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Fire behaviors of flame-retardant cables part I: Decomposition, swelling and spontaneous ignition

Tai Gong [a], Qiyuan Xie [a,*], Xinyan Huang [b,**]

[a] State Key Lab of Fire Science, University of Science and Technology of China, Hefei, 230027, Anhui, China
[b] Department of Building Service Engineering, Hong Kong Polytechnic University, Kowloon, Hong Kong

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ABSTRACT

Electrical cable is a potential ignition source and fire hazard in residential houses, nuclear power plants, aircraft, and spacecraft. In this work, a bench-scale flame-retardant cable, consisted of the outer PVC sheath, middle XLPE insulation, and inner copper core, was heated uniformly inside a novel cylindrical heating chamber. The applied heat flux was transient, which increased with time close to a parabolic function. Once heated, the outer PVC sheath swelled and shrank under multiple stages. Before ignition, the swelling behavior was found to follow the same trend as the mass-loss rate. Analysis showed that the observed spontaneous ignition was likely a result of pyrolysis gas from inner XLPE insulation piloted by the smoldering hot spot (600~700 °C) on the outer charring PVC sheath. For the first time, the spontaneous ignition time was found to linearly increase with the integral heat flux, and it was different from other ignition experiments under the transient heat flux in the literature. Moreover, the measured critical mass flux of ignition increased with the heating power, and the critical surface temperature of PVC was above 500 °C. The results of this work provide important information about the swelling and ignition behaviors of the flame-retardant cable under a real fire, and may guide the design of future fire-safety cable.

1. Introduction

The electrical malfunction is one of the most important fire causes. It is responsible for 541,879 fires in China and 23,900 fires in the USA over 2005–2014, about one-quarter of total residential fires [1]. In particular, about 5% of home structure fires are initiated in the electrical wire or cable insulation [2]. In nuclear power plants (NPPs), electrical cables are a major source of fire ignition, consisting of nearly 42% of total fire cases where the cable insulation layer is the main combustible component [3]. Electrical cables with flammable insulation have been considered as a possible source of fire in residential buildings, nuclear power plants, aircraft and space vehicles. That is because electrical wires and harness can be ignited easily due to short circuit, poor contact, ground fault and external heating [4].

Fundamentally, what makes the combustion phenomenon in cable fire unique is its default combination of the outer sheath, plastic insulation and the inert metal core. The fact that the thermal conductivity of metal core is 2-3 orders of magnitude greater than the plastic insulation or sheath might significantly alter the heat transfer processes in ignition and fire spread. In the literature, most fundamental studies focused on the fire behaviors of thin research wires (diameter < 1 cm), e.g. Refs. [5–9]. For those thin wires, the decomposition of insulation and radial heat transfer were so fast that these processes were often neglected. However, commercial cables often have several thick plastic layers which can be flame retardant. These flame-retardant cables become more widely used under new fire-safety code and regulations, particularly in new high-rise buildings, NPPs, data center, and telecommunication rooms. At the same time, these flame-retardant cables also have more complex fire phenomena, including swelling, melting, dripping, cracking, auto-ignition, and smoldering ignition, which desire a better understanding.

Only a few studies have investigated the fundamental combustion in real cable fires. For example, Fernandez-Pello et al. [4] studied the piloted ignition time and the flame spread rate of several commercial cables under various external radiation and showed the similarity between the pyrolysis temperature of cable insulation and the ignition temperature. Tewarson and Khan [10] tested the upward flame spread over 35 commercial electrical cables with a copper or aluminum core, and found the metal core acted like the heat sink to slow down the flame spread. Xie et al. [11] conducted small-scale experiments (TG, FTIR, and

* Corresponding author.
** Corresponding author.
E-mail addresses: xqy@ustc.edu.cn (Q. Xie), xy.huang@polyu.edu.hk (X. Huang).

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MCC) on the new and aged cable PVC sheaths and found a strong aging effect on the heat release rate and toxic gas emission.

The external heat flux is one of the most important parameters for ignition (piloted or spontaneous). To better understand the ignition criteria, most works in the literature used a constant external heat flux, as reviewed in Ref. [12]. However, in most real fire scenarios, materials are ignited under a transient external heat flux, rather than a constant heat flux. In pre-flashover fires, with the increase of fire size and intensity, the material is more likely to be heated and eventually ignite under an increasing heat flux. Because of its complex nature, very limited studies have looked into the ignition behavior under a transient heat flux [13–16]. Vermesi et al. [13,14] studies the piloted and spontaneous ignition processes of plastic and wood under the transient external heat flux (parabolic time-dependent curves) and revealed that the traditional ignition criteria for constant heat flux might become inappropriate. To the best of authors' knowledge, there is no fundamental study on the spontaneous ignition of real cables yet.

In this work, a new facility was developed to uniformly heat the commercial cables under an increasing external heat flux. The detailed swelling and the spontaneous ignition behaviors of a bench-scale flame-retardant cable were investigated. The spontaneous ignition delay time and the corresponding ignition criterion under variable heating scenarios were quantified and analyzed.

2. Experimental methods

2.1. Experimental setup

According to the long multi-layer cylindrical shape of the cable, an annular heating chamber was designed to simulate the axially uniform heating conditions for vertical cables. Fig. 1 shows the schematic of the new fire-test facility. It includes three main parts, namely, an annular heating chamber, a frame for the vertical holding of cable sample and the data measurement system. The cylindrical heating chamber was made of Mullite bricks of 65-mm, thick and was covered by the steel shell to ensure the good heat insulation and structure stability. To ensure a uniform heat flux to the cylindrical samples in the central axis, 18 electric heating rods of 120 cm length were placed equidistantly around the inner wall of the chamber.

For an easy observation, there was a narrow vertical gap in the side wall of the heating chamber, as shown in Fig. 1c. Through this gap, the swelling and burning behaviors of the sample were monitored by a CCD camera (50 fps). The cable sample was hung vertically in the centerline of the chamber, and its mass loss was recorded by a digital scale (precision 0.1 g) using a T-shape frame and a mass balancer. Such design allows the scale to stay outside of the heating and prevents the influence of high-temperature chamber on the accuracy of the scale. Also, the temperature of the cable surface and centerline and the air temperature slightly above the sample were monitored by thermocouples (Type K, 0.5 mm bead), and their locations are shown in Fig. 1b. Note that this work studied the spontaneous ignition, so there was no pilot source (flame or spark) in the system.

2.2. Cable samples

In this experiment, a typical commercial flame-retardant cable (ZR-YJV) was tested, as shown in Fig. 2. The cable had three layers, namely, the polyvinyl chloride (PVC) sheath layer, the cross-linked polyethylene (XLPE) insulation layer and a bunch of copper core conductor. Once heated, the charring of flame-retardant sheath layer can lead to a poor electric insulativity and waterproofness [17]. The inner XLPE layer has a good intactness and electric insulativity, but it is more flammable.

The diameter of the cable sample is 22 mm, and the length of the sheath and insulation layer is 100 mm which is much shorter than the heater rod. Another 10-mm copper core was left at both ends to help hold

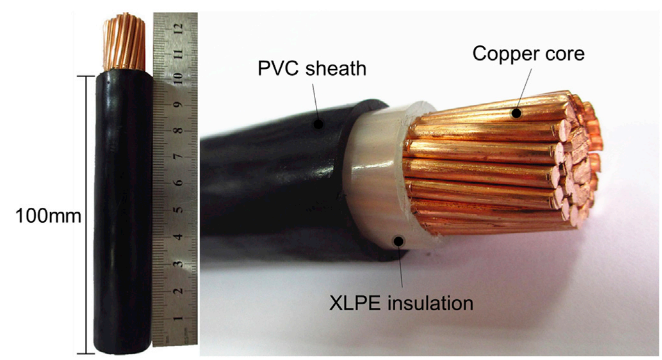

Fig. 2. Typical three-layer structure of single cable sample with 100 mm of the outer polymer layer.

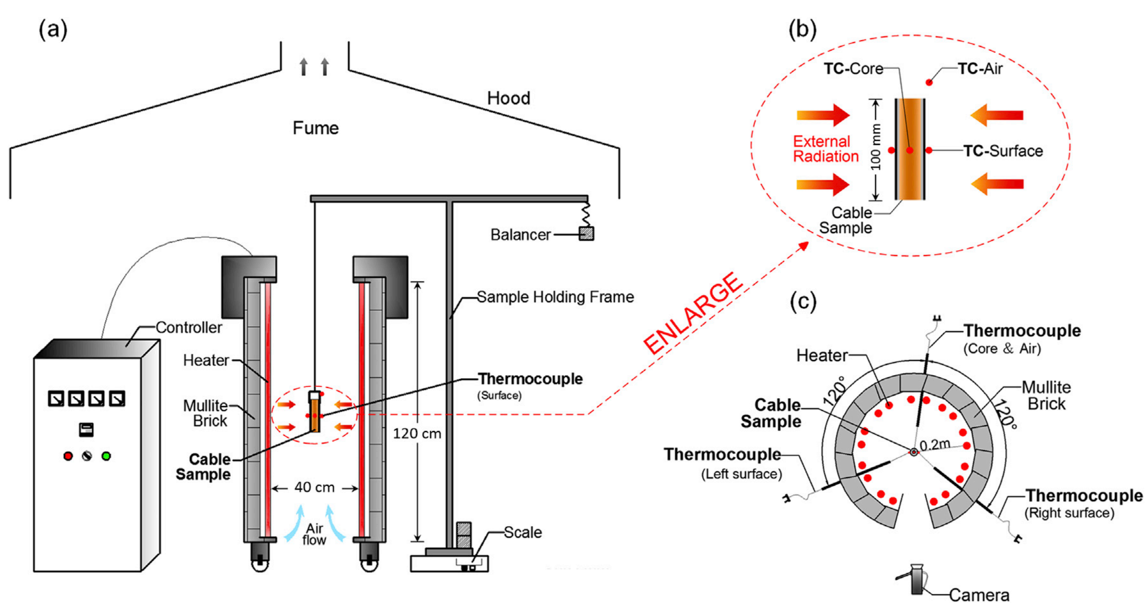

Fig. 1. (a) Schematic of the facility for ignition and flame spread mechanism of flame-retardant cables, (b) thermocouples locations around cable sample and (c) heating rods distribution in the top view of the heating chamber.