number flow. It puts emphasis on heat and smoke transport from fires in a computational domain where boundary conditions are applied to flow boundaries as well as the solid surfaces with specified or solved thermal characteristics (conjugate heat transfer). The solid surfaces are built using rectangular obstructions, and based on their thermal properties, they can conduct heat, burn, remain inert or adiabatic, etc. Fire is also one type of boundary condition. FDS provides different options to create boundary conditions to simulate a fire. Interested readers can refer to the software literatures [12,13] for detailed descriptions of various theoretical models and numerical implementations. Some of the relevant theories, models, and mathematical equations are summarized below.

FDS has four basic modes of simulation: “Large Eddy Simulation” (LES), “Very Large Eddy Simulation” (VLES, default simulation option), “Simple Very Large Eddy Simulation-VLES with simplified physics” (SVLES), and “Direct Numerical Simulation” (DNS). VLES mode along with its default models and sub-models has been used in the various simulations unless stated otherwise. Under VLES mode, Deardorff’s model is used to calculate sub-grid viscosity ($\mu_{LES}$) as

$$\mu_{LES} = C_\mu \Delta \sqrt{k_{vis}}$$

where, $\rho$ is the density of the fluid, $C_\mu = 0.1$, $k_{vis}$ is the sub-grid kinetic energy, and $\Delta$ is the LES filter width calculated as the cube root of local cell volume. The viscous stress on the wall, $\tau_{vis}$, is calculated as

$$\tau_{vis} = \rho \nu \frac{\partial u}{\partial y}$$

where $\nu$ is the friction velocity defined for near-wall region. Non-dimensional streamwise logarithmic velocity profile based on wall-function is used to account for $\nu$. For eddy viscosity in the first grid cell off-wall (near wall turbulence model), Van Driest model is used in which the sub-grid mixing length, $l_{mix}$, is calculated as

$$l_{mix} = C \Delta \left(1 - e^{-\frac{y^+}{\delta}}\right)$$

where, $A = 26$ (dimensionless empirical constant), $y^+$ is the wall-normal distance calculated as $y^+ = \frac{\nu^+}{u'}$ and $\delta$ is the viscous length scale.

FDS incorporates an explicit time advancement scheme. The time step plays a crucial role to maintain numerical stability and accuracy. A well-known Courant-Friedrichs-Lewy (CFL) constraint is used on time step for stability considering diffusion, advection, and expansion of the velocity and scalar fields. CFL is expressed as

$$\text{CFL} = \frac{\Delta t}{\Delta} \frac{U}{\Delta x} < 1$$

where $\Delta t$ is the time step, $U$ is the velocity with components $u, v$ and $w$ in $x, y$ and $z$ direction respectively. Physically, the constraint means that a fluid element within one time step should not transverse more than one computational cell width. For VLES mode, $\frac{U}{\Delta x}$ is expressed as

$$\frac{U}{\Delta x} = \max \left(\frac{|u|}{\partial x}, \frac{|v|}{\partial y}, \frac{|w|}{\partial z} + |\nabla U|\right)$$

which corresponds to the $L_{\infty}$ norm of the velocity vector.

Regarding the pyrolysis of solids, FDS provides several options to model the fuel. One among them is based on the surface ignition temperature of a solid, which has been used in this work. Under such approach, a solid follow a pre-defined burning rate as a function of the time from when it gets ignited. Its ignition happens when its surface temperature reaches a pre-defined value. In general, the temperature at a distance $x$ from the surface ($x = 0$ represents the surface) at time $t$ under one-dimensional heat conduction model with conduction in the $x$ direction (pointing into a solid layer) is computed as:

$$\frac{\partial T_s}{\partial t}(x,t) = -\frac{k_s}{\Delta x} \left(\frac{\partial T_s}{\partial x}(x,t)\right) + q_{\text{ch}}^\prime$$

where $\rho_s, c_r$ and $k_r$ represent the density, specific heat, and conductivity of the solid layer. $q_{\text{ch}}^\prime$ is a source term to account for chemical reactions and radiative absorption.

The boundary condition on the front surface of a solid obstruction is computed as:

$$-k_r \frac{\partial T_s}{\partial x}(0,t) = q_{\text{ch}}^\prime + q_{\text{g}}^\prime$$

where $q_{\text{g}}^\prime$ and $q_{\text{ch}}^\prime$ are convective and radiative heat fluxes, respectively, constituting total heat flux at a surface. The convective heat flux with the convective heat transfer coefficient, $h$, is calculated as:

$$q_{\text{g}}^\prime = h (T_g - T_s)$$

where $T_g$ is the gas temperature. The convective heat transfer coefficient, $h$, is calculated as:

$$h = \max \left[\frac{C(T_g - T_s)^\frac{1}{2}}{L Na} \frac{2k}{\delta_t} \right] W / (m^2 K)$$

where $C$ (empirical coefficient for natural convection) = 1.52 for horizontal plate and 1.31 for a vertical plate, $k$ is the thermal conductivity of the gas, $\delta_t$ is the cell size (gas phase), and $L$ is the characteristic length related to the physical size of an obstruction. The radiative heat flux, $q_{\text{r}}^\prime$, is calculated as follows:

$$q_{\text{r}}^\prime = \varepsilon (q_{\text{r},in} - \sigma T_s^4)$$

where $q_{\text{r},in}$ is the incident radiative heat flux, and $\varepsilon$ is Stefan–Boltzmann constant. Equation (10) is applicable based on the assumption that the thermal radiation from the surrounding environment is absorbed within an infinitely thin layer at the surface of the solid obstruction. In the surface temperature ignition model, when $T_g(0,t)$ (temperature of the surface) reaches pre-defined ignition temperature value, it starts to burn following a given HRRPUA(t) as function of time. In such cases, the intended HRRPUA(t) is translated into mass flux (MLRPUA(t)) for the fuel at a given solid surface as follows:

$$\text{MLRPUA}(t) = \frac{\text{HRRPUA}(t)}{\Delta H_{\text{com}}}$$
where, $\Delta H_{com}$ is the gas heat of combustion. When a surrogate fuel with heat of combustion, $\Delta H_c$, and HRRPUA($t$) is used for a different burning material having a different heat of combustion, $\Delta H_d$, then to account for intended HRRPUA($t$) from such material, FDS adjusts the mass flux of surrogate fuel from those burning material surface. The appropriate mass flux, MLRPUA($t$)$_d$, from such surface is internally computed as

$$MLRPUA(t)_d = \frac{HRRPUA(t)}{\Delta H_d} = MLRPUA(t) \cdot \frac{\Delta H_c}{\Delta H_d} \tag{12}$$

Regarding combustion, default mixing-controlled combustion model in FDS has been used for chemical reactions. In such case, the reaction rate is infinitely fast and species concentration limits the reaction. FDS invokes semi-empirical rules to calculate the rate of mixing of oxygen and fuel for a given cell at each time step. Each computational cell can be viewed as a batch reactor where reaction of only mixed composition can take place. The differential equation which governs the evolution of unmixed fraction of mass, $\xi$, within a cell is as follows:

$$\frac{d\xi(t)}{dt} = -\frac{\xi(t)}{\tau_{mix}} \tag{13}$$

where $t$ is time and $\tau_{mix}$ is the mixing time scale. The solution of equation (13) as follows:

$$\xi(t) = \xi_0 \cdot e^{-t/\tau_{mix}} \tag{14}$$

where, $\xi_0$ is the initial condition of unmixed fraction of mass within a cell. $\xi_0 = 1$ is the default value in FDS and an appropriate assumption for a turbulent diffusion flame in which mixing takes place before combustion takes place. $\xi_0 = 0$ for a cell indicates an initially fully mixed condition where premixed combustion can take place. At any given time, the chemical composition of a computational cell depends on the combination of a mixed and unmixed portions of a specie. If the mixing is slow enough, then even in the presence of sufficient oxygen in a grid cell to combust all the fuel, the fuel may be left unburnt at the end of the time step. The cessation of combustion in the simulations has been governed by the sufficient fuel and oxygen level within the computational cells, with temperature being beyond the critical flame temperature (FDS’s Extinction Model 2 [12]).

3.2. Adapted approach

A literature review was conducted to study the applicability and limitations of the existing methods developed to predict cable fires on horizontal trays. The major thrust was to combine and alter (if required) the existing methods to minimize their prescriptive values and shortcomings or formulate a new method, and to adapt the available data into simulation with more flexibility for predictive fire spread.

Under CHRISTIFIRE project [7], the burning characteristics of grouped electrical cables used in NPPs were quantified. Many experiments were conducted where electrical cables on horizontal ladder cable trays used in NPPs were burnt in a relatively open configuration to study the heat release rates. Based on the study, a simplified approach named as FLASHCAT (Flame Spread over Horizontal Cable Trays) was proposed for such cables.

FLASHCAT model stipulated many assumptions for its use. A few among them, like cables should be away from walls, the ignition source should be beneath the lowest tray, or the extent of fire in the lowest tray in the initial phase of the test should be of the same width as that of the ignition source, did not fit well with PRF BCM-S2 experiment set up. Under such assumptions, along with others mentioned in Ref. [7], a fire is assumed to propagate upwards through a series of cable trays following an empirically determined time sequence (defined as vertical spread rate). Upon ignition of a cable tray, a lateral spread of fire begins and continues towards both ends of the tray (defined as horizontal spread rate). With such fire spread, an overall V-shaped burning pattern develops, which expands laterally with time. The vertical spread rates and horizontal spread rates are numerically fixed for cables. As the assumptions conflict with the configuration of the PRF BCM-S2 experiment, the spread rates are not used in the FDS simulations. However, the concept and empirical formula (with some changes) provided by the FLASHCAT for local fire duration ($\Delta t_{fire}$) at a given location is used and implemented in FDS. With such implementation, each computational cell having the cable surface burns (upon ignition) for $\Delta t_{fire}$ seconds following the idealized HRRPUA($t$) curve shown in Fig. 2. Average HRRPUA of 245 kW/m$^2$ and 314 kW/m$^2$ obtained from the cone-calorimeter test denotes steady HRRPUA value between $\Delta t_{fire}$ and $5\Delta t_{fire}$, i.e., ($\bar{q}^{avg}_{avg}$) in Fig. 2 for idealized HRRPUA($t$).

It can be noted that when a cable surface computational cell burns in FDS, the consequent heat release rate from each burning cell will be internally computed as

$$HRR_{cable surface cell} = HRRPUA(t) \cdot A = MLRPUA(t) \cdot \Delta H_c \cdot A \tag{15}$$

where A is a single computational cell area used for cable surface in FDS. Clearly, as A ($\Delta H_c$ accounting for the MLRPUA($t$)) remains fixed throughout the simulation, the number of cells being on fire at a time will dictate the overall development of HRR for such fires. Thanks to the FLASHCAT model, the inputs required to calculate such idealized HRRPUA($t$) (and hence mathematically the idealized MLRPUA($t$) for a fixed $\Delta H_c$) consider and include many important parameters, as indicated by the formula for $\Delta H_{fire}$ as follows:

$$\Delta t_{fire} = \frac{m_c' \Delta H_c}{2\bar{q}_{avg}} \tag{16}$$

where $m_c'$ (kg/m$^2$) is the combustible mass per unit area. $m_c'$ is calculated as follows:

$$m_c' = \frac{n t_f (1 - \nu) m_c'}{W} \tag{17}$$

where n is the number of cables on each cable tray, W is the width of the cable tray, and $\nu$ is the char yield.

It is important to note that equation (17), if directly implemented into FDS, will distribute all combustible mass on the top side of a cable tray. Zavaleta et al. in Ref. [1] made an assessment of fire spread over horizontal cable trays supported by video fire analysis. They proposed new measures to improve the FLASHCAT model prediction. One among them was to include both top and bottom areas of the cable trays as cable fires may involve both the top and bottom areas of each tray. Thus, W in
equation (17) was replaced with $2W$ to account for both sides of cable trays (originally done in Ref. [1]). Equation (18) shows the new formula for $m''_c$ as follows:

$$m''_c = \frac{n_{\gamma_p}(1 - \nu)m^2}{2W}$$

The distribution of the combustible mass over the top and bottom side of cable trays in FDS is also required to implement the idealized cable structure for one-dimensional heat transfer (explained later), which will lead to the spread of fire over the bottom and top areas of cable trays. Holes which will be incorporated over cable trays (explained later) will lead to the ascending of flammable gases and flames released from the bottom surface through holes upwards and sideways of the cable trays. It is to be noted that as (widely spaced) ladder type cable trays are used in the experiment and their presence does not obstruct the ascending of flammable gases and flames, their physical structure is not made in simulations.

Beji et al. in Ref. [6] mentioned that using a homogenous rectangular slab to represent a cable surface with material properties will not produce a realistic flame pattern. In a numerical simulation set-up, such slabs without holes or voids will not allow flame to penetrate various trays and naturally spread the fire. They introduced openings between cable geometry in the simulation to allow the easy passage of smoke, heat, and flame through trays. The introduction of the openings was justified with adjustments to the dimensions of the rectangular cable slabs. Through a calculation, it was shown that the actual dimensions of the cable slabs did not affect the heat transfer calculations as long as their depth remained greater than the thermal penetration length during a fire.

Vitān et al. in Ref. [14] developed a stochastic approach to make simplified cable geometries for numerical simulations. It used the randomness of laying cables loosely along the horizontal tray to calculate the percentage of the area representing the openings between loose cables. The method considered the dimensions of the cable tray, cable diameter and cable length to estimate the area of the openings stochastically (interested readers can look through the paper for details with visual explanation). The same method was applied for the considered case, and the percentage of opening area to cable surface area on a tray was calculated as 7.64%. Openings were randomly distributed on the obstruction representing the cable surface slab, as shown in Fig. 3.

Clearly, the effective area of the cable surface slab was reduced by including openings. To take into account, the new effective area in this work, the new effective width, $W_{eff}$, was calculated as follows:

$$W_{eff} = \frac{\text{Area of the cable slab} - \text{Area of the openings}}{\text{Length of the slab}}$$

So, $m'_{c}$ is now calculated hereafter as follows:

$$m'_c = \frac{n_{\gamma_p}(1 - \nu)m^2}{2W_{eff}}$$

Using equation (20) in equation (16) provides a new estimate for $\Delta t_{fire}$ as follows:

$$\Delta t_{fire} = \frac{n_{\gamma_p}(1 - \nu)m^2 \Delta H}{q_{avg} W_{eff}}$$

Consequently, the new estimate of $\Delta t_{fire}$ will change the idealized HRRPUA(t) curve. However, with such adjustment, there will not be any change in the steady magnitude of HRRPUA(t) given by $q_{avg}$, but only $\Delta t_{fire}$ will get reduced with consequent changes in $\frac{\Delta H}{q_{avg}}$ and $\frac{W_{eff}}{W}$. This implies that the equivalent steady MLRPUA(t) from the computational cells of the cable surface will remain the same as before such adjustment. Regarding the implementation of idealized HRRPUA(t) in FDS simulations, based on $\Delta H_c$, equivalent MLRPUA(t) has been directly given as an input to model the idealized HRRPUA(t) as FDS provides an option to provide either HRRPUA(t) or equivalent MLRPUA(t).

The internal structure of a cable is generally non-uniformly layered and cannot be directly used in FDS. In FDS, solid surfaces are built with multiple layers, each consisting of multiple material components with different mass fractions. Thermo-physical properties of such solid surfaces comprising different materials and their thickness will govern the one-dimensional heat transfer (conduction) in the direction normal to the surface and heating the solid surface. So, the cables’ internal structure needs to be simplified, adapted, and approximated to be modelled in FDS.

The idealized internal structure of the cable used in the experiment is shown in Fig. 4. It is clear that geometrically, the cable consists of seven small (insulation) circles of an equal area contained in one larger (Sheath/Jacket) circle and can be divided into two symmetrical halves through a dashed line. Therefore, cable structure simplification for one-dimensional heat transfer in FDS is done using its idealized geometrical and symmetrical features. Such simplification is utilized in related adaptation and approximation.

In the adaptation and approximation, only combustible matter is...
considered. As the internal combustible, i.e., insulation, is in contact with each other, the conduction path through such contacts is always available for insulation material. Moreover, it is fairly assumed that upon heating, and consequent thermal expansion, such contact for heat conduction will increase with the increasing temperature. Furthermore, as the conductor’s thermal conductivity was approximately 2500 times that of the thermal conductivity of insulation material, it was also assumed that heat absorbed by the conductor would be transferred to the insulation. Therefore, the metallic part, i.e., the conductor, is not considered in simplifying the cable structure.

Fig. 5 shows the two considered heat conduction paths from top to bottom (same for the bottom-to-top direction) for the idealized cable structure. The thickness “t1” and “t2” of cable materials will affect the one-dimensional heat conduction for the paths in Case-A and Case-B differently. As the same material of plastic (Table 2) was used for the jacket and insulation, thickness for the short path (Case-A) and long path (Case-B) was cumulatively summed as “thickness_short_path” and “thickness_long_path”, respectively, to represent the overall thickness for those paths in the symmetrical half of cable. As the actual path for one-dimensional heat transfer in the idealized cable structure cannot be determined, the average of the “thickness_short_path” and “thickness_long_path” was calculated to represent the thickness for the symmetrical half of the idealized cable. Finally, the cable surface properties on the upper and lower sides of the FDS cable slab obstruction were given the representative thickness. The sensitivity of HRR on such representative thickness is discussed later.

3.3. Computational domain and simulations

The computational domain with flame and smoke visualization is shown in Fig. 6. The white boundary lines in the x, y and z directions limit the computational domain with a uniform mesh of grid size 0.05 m. The dimension of the domain is 1.5 m × 4.4 m × 5.2 m. PE/PVC has been used as fuel species for cables using combustion reaction defined above in the experimental section. In the reaction, Methane of the combustion products was specified as an inert gas which did not participate in combustion. and Propane has been used as fuel species for blowtorches, and thus, the simulation involved two infinitely fast combustion reactions. Complex stoichiometry option of FDS involving multiple fuels in a simulation has been used to incorporate the combustion of PE/PVC and Propane in FDS [12]. The floor has the properties of concrete, and top and side boundaries are given OPEN boundary conditions [12]. The modelled blowtorches provide a power of about 6.5 kW for the first 150 s, then increased to 9 kW for the next 610 s.

Table 4 shows test cases used in simulations. A simulation with \( \dot{q}_{\text{avg}}' = 279.5 \text{ kW/m}^2 \) (average of 245 kW/m² & 314 kW/m²) was taken as a reference case simulation as not all the cable surface computational cells will receive irradiance having extreme values of 50 kW/m² or 75 kW/m² in the entire duration of the actual fire. To check the effect of extrema, simulations were also run with \( \dot{q}_{\text{avg}}' = 245 \text{ kW/m}^2 \) and \( \dot{q}_{\text{avg}}' = 314 \text{ kW/m}^2 \) to check the sensitivity of HRR on such values. Moreover, another simulation was also run in which the cable surface had (discrete) uniform distribution of \( \dot{q}_{\text{avg}}' = 245 \text{ kW/m}^2 \) and \( \dot{q}_{\text{avg}}' = 314 \text{ kW/m}^2 \) over its computational cells to check their combined and average effect on the development of HRR in a single simulation and compare it with the test case T1.

4. Results and discussion

4.1. HRR prediction

Fig. 7 shows the profile of HRR obtained in test case T1 and the experiment (experimental data taken from Ref. [8]). Overall, the HRR
profile obtained in test case T1 matches the experimental HRR profile well. The initial swift growth of the fire is closely captured. The peak HRR is underestimated by 4% and the time to reach peak HRR is over-estimated by 5%. However, fire decay happens approximately 180 s before the experimental time. It is suspected that in the decay phase, some combustibles should remain to burn, probably with $\dot{q}''_{av}$ lower than the ones used in the simulations. Adaptive HRRPUA(t) based on thermal feedback could improve the result.

4.2. Gas/flame temperature prediction

Fig. 8 shows various thermocouple positions above each tray. Thermocouples at positions 1, 3, 5, 18, 24, 26, and 28 (marked with blue circles) were considered in the simulation. Thermocouples were placed a few centimeters above the cables in the experiment and simulations to measure gas/flame temperatures. Since the properties of thermocouples used in the experiment were not available, in simulations the default properties of a thermocouple were used as mentioned in the FDS user manual guide [12]. The default bead diameter is 0.001 m, emissivity is 0.85, bead density is 8908 kg/m³ and specific heat is 0.44 kJ/kg/K.

Figs. 9 and 10 show the temperatures recorded above the lower and upper trays at different thermocouple locations and the test case T1. CC1 denotes the lower tray, and CC1_1, CC1_3, CC1_5, CC1_18, CC1_24, CC1_26, and CC1_28 denote the thermocouples at various locations above the lower tray as shown in Fig. 8, with numbers in blue circles. CC2 denotes the upper tray, and CC2_1, CC2_3, CC2_5, CC2_18, CC2_24, CC2_26, and CC2_28 denote the thermocouples at various locations above the upper tray as shown in Fig. 8, with numbers in blue circles. In general, the temperature predicted in the simulation is greater than the experimental values for the lower tray. Excluding the temperature recorded at location 3 (CC1_3), the simulation’s growth and steady phase profile matched close to the experimental values. At location 3 in the simulation model, the blowtorch modelled as a rectilinear FDS obstruction (with burner surface) was very close to the thermocouple leading to the initial spike in temperature recording compared to the experimental values. For the upper tray, excluding the temperature recorded at locations 24 (CC2_24) and 28 (CC2_28), the simulation’s growth and steady phase profile matched closely to the experimental values. At locations 24 (CC2_24) and 28 (CC2_28), there is a delay in flame to develop or reach the location compared to the experiment resulting in the recording of lower temperature by thermocouples. Moreover, the difference in the temperature past the initiation time of decay in the simulation compared to the experiment for thermocouples above both the trays is most likely because of the difference in the thermal inertia of thermocouples used in the simulation and the experiment.

Table 4

<table>
<thead>
<tr>
<th>Test Case</th>
<th>HRRPUA ($\dot{q}''_{av}$), kW/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>279.5</td>
</tr>
<tr>
<td>T2</td>
<td>245</td>
</tr>
<tr>
<td>T3</td>
<td>314</td>
</tr>
<tr>
<td>T4</td>
<td>(discrete) uniform distribution of 245 and 314</td>
</tr>
</tbody>
</table>

Fig. 6. Computational domain with flame visualization.
4.3. Sensitivity study of physical parameters

4.3.1. Different average HRRPUA

The effect of different average HRRPUA has been clearly shown by test case T2 and T3 results (Fig. 11). When lower HRRPUA was used in T2, fire growth was the slowest than others, but the decay was closer to the experimental value. On the other hand, when higher HRRPUA was used in T3, fire growth was faster than others, but the decay was the earliest among all the test cases. Such results are easily explainable by equation (15), which clearly states that HRR developed is directly proportional to HRRPUA in the used model of FDS. Therefore, for a fixed area, which has been ignited (given that heat of combustion does not change), the overall HRR developed will be dictated by HRRPUA. Furthermore, a higher value of HRRPUA will lead to greater cumulative HRR from a location, thereby raising the temperature of surrounding cables by greater heat fluxes. Thus, surrounding cables based on the attainment of surface ignition temperature will also start to burn fast, leading to early decay. Vice versa holds for lower HRRPUA. It is also to be noted that test case T4 resulted in HRR very close to the test case T1. This indicates that the choice of $\dot{q}''_{avg} = 279.5\ kW/m^2$ represented well the combined and average effect of 245 kW/m$^2$ & 314 kW/m$^2$ in the test case T1. All the fuel mass was consumed in the simulation, and the difference from the test case was approximately $-4\%$ for each case.

Generally, the choice of HRRPUA is motivated by the availability of the experimental data [6], and it has also been the case here. Two different average HRRPUA, 245 kW/m$^2$ and 314 kW/m$^2$, were available based on two different irradiances, 50 kW/m$^2$ and 75 kW/m$^2$, respectively. However, the best fit to the experimental HRR curve was provided by the intermediate average HRRPUA ($\dot{q}''_{avg} = 279.5$). Intermediate average HRRPUA is expected for some irradiance between 50 kW/m$^2$ and 75 kW/m$^2$ in the cone-calorimeter tests.

In case of uncertainty, using different average HRRPUA, as done using 245 kW/m$^2$ and 314 kW/m$^2$ can still provide useful information regarding minimum and maximum values limited by dashed lines, as shown in Fig. 11. $\Delta HRR_{peak}$ having extrema interval as [1942 kW, 2479 kW] covers the peak experimental HRR, i.e., 2294 kW. $\Delta t_{peak}$ having extrema interval as [983 s, 1226 s] covers the time to reach the peak HRR i.e., 1034 s. However, while estimating different average HRRPUA from a cone calorimeter, a range of realistic irradiance values expected to be encountered during a cable fire is to be used as done for background data made available for this study so that target parameters are captured with acceptable uncertainty.

4.3.2. Different layer thickness in idealized cable structure

Fig. 12 shows the effect of different layer thicknesses. Apart from

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Fig. 7. Heat release rates of reference case simulation and experiment.

Fig. 8. Illustration of thermocouple positions above each tray [8].
layer thickness represented by “Thickness_short_path”, “Thickness_avg_path”, and “Thickness_long_path” (Fig. 5), two more thickness values were used to clearly spot the effect of such thickness. The simulations used one with a value 30% lesser than “Thickness_short_path” and one with a value 30% greater than “Thickness_long_path” to check the sensitivity of HRR to the layer thickness.

As the cable slab obstruction in FDS was one cell thick with “EXPOSED” cable surface properties on the top and bottom sides, it accounted for 1-D heat transfer in the ±z direction. The minimum layer thickness represented by “30% less “Thickness_short_path” led to the fastest growth in HRR compared to the rest of the cases, and as the layer thickness increased, the evolution of HRR got delayed. “Thickness_avg_path” led to the evolution of HRR slower than “Thickness_short_path”, but faster than “Thickness_long_path”. The heat transfer to the other side of the cable slab obstruction is suspected to be faster when the thickness is less, raising the other side layer temperature more than the rest of the cases. The computational cells with already raised temperatures are expected to start a fire faster as they have less temperature left to gain to reach the predefined surface ignition temperature. Vice versa holds when the thickness is increased, in which the surface

Fig. 9. Temperature recorded above the lower tray in reference case simulation and experiment.
ignition on the other side gets delayed as its surface has to gain more temperature (by receiving heat flux on its surface) to reach the pre-defined surface ignition temperature. It is clear that the layer thickness should be carefully chosen while using with surface temperature ignition model, otherwise the evolution of HRR will be affected.

4.4. Effect of numerical parameter

4.4.1. Different grid sizes

Fig. 13 shows the HRR for three different mesh resolutions with cell sizes 0.1 m (coarse mesh), 0.05 m (intermediate mesh), and 0.025 m (fine mesh). Mesh refinement with a cell size of 0.025 m was done only in the fire area.

The prediction of HRR by computational domain having coarse mesh was poor and is not discussed further. In general, the profile of HRR remains the same for the growth and decay phases in both the case of intermediate and fine mesh simulations. The fine mesh simulation underpredicts the peak HRR by 3% compared to the intermediate mesh, which under-predicts the HRR by 4%. Moreover, the time to reach the peak HRR is under-predicted by 6% by fine mesh simulation compared

Fig. 10. Temperature recorded above the upper tray in reference case simulation and experiment.
to the intermediate mesh simulation, which over-predicts the time to reach the peak HRR by 5%. Clearly, there is not a significant improvement using the fine mesh compared to the experimental values and to the intermediate mesh, however the comparative computational time with the intermediate mesh was very high. It took about 12 days to finish the fine mesh simulation against the 2.5 days completion time with the intermediate mesh. Fine mesh simulation ran 20 MPI processes compared to the other mesh, which ran with 13 MPI processes. Each process in both cases had one mesh. Given the higher computational cost with no drastic improvement in fine mesh simulation, all results

Fig. 11. Effect of average HRRPUA on heat release rate.

Fig. 12. Effect of different layer thickness on heat release rate.

Fig. 13. Heat release rate in different grid size computational domains.
presented in this paper have the intermediate mesh size.

It is also to be noted that even though the fine mesh simulation has led to a slightly different result than the intermediate mesh simulation, the difference in the result could be compensated by different layer thicknesses. More specifically, using a layer thicker than “Thickness_avg_path” in the fine mesh simulation could shift the result towards the intermediate mesh simulation with “Thickness_avg_path” layer thickness. Such uncertainties and compensation effects can be covered by running well-designed multiple simulations, which is out of the scope of the present work.

4.4.2. Mode of turbulence modelling (LES/VLES)

Fig. 14 shows the HRR profile for the test case T1 when ran under VLES and LES simulation mode. Clearly, no considerable difference was found when the simulation mode was changed from VLES to LES. With the grid size of 0.05 m used in such simulations, it is speculated that the cable surface cells adjacent to burning cells receives approximately the same heat flux in both the simulation modes to attain the pre-assigned ignition temperature and cause fire spread. The change of simulation mode does not change the combustion dynamics near cable surface cells. Thus, all the simulations, as mentioned before, were run in default simulation mode, i.e., VLES.

5. Conclusion

The assessment of the heat release rate of cable fires is of critical importance for the nuclear industry as HRR dictates the production of smoke, toxic gases, and soot, augments in radiative heat flux, and timeline of visibility which affect fire spread, evacuation, and firefighting. This paper presents the steps taken using CFD-based Fire Dynamics Simulator software along with a modified and adapted FLASHCAT model to predict the heat release rate of fire spread over two horizontal cable trays replicating an experiment. The experiment was conducted by IRSN as part of the OECD PRISME3 program in an open atmosphere with insulated wall-supported trays.

The methodology includes using solid slabs (depicting trays with cables) with cable properties on both top and bottom sides, along with an estimated number of holes on slabs to allow the smoke and flame to penetrate the trays and produces an actual flame shape over the trays. The internal structure of the cable has been idealized for one-dimensional heat transfer in FDS and implemented with appropriate thickness and material properties on solid slabs. Once a computational cell on such slab surface reaches a pre-defined temperature, it starts to burn following the idealized HRRPUA(t) curve, which has a steady phase of average HRRPUA. The reference case simulation with the average HRRPUA of 279.5 kW/m² has produced acceptable results where peak HRR was underestimated by 4% and the time to reach peak HRR was overestimated by 5%. Overall, the HRR development profile was also satisfactorily captured. The other two values for average HRRPUA, i.e., 245 kW/m² and 314 kW/m², used in the simulations showed the sensitivity of HRR to it. Moreover, HRR was also found to be sensitive to the layer thickness used for idealized cable structure. It is clear that the choice of average HRRPUA and layer thickness is crucial to produce a reliable result using the methodology outlined in this paper.

In future, work can include testing the outlined methodology using more test cases with different cable types and tray arrangements to assess its reliability. Input variables can also be varied in different mesh size computational domains to carry out Monte Carlo simulations to cover their uncertainties and compensation effect in the desired output. Furthermore, adapting the idealized HRRPUA curve to the dynamic thermal feedback in the simulation should also be researched to improve the results, as it adds flexibility to fire spread based on any changes in the surrounding environment.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Co-author, S. Hostikka, is one of the editorial board member of fire safety journal.

Data availability

The authors do not have permission to share data.

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References


