Numerical analysis of fire propagation on a horizontal cable tray using the fire dynamics simulator (FDS) model

Jaiho Lee*, Young-Seob Moon
Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yuseong-Gud, Daejeon, Korea 34142
**Corresponding author: jlee@kins.re.kr*

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1. Introduction

Nuclear power plants (NPPs) that adopt risk-informed performance-based fire protection programs assess the fire risk contribution to core damage frequency based on fire modeling analysis [1]. Even in the case of deterministic fire protection programs, fire modeling is applied as a resolution methodology for important-to-safe-shutdown components that are non-compliant in the post-fire safe shutdown analysis considering multiple spurious operations [2]. In NPPs, various power, instrument, and control cables are used to operate non-safety or safety equipment. These cables are treated as one of the main combustibles in fire hazard analysis [2]. For this reason, several experimental and numerical studies on cable tray fires have been conducted in the NPP industry [3-5].

The US NRC developed a FLASH-CAT model that analytically predicts the idealized time history of local heat release rate per unit area (HRRPUA) of cable tray fires based on several cable tray fire experiments [6]. In the NPP industry, the FLASH-CAT model has been widely used to simulate cable tray fires. However, the FLASH-CAT model cannot be applied to all cable tray fires, because it was developed based on experimental results in the open space where cable trays were away from walls and a ceiling.

OECD/NEA has been carrying out an international joint research project, i.e., PRISME [7-8]. In the PRISME project, experimental studies on cable tray fire propagation have been conducted in an open atmosphere condition and under a confined mechanically-ventilated multi-compartment environment for improving nuclear power plant fire safety. Several numerical studies on cable tray fires have been conducted to validate various fire models based on the experimental results of the PRISME project [9-11].

Lee et al. [11] investigated the propagation of cable tray fire with different cable fire models using a fire dynamics simulator (FDS). They applied a simple model using a specified burning rate for fuel combustion. In their study, the cable tray fire propagation in the simple model was affected by the thicknesses of the cuboid surfaces representing cables. In addition, the cable tray fire propagation was affected by the grid size.

This paper aims to describe the effect of the input parameters of the simple model of the FDS on the fire propagation of a single horizontal cable tray loaded with thermoplastic cables. Herein, we consider the following parameters: grid size, fire growth curve, and cable tray surface thickness.

2. Methods

2.1 FDS Model

An FDS is a computational fluid dynamics model that predicts low-velocity turbulent flows, such as thermal flows caused by fires [12]. The FDS uses a simple model (where burning rate is specified) or pyrolysis model (where burning rate is not specified) to predict the time-dependent heat release rate (HRR) curve based on fuel combustion. In FDS, specifying the burning rate, i.e., heat release rate per unit area (HRRPUA) or mass loss rate per unit area (MLRPUA) is referred to as the simple model [12]. The pyrolysis model calculates the time history of fire growth based on the thermophysical properties of the fuel. In the pyrolysis model of the FDS, the gas-phase reaction must be explicitly defined. In the case of liquid fuel, the pyrolysis model is applied by specifying the boiling temperature [12]. However, in the case of solid fuels, input variables such as pre-exponential factor and activation energy must be set to use the pyrolysis model. The input parameters of the solid fuels of composite-material-based components, e.g., cables, should be determined via thermal gravimetric analysis or using microcalorimeters. Therefore, it becomes difficult to simulate cable tray fire using the pyrolysis model in the FDS.

In the simple model, the pyrolysis rate of the fuel is not calculated, and the fire growth rate in terms of HRRPUA or MLRPUA curve is prescribed. When the local surface temperature of the fuel achieves the ignition temperature, the burning rate of the fuel is determined based on the prescribed fire growth curve (e.g., MLRPUA or HRRPUA curve), and then, the HRR is calculated based on the effective heat of combustion. The fire growth curve of fuel to use a simple model should be determined experimentally or assumed based on an appropriate reference.

The FLASH-CAT model analytically predicts the fire duration and spread rate of flame in vertical or horizontal directions for cable trays based on cable tray fire experimental results [6]. Using the FLASH-CAT model, the local HRRPUA time history of cable tray fire can be manually predicted. The spread rates of the FLASH-

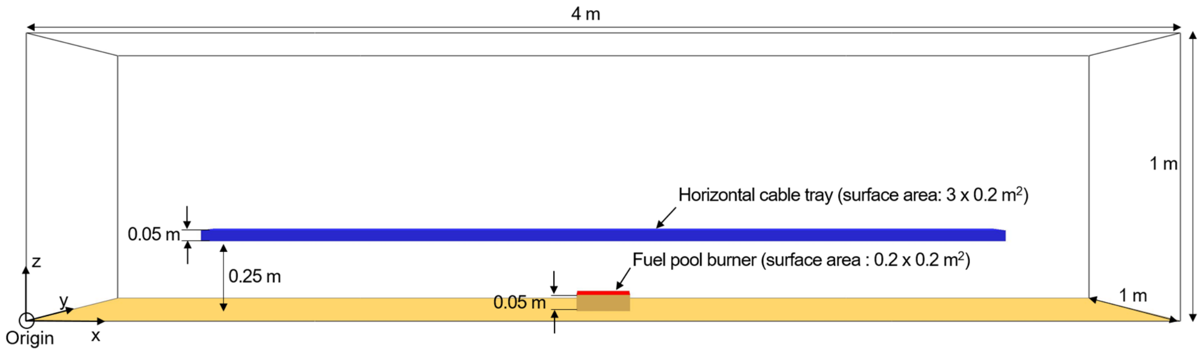

Fig. 1. Computational domain of a thermoplastic cable tray fire

CAT model in the horizontal and vertical directions of cable trays are referenced from NUREG/CR-6850 [1].

In the FDS model, the spread rate in the horizontal direction of a cable tray fire event can be specified as an input value. If the horizontal spread rate of FLASH-CAT is considered as an input to the FDS model, the HRR curve generated by the FDS should be similar to the curve derived manually using FLASH-CAT. However, in the simple model, if the horizontal fire spread rate is not prescribed, the HRR predicted by the FDS is different from the HRR predicted manually. As the FDS calculates the surface temperature locally based on the resolution of one cell size, the horizontal fire spread rate in the simple model is influenced by the cell size.

2.2 Input parameters

With regard to the input parameters in the simple model of the FDS, the grid size significantly affects on the local temperature. In previous studies [13-14], the characteristic diameter normalized by cell size, also known as the characteristic diameter ratio, is considered to determine an optimal cubic cell size. The characteristic diameter is determined as follows [14]:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{2/5} \quad , \qquad (1)$$

where $\dot{Q}$ (kW) denotes the heat release rate , ρ_∞ (kg/m^3) denotes the ambient density of air, c_p (kJ/kg/K) denotes the specific heat of air, T_∞ (K) denotes the ambient air temperature, and g (m/s^2) denotes the acceleration of gravity.

Previous studies indicated that a ratio of 5 to 10 provides favorable results for problems related to the gross smoke movement. Herein, three cubic cell sizes of 0.05, 0.025, and 0.02 m were considered for measuring the grid sensitivity. Table I shows characteristic diameter ratios for the grid sensitivity.

In the FDS, multiple cable bundles loaded on a ladder-type cable tray are modeled as a cuboid obstruction with thermally thick solid surfaces. Previous studies have treated the top and bottom surfaces of the obstruction with cable materials [9-10]. In the pyrolysis model, the burnout time of pyrolyzing solid fuels is calculated automatically based on the surface thickness, component density, and reaction rates of the materials. In the simple model, the burnout time of solid fuels is not calculated automatically; the burning rate and duration are not determined by the composition or thickness of the solid surface. The solid surface thickness is used for the solid phase heat transfer calculation [12]. In the simple model, the thickness of the solid surface treated with cable materials can affect the local temperature. Herein, four thicknesses of 0.001, 0.005, 0.01, and 0.02 m were considered for the solid surface with cable materials.

Table I: Grid size for a single horizontal cable tray fire event

Cubic cell size (m)	Total number of cells	D*/dx
0.05	32,000	12
0.025	256,000	24
0.02	500,000	30

Fig. 1 shows the FDS simulation domain for one horizontal cable tray fire. To avoid the influence of the hot gas layer or ventilation condition, etc., the simulation domain was assumed to be an open space. Similar to previous studies, multiple cables placed on one cable tray were assumed to be one cuboid obstruction regardless of the arrangement of the cables. Only the top and bottom surfaces of the obstruction were considered as cable materials.

The top and bottom surfaces representing the cables were ignited by heptane pool fire placed under the tray. The HRR and fire duration of the heptane pool were calculated as follows [15]:

$$\dot{Q} = m''\Delta H_{c,eff}(1 - e^{-k\beta D})A_{dike} \text{ , and} \qquad (2)$$

$$t_b = \frac{4V \cdot \rho}{\pi D^2 m''} \qquad (3)$$

where $\dot{Q}$ (kW) denotes the pool fire heat release rate, m''(kg/m^2-sec) denotes the mass burning rate of fuel per unit surface area, $\Delta H_{c,eff}$ (kJ/kg) denotes the effective heat of combustion of fuel, A_{dike} (m^2) denotes the surface area of the pool fire, $k\beta$ (m^{-1}) denotes the empirical constant, D (m) denotes the diameter of the pool fire, V (m^3) denotes the volume of liquid, and ρ (kg/m^3) denotes the liquid fuel density.

Table II: Thermo-physical properties of heptane and PVC

Thermal Properties	Heptane	PVC
Area (m^2)	0.04	0.6
Volume	0.65 liter	0.03 m^3
Mass burning ratio (kg/m^2-sec)	0.101	0.0127
Effective heat of combustion (kJ/kg)	44,600	16,400
Density (kg/m^3)	675	1,380
Empirical constant (m^{-1})	1.1	NA
Thermal Conductivity (W/m/K)	0.13	0.156
Specific heat (J/kg/K)	2,242	1,280

Thermocouple cables were assumed to be polyvinyl chloride (PVC), and the thermo-physical properties of the cables were referenced from the SFPE handbook [16]. The peak HRRPUA of the thermocouple cables was assumed to be 250 kW/m^2 [6]. Table II lists the thermo-physical properties of heptane and PVC.

In the FLASH-CAT model, the fire duration time was calculated using the following equation [6]:

$$\Delta t = \frac{nY_p(1-v)m'\Delta H_{c,eff}}{5W\,\dot{q}''_{avg}/6} \quad , \qquad (4)$$

where $\Delta H_{c,eff}$ denotes the effective heat of combustion, and $\dot{q}''_{avg}$ represents the HRRPUA, *n* denotes the number of cables per tray, Y_p denotes the mass fraction of non-metallic material, v denotes the char yield, m′ denotes the mass per unit length of cable, and W denotes the width of the tray.

Table III: Input parameters of FLASH-CAT

Thermal Properties	Value
Cable tray width (m)	0.2
Number of cables per tray	6 for fire duration of 380 s 12 for fire duration of 765 s
Char yield	0 for thermoplastic
Mass per cable length (g/m)	0.36
Heat of combustion (kJ/kg)	16,400
Peak HRRPUA (kW/m^2)	250
Mass fraction	0.45

In previous study [6], the cable arrangement on the tray significantly affected the fire propagation in case of horizontal cable tray fires. The loose cable arrangement favored the preheating of cables, leading to higher fire HRR compared to dense arrangement. However, in this study, the cable arrangement was not considered because the cables on a tray were modeled with a cuboid obstruction. We used the simple model in which burning rate is based on FLASH-CAT and the onset of the burning is controlled by ignition temperature. This simple model can be referred to as temperature-dependent FLASH-CAT (TFC) model. Table III lists the input parameter values of the FLASH-CAT model. Herein, it was assumed that 6 or 12 cables were loaded on a tray to investigate the effect of the amount of combustibles on the fire HRR. Fig. 2 shows two HRRPUA curves for a cable tray fire event. The fire duration was calculated using Equation (4), and the initial growing time and decay time were assumed to be 1/6 times the fire duration. According to Equation (4), the fire durations were 380 s for 6 cables and 765 s for 12 cables.

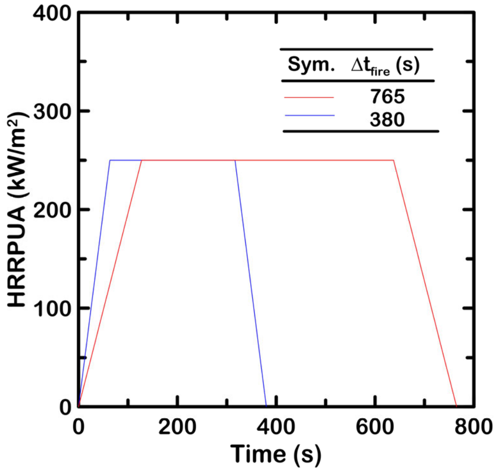

Fig. 2. HURRPUA curves of thermoplastic cable fire used as inputs for the FDS.

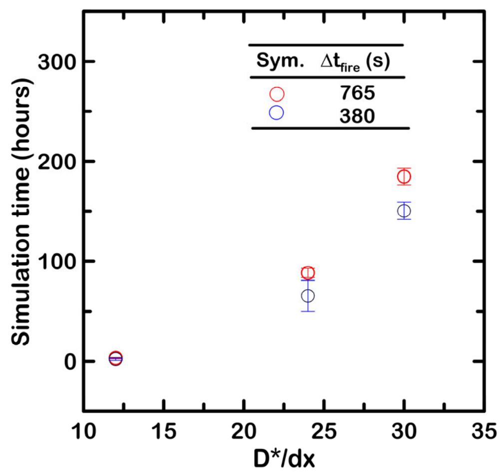

Fig. 3. Averaged simulation time considering different characteristic diameter ratios.

3. Results and discussion

3.1 Simulation time

Herein, each simulation condition was calculated using four message-passing interfaces (MPIs). Three OpenMP (Open multi-processing) threads were assigned to each MPI. Therefore, one simulation test was performed using 12 logical processors. Even if the grid size and duration were constant, the change in the surface thickness changed the value of the elapsed simulation time. Fig. 3 shows the averaged elapsed simulation time for different grid sizes.

Each data point represented the averaged simulation time for four surface thickness conditions when the grid size and duration were constant. The error bar represented the standard deviation of the data for each average value. The larger the characteristic diameter ratio (D*/dx), the longer the simulation time. As the time duration increased, the simulation time increased. However, when the grid size was large (D*/dx = 12), the change in the time duration negligibly affected the simulation time.

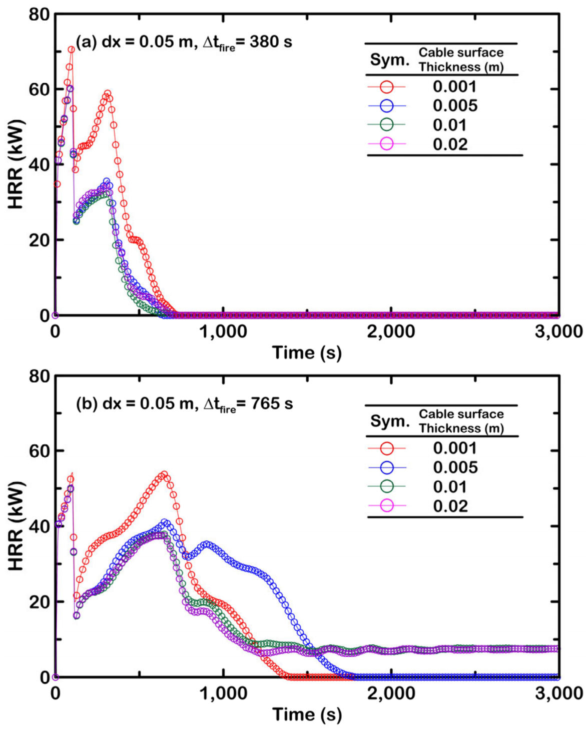

Fig. 4. Heat release rate time curve for different fire durations: (a) 380, and (b) 765 s considering a cubic cell size of 0.05 m.

3.2 HRR time curves

Fig. 4 shows the change in the HRR curve for different fire durations and surface thicknesses when dx = 0.05 m. The first peak was caused by a heptane pool fire event and the second peak was caused by a cable tray fire event. Analytically, the second peak should reach approximately 300 kW; however, it did not even reach 60 kW. This indicates that the fire extinguished before the cables burned out. A cubic cell size of 0.05 m predicted a significantly low local temperature near the cable tray owing to lower spatial resolution. As a result, the cables did not burn completely and were extinguished early. When the fire duration increased from 380 to 765 s, the time to reach the peak HRR increased. In Fig. 4(a), the HRR curves were similar regardless of the surface thickness, except for the condition where the surface thickness was 0.001 m. However, in Fig. 4(b), the peak HRR decreased as the surface thickness increased. In the previous study [11], the thickness of the surface affected the HRR curve when the simple model was used.

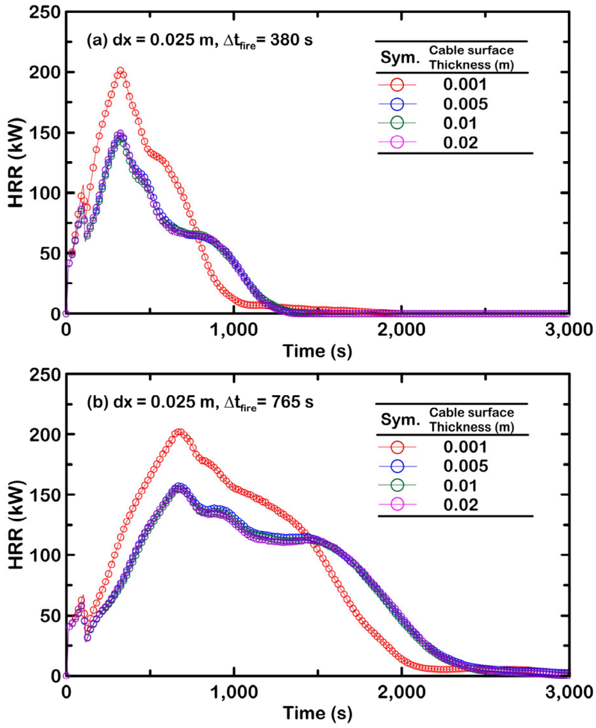

Fig. 5. Heat release rate time curve for different fire durations: (a) 380 and (b) 765 s considering a cubic cell size of 0.025 m.

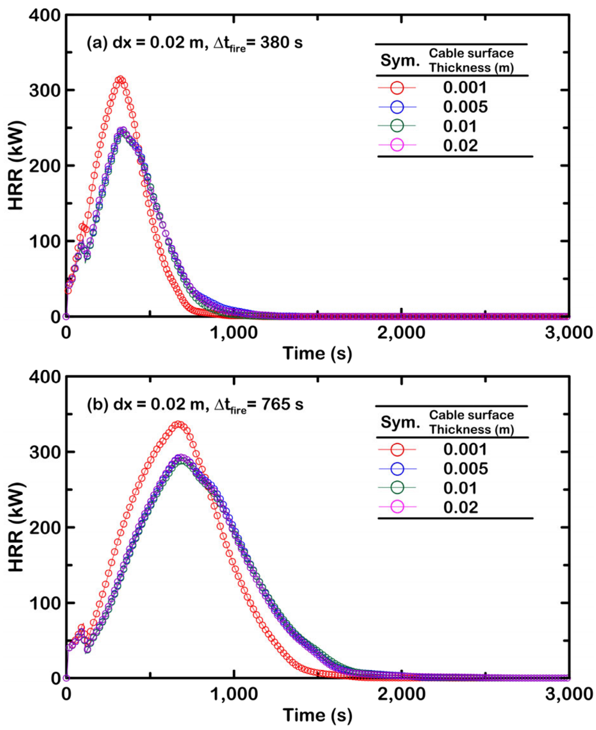

Fig. 6. Heat release rate time curve for different fire durations: (a) 380 and (b) 765 s considering a cubic cell size of 0.02 m.

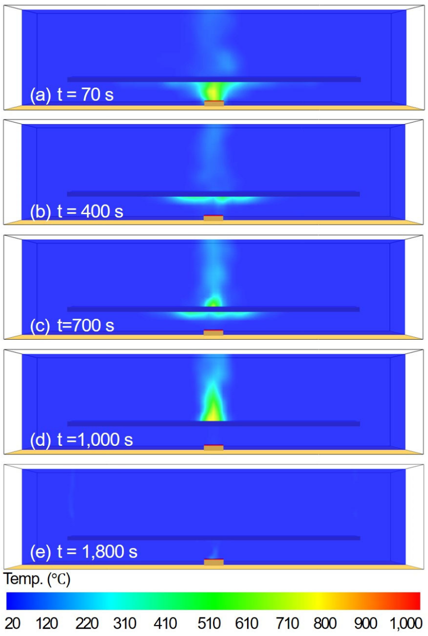

Fig. 7. Temperature distribution for different times at the condition of dx = 0.05 m, Δt_{fire} = 765 s, and surface thickness of 0.001 m.

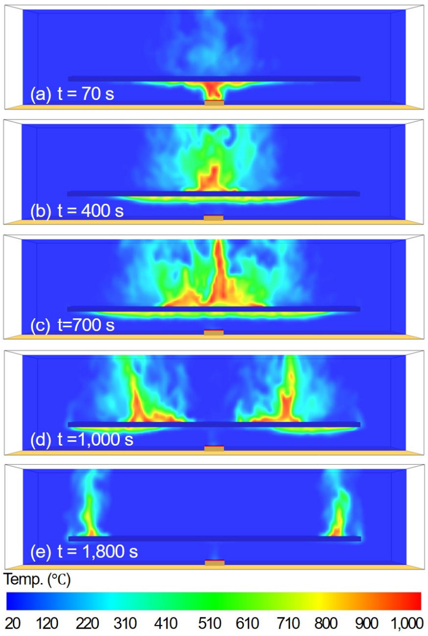

Fig. 8. Temperature distribution for different times at the condition of dx = 0.025 m, Δt_{fire} = 765 s, and surface thickness of 0.001 m.

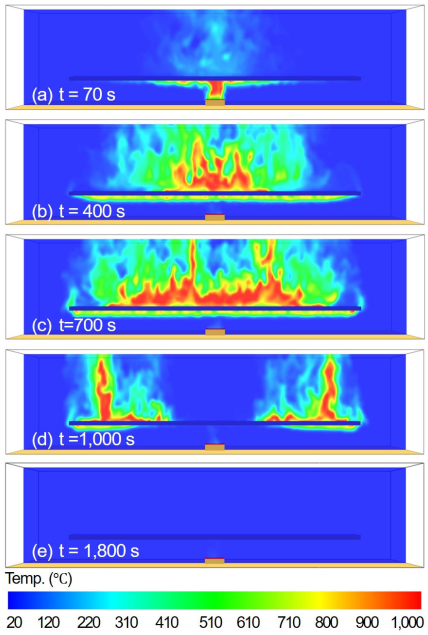

Fig. 9. Temperature distribution for different times at the condition of dx = 0.02 m, Δt_{fire} = 765 s, and surface thickness of 0.001 m.

Fig. 5 shows the change in the HRR curve for different fire durations and surface thicknesses when dx = 0.025 m. When the fire duration increased, the time to reach the peak HRR increased, and the fire extinguished later. Regardless of the fire duration, the peak HRR was 200 ± 1 kW for the surface thickness of 0.001 m and 153 ± 4 kW for other conditions. Under each fire duration condition, the HRR curves agree with each other except for the condition where the thickness was 0.001 m.

Fig. 6 shows the change in the HRR curve for different fire durations and surface thicknesses when dx = 0.02 m. As shown in Fig. 6, the cable tray fire extinguished earlier, and the value of peak HRR increased more. This is because the spatial resolution for local temperature prediction increased as the cubic cell size decreased. However, as shown in Fig. 6, the peak HRR value was more affected by the fire duration when compared to Fig. 5. In Fig. 6(a), the peak HRR was 315 kW (increased by 57.5%) at a thickness of 0.001 m and 247 kW (increased by 68.5%) under other conditions, when compared to Fig. 5(a). Then, in Fig. 6(b), the peak HRR was 337 kW (increased by 61.4%) at a thickness of 0.001 m and 293 kW (increased by 91.5%) under other conditions, when compared to Fig. 5(b). As the fire duration increased, the peak HRR increased. This is because the amount of combustibles increased, causing the fire to spread to a wider area and the burning to last longer.

When the cubic cell size increased, the time to reach the peak HRR reduced, and the value of peak HRR increased significantly. Therefore, when simulating a cable tray fire event using the simple model, i.e., TFC model, sensitivity analysis for an appropriate grid size should be performed.

3.3 Temperature distribution

Figs. 7–9 show the temperature distribution over time for cubic cell sizes of 0.05, 0.025, and 0.02 m considering a surface thickness of 0.001 m and a fire duration of 765 s. The temperature distribution in Figs. 7–9 is related to the HRR curves with a surface thickness of 0.001 m in Figs. 4(b)–6(b).

At t = 70 s, the pool fire heated the cable tray, as shown in Fig. 7. The cable ignited when its surface reached 218 °C owing to the pool fire. However, the relatively large cell size did not accurately calculate the local temperature near the cable tray. Therefore, the surface of the cable, which ignited when the temperature reached 218 °C, did not ignite further, and the fire did not grow.

The cable fire ignited by the pool fire propagated to both sides and fully ignited at approximately 700 s, as shown in Figs. 8 and 9. At t = 1000 s, the flame slowly diminished as it moved to both ends of the cable. As shown in Fig. 9, compared to Fig. 8, the temperature around the cable increased significantly. At t = 1800 s, the flames appeared at both ends of the cable tray in Fig. 8; however, the fire completely extinguished in Fig. 9.

In the original FLASH-CAT (OFC) model, the horizontal fire spread rate and the peak HRR were not affected by the grid size, because the horizontal spread rate was predefined [11]. However, in the TFC model, the growth of the HRR curve was influenced by the temperature distribution in the simulation space. The grid cell size significantly affected the local temperature near the cable tray, as shown in Figs. 7–9.

4. Conclusions

In this study, the HRR growth of a single horizontal cable tray fire event was numerically investigated using FDS. In the FDS simple model, i.e., TFC model, the burning rate was determined by FLASH-CAT, and the onset of the burning was determined by the local surface temperature. The main conclusions are as follows:

- When the characteristic diameter ratio in the TFC model increased from 24 to 30, the elapsed simulation time averaged over the surface thickness change increased by 2.1 times for a fire duration of 765 s and 2.3 times for 380 s.
- In the TFC model, the grid size significantly affected the HRR time curve of cable tray fire events. When the cell size was 0.05 m, the cable fire did not grow properly. When the cell size decreased from 0.025 to 0.02 m, i.e., when the characteristic diameter ratio increased from 24 to 30, the peak HRR increased up to 91.5%.
- Under simulation conditions, when the fire duration increased from 380 to 765 s, the time at which the fire extinguished increased. Regardless of the grid size, the peak HRR value at a surface thickness of 0.001 m was higher than those at other scenarios.
- In the TFC model, the temperature distribution and the growth curve of HRR exhibited a very close relationship. At dx = 0.05 m, the local temperature near the cable tray did not increase significantly. This prevented the HRR curve from growing to a higher level. When the characteristic diameter ratio increased from 24 to 30, the flame size increased and the local temperature near the cable tray increased.

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