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An enhanced fire hazard assessment model and validation experiments for vertical cable trays

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HIGHLIGHTS

- An enhanced model was developed for vertical cable fire hazard assessment in NPP.
- The validated experiments on vertical cable tray fires were conducted.
- The capability of the model for cable tray with different cable spacing were tested.

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ABSTRACT

The model, referred to as FLASH-CAT (Flame Spread over Horizontal Cable Trays), was developed to estimate the heat release rate for vertical cable tray fire. The focus of this work is to investigate the application of an enhanced model to the single vertical cable tray fires with different cable spacing. The experiments on vertical cable tray fires with three typical cable spacing were conducted. The histories of mass loss rate and flame length were recorded during the cable fire. From the experimental results, it is found that the space between cable lines intensifies the cable combustion and accelerates the flame spread. The predictions by the enhanced model show good agreements with the experimental data. At the same time, it is shown that the enhanced model is capable of predicting the different behaviors of cable fires with different cable spacing by adjusting the flame spread speed only.

1. Introduction

In commercial nuclear power plants, cables are probably the most common combustibles (Najafi and Nowlen, 2004). A serious fire involving electrical cables occurred at the Browns Ferry Nuclear Power Plant in 1975 (O'Reilly et al., 1975), in which more than 1600 cables were damaged. The fire resulted in the loss of all Unit 1 emergency core cooling system. The damage was extensive because of the flammability of the cables. As a result of cable fires in Browns Ferry Plant, a large quantity of investigations were performed to study on the flammability of a single cable or cable trays. From 1975 to 1987, Sandia National Laboratories carried out various nuclear power plant fire safety researches (Klamerus, 1977) and identified the V-shaped burning pattern in a vertical stack of horizontal cable trays (Nowlen, 1989). For quantifying the burning behavior of electrical cables, a number of bench-scale and full-scale experiments were conducted at Factory Mutual Research Corporation (FMRC) from 1975 to 2000, which were summarized in the Society of Fire Protection Engineer (SFPE) Handbook (DiNenno et al., 2008). Valtion Teknillinen Tutkimuskeskus (VTT) Technical Research Centre of Finland also conducted some experimental work on cable fires under specific configuration (Mangs and Keski-Rahkonen, 1997). FIPEC (Fire Performance of Electrical Cables) project was performed by the European Commission since 2000. Different scales of experiments ranging from small-scale, full-scale to real-scale tests of various cables in the European market were carried out in the FIPEC project (Grayson et al., 2000).

In addition to experimental investigations, many researchers carried out cable fire modeling. Empirical correlations were used to predict the spread and flame height of cable fires, ignition time etc., e.g. Hees and Thureson (1996). CFD (Computational Fluid Dynamics) models were applied to cable burning since late 1990s (Hietaniemi et al., 2004), which greatly enhanced the development of cable fire simulation, and several simulation software

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packages were developed such as FDS, CFAST and so on. Based on the experiment results from 1975 to 2000, investigators developed some relatively simple methods to assess various cable fire phenomena. According to experimental measurements made by Tewarson et al. (1979) and Sumitra (1982), Lee (1985) found that the heat release rate per unit area of cables within stacked horizontal tray was approximately 0.45 times of that measured in the FMRC apparatus. Nowlen (1989) developed a model for the fire spread upwards through the array of horizontal cable trays based on the Sandia National Laboratories experiments. Babrauskas (1999), Karlsson (1992), Baroudi and Kokkala (1992) and Grant and Drysdale (1995) successfully developed a software package, which can be used for upward flame spread. However, complicated components, various ways of mounting and the presence of conductor and flame retardant material made its applications in the FIPEC project difficult. According to the experimental results, Hees et al. (2001a, 2001b) determined the optimum parameters for the *spreadup* package applying to cable fires. Hees and Thureson (1996) attempted to predict the spread of cable fires in full-scale by means of cone calorimeter test results. Correlations between small-scale and full-scale studies were investigated and analytical and numerical models were also developed.

In the previous investigations, most works were concentrated on the effects of several parameters such as the cable materials (U.S. NRC and EPRI, 2004), mounting location (Robinson and Samson, 2000), ventilation (Andersson et al., 2004), ignition (Babrauskas, 2005) and pyrolysis (Hirschler, 2014; Hees et al., 2001a, 2001b) on the cable fires. There were also some researches focused on the correlations between different scales of cable burning, whose main objective was to predict the fire hazards in full-scale by the data from the bench-scale experiments (Grayson et al., 2001; Hirschler, 1996; Nam et al., 2006).

Although there are a large number of simplified models for engineering applications and detailed models, these models usually were developed from very specific scenarios and configurations. To date, no generalized analytical theory or predictive model is available to accurately assess the fire risk and fire hazard in all possible configurations in commercial nuclear power plants. For this reason, a number of experiments were conducted in the CHRISTIFIRE (Cable Heat Release, Ignition and Spread in Tray Installations during Fire, U.S. NRC, 2013a, 2013b) program. Besides, with the aid of previous empirical correlations, CHRISTIFIRE developed a relatively simple model, FLASH-CAT (Flame Spread over Horizontal Cable Trays), for the prediction of spread and heat release rate (HRR) of a horizontal cable tray fire (U.S. NRC, 2013a), which was later extended to vertical cable tray fires (U.S. NRC, 2013b).

This study was motivated by the lack of understanding on fire characteristics of vertical cable trays with different cable layouts. A simple enhanced model to estimate heat release rate and cable flame length was developed by incorporating flame length correlation into the FLASH-CAT model. In order to validate the enhanced model, fire experiments on vertical cable trays with different cable line spacing were conducted. The effect of spacing between cables on the fire behaviors was investigated. The comparison on heat release rate and flame height between predictions and experimental data was subsequently carried out. Finally, the reliability of the enhanced model applied in estimating the heat release rate and flame length was discussed.

2. Enhanced model for vertical cable tray

The FLASH-CAT model was first proposed to predict HRR of horizontal cable tray fire and then extended to vertical cable tray fires. The model assumed that the spread rate is constant and the total heat release rate of the fire is mainly related to the burning cables (U.S. NRC, 2013b). In our cable fire experiments, it was found that the flame length plays a significant role in the cable burning behavior. This motivated the current modeling effort on incorporating the flame length into the FLASH-CAT model. An enhanced model incorporating the flame length correlation into the existing model was therefore proposed, where the model assumptions mainly followed those of the FLASH-CAT model:

(1) The cables burn in open spaces without impacts of external factors such as wind, sprinkler and so on;
(2) Except for the pilot premixed propane flame, there are not any other external heating sources for the cable burning;
(3) There are no heat losses through the conductors;
(4) The cables are not protected with coating and separated by barriers in the vertical trays;
(5) The thermo-physical properties of all materials, for example thermal conductivity, thermal diffusivity etc., do not change with temperature;
(6) The local heat release rate per unit area (HRRPUA) in the vertical cable tray is the same, denoted by $\dot{q}$;
(7) Vertical spread of the fire begins as soon as the cables are ignited by the pilot flame.

Based on these assumptions, the total heat release rate of burning cables $\dot{Q}(t)$ can be estimated as:

$$\dot{Q}(t) = \dot{Q}_{\text{burner}} + \dot{q}'' \cdot A(t) \tag{1}$$

where $\dot{Q}_{\text{burner}}$ is the heat release rate of the igniter, $A(t)$ is the burning area of the vertical cable tray. The burning area can be calculated by:

$$A(t) = W \cdot L_{\text{burning}} \tag{2}$$

where W is the width of the vertical tray, L_{burning} is the burning length of the cables. Due to various limitations, not all the non-metallic materials will burn during a cable fire, there will almost always be some char or solid residue left after the fire. The value of the residue mass divided by the original combustible mass is called char yield, which is designated by v. It can be determined from bench-scale tests. For the thermoset cable, the char yield ranges from about 0.1 to 0.5. While for the thermoplastic cable, it is assumed as 0 which means that all of the combustibles burnt out. Another important parameter for the calculation of L_{burning} is the vertical spread rate, which is considered as constant.

For a given specified heat release rate and a known combustible mass, Δt can be estimated as follows:

$$\Delta t = \frac{m_c'' \Delta H}{5\dot{q}''/6} \tag{3}$$

where m_c'' is the combustible mass per unit area of a single cable and ΔH is the combustion heat of the cable. In addition, the value of ΔH can also be used to convert the measured mass loss rate to the heat release rate which is useful for the model validation. The combustion mass per unit area of a single cable is calculated as follows:

$$m_c'' = \frac{nY_p(1-v)m'}{W} \tag{4}$$

where n is the number of cables in the vertical cable tray, Y_p is the mass fraction of non-metallic material, v is the char yield and m' is the mass per unit length of a single cable.

The flame length is not considered in the FLASH-CAT model. In the enhanced model, the correlation for predicting vertical cable flame length is added. Delichatsios (1984) and Quintiere et al. (1998) established correlation of flame length and the heat release rate per unit width, which is written as following:

$$L_f = K\dot{Q}'^{\alpha} \tag{5}$$