ARTICLE IN PRESS

Fire Safety Journal xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Flame spread over horizontal and vertical wires: The role of dripping and core

Yoshinari Kobayashi[a], Xinyan Huang[b,*], Shinji Nakaya[a], Mitsuhiro Tsue[a], Carlos Fernandez-Pello[b]

[a] Department of Aeronautics and Astronautics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
[b] Department of Mechanical Engineering, University of California, Berkeley, CA 94720, USA

ARTICLE INFO

Keywords:
Polyethylene (PE)
Dripping fraction
Burning rate
Core temperature profile

ABSTRACT

Dripping of polymer insulations in wire fire has a potential risk of igniting nearby objects and expanding the size of fire, but has not been well studied so far. In this experimental study, dripping behaviors during the flame spread over horizontal and vertical polyethylene (PE) insulated wires were investigated without external airflow. Two different wire dimensions – core/wire diameter of 3.5/8.0 and 5.5/9.0 mm – and three different PE insulations were tested. To identify effects of the core, wires with solid copper (Cu) core, hollow stainless steel (SS) core, and without core were tested, and both core and insulation temperatures were also measured during the flame spread. Experimental results showed that the high-conductance copper core acted as a heat source downstream to increase the flame-spread rate. However, in the upstream burning zone, the copper core also acted as a heat sink to cool the molten insulation and reduce its mobility. Thus, the copper core extended the residence time of molten insulation inside the flame to facilitate the burning while reducing the dripping. Moreover, for the downward flame spread, the heating by the dripping flow of hot molten insulation dominated over the heating by the core. The downward dripping flow is driven by gravity while limited by the viscous and surface tension forces. Therefore, the limited dripping flow along the cooler copper core reduced the downward flame spread. The trend of results was also found to be insensitive to the type of PE insulation. This is the first time that within a single flame, the simultaneous dual effect of the heat source and heat sink for the wire core was observed, and the influence of dripping on the flame spread over the wire was discovered.

1. Introduction

Electrical wires with flammable polymer insulation and metal core are responsible for many fire accidents in residential and commercial buildings, nuclear power plants, and space exploration missions. Because of poor contact, short circuiting, external heating, and ground fault, electrical wires and harnesses are easy to ignite. Between 2009 and 2011, the residential electrical fires in the US alone caused 280 deaths, 1125 injuries, and $1.1 billion in property losses, 53% of which involved electrical wires [1]. In nuclear power plants, electrical wires are a major source of fire ignition. In nearly 42% of total fire cases, the wire insulation was the main combustible component [2].

In recent years, space exploration activities have reached new heights, including the growing worldwide collaborations in the International Space Station (ISS), new human spaceflight projects in multiple developing countries, and space transport businesses by private companies like SpaceX, Blue Origin, Virgin Galactic, etc. In 2015, NASA published its official plans for human exploration and colonization of Mars [3]. Since the Apollo 1 fire claimed lives of three astronauts in 1967, fire in the isolated habitat such as spacecraft cabin has been identified as one of the largest risk factors causing tragic accidents [4,5]. In particular, electrical wires and harnesses have been identified as a potential source of fire in spacecraft [6–8].

The fundamental fire phenomena for thin wires (diameter of ~1 mm) have been studied by several groups in the last two decades, and they mainly focused on the role of wire core (heat sink or source) in the ignition or flame spread over the wire. For example, Leung et al. [9] modeled the influence of core under the external heating and non-flaming pyrolysis. Fujita et al. [10–12] conducted a series of studies on the influence of wire initial temperature, core diameter, oxygen concentration, external flow, pressure, and dilution gas on wire combustion. Umemura et al. [13] proposed a numerical model for flame spread over the wire and found that the copper core acted as a heat sink near extinction. Such heat sink was also observed in the

* Corresponding author.
E-mail address: xinyan.huang@berkeley.edu (X. Huang).

http://dx.doi.org/10.1016/j.firesaf.2017.03.047
Received 25 January 2017; Received in revised form 16 March 2017; Accepted 22 March 2017

Nomenclature

Symbols

A	cross-section area (mm^2)
c	specific heat (kJ/kg/K)
d	diameter (mm)
f	frequency (Hz)
g	gravity acceleration (m/s^2)
ΔH	heat of reaction (MJ/kg)
l_m	length of the molten layer (m)
m	mass (g)
$\dot{m}$	mass-loss rate (mg/s)
M_{dr}	mass of one drip (mg)
N	number (-)
$\dot{q}''$	heat flux (kW/m^2)
S	flame-spread rate (mm/s)
t	time (s)
T	temperature (°C)
V	speed (m/s)
Y	mass fraction (%)

Greeks

α	angle (degree)
γ	surface tension (Pa)
δ	length (mm)
ρ	density (kg/m^3)
λ	thermal conductivity (W/m/K)
μ	dynamic viscosity (Pa -s)

subscripts

b	burning
c	core
dr	dripping
f	flame
h	horizontal
g	gas
m	melting
o	outer
p	pyrolysis/plastic
t	total
v	vertical

experiments of Miyamoto et al. [14]. Nakamura et al. [15,16] revealed that the flame-spread rate over polyethylene (PE) insulated wires increased with decreasing pressure and increasing core conductance (both the size and thermal conductivity). Huang et al. [17] found that wire core acted as a heat sink during the ignition and its transition to flame spread. Bakhman et al. [18,19] first studied the flame spread over thin wires with both horizontal and vertical orientations. Hu et al. [20] further studied the effect of wire inclination on the flame spread. However, in the literature there were very few temperature measurements for the wire core and insulation or the quantification of the heat sink or heat effect of the core, especially for the larger wire (diameter of ~1 cm).

Moreover, the melting and dripping phenomena of wire insulation are potential fire risks since they can ignite other objects and expand fire. Only a few studies have addressed their fire hazards. Moreover, the dripping phenomenon only occurs under gravity [21], so it is expected not to affect microgravity wire combustion. Williams [22] suggested the melting and dripping flow of burning fuel might control the downward flame spread. Cahill [23] tested the dripping behaviors of several commercial electrical wires for the aircraft safety application. NASA previously designed an empirical test (Test 4 of NASA-STD-6001B) to evaluate the fire hazard of dripping: if the dripped flaming debris does not ignite a piece of K-10 paper placed 20 cm below the sample, the insulation material is judged to be “safe” [24]. Miyamoto et al. [14] found that the easier dripping of molten PE insulation reduced the wire flammability near the limiting oxygen concentration (LOC). He et al. [25] showed that the melting and dripping of wire insulation increased with the overload current. Lim et al. [26] observed that the excessive dripping of molten PE insulation under high AC frequency in wires led to flame extinction. Kim et al. [27–29] simulated the melting and dripping of polymer subjected to external heating using the methods of the volume of fluid and enthalpy-porosity and studied the influence of material properties. However, the influence of core on dripping and the effect of dripping on flame spread have not been studied.

In this work, temperatures of core and insulation were measured in the opposed flame spread over both horizontal and vertical oriented wires. Then, the dripping behaviors of molten insulation in the wire fire were investigated experimentally for different wire configurations and orientations. The discussion focuses on the effect of dripping and core.

2. Experimental setup

The tested wires were specially made for the research purpose and could be manually assembled by mating a plastic tube and a metal core. Fig. 1(a) shows the tested wire samples with different dimensions: (I) d_c/d_o =3.5/8.0 and (II) 5.5/9.0 mm (the same samples used in [14]), and Table 1 lists their configurations. Note that these wires were almost 10 times thicker than those tested in [10–12,15,17–19,25,26]. Also, three core conditions were used to investigate the core effect: (i) a solid copper (Cu) core, (ii) a low-conductance stainless steel (SS) hollow core, and (iii) a 1 mm steel hollow bar which only held the position of insulation tube and simulated the no-core case. The test wires were 100 mm long and had three different PE insulations: (1) the semi-transparent low-density polyethylene (LDPE), (2) the white opaque high-density polyethylene (HDPE), and (3) black LDPE (B-LDPE).

The physicochemical properties of PE insulations and cores are shown in Table 2. The B-LDPE was produced by doping 5wt% black carbon particles into the pure LDPE, and had a higher melt viscosity [30]. Thermally, LDPE had lower temperature and heat of both melting (T_m and ΔH_m) and pyrolysis (T_p and ΔH_p), and a smaller thermal inertia ($\rho\lambda c$ [31]) than HDPE. Without external radiation, their flammability ranked as LDPE > B-LDPE ≥ HDPE [14].

Fig. 1(b–d) illustrated the experimental apparatus, including the wire, scale, sample holder, and the configuration of wire and thermocouple. The entire apparatus was placed inside laboratory without external airflow. The wire was fixed by an aluminum sample holder with the same diameter, and the insulation was extended out of the core by 10 mm as the ignition zone. For each test, a regular lighter was used to heat the ignition zone for 10 s to start a uniform ignition. To measure the temperature of Cu core and SS tube wall, three 1-mm holes were drilled in each core, and the hole was used to tightly accommodate the bead (about 0.5 mm diameter) of the K-type thermocouple (TC). The surface temperature of PE insulation at the same position was also measured by the same type of TC, as shown in Fig. 1(b). The TC bead was embedded half in the insulation and half in the air using a soldering rod.

The total mass-loss rate ($\dot{m}_t$) of wire is equal to the melting rate of insulation ($\dot{m}_m$), which is the sum of burning rate ($\dot{m}_b$) and dripping rate ($\dot{m}_{dr}$) as