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Effect of insulation melting and dripping on opposed flame spread over laboratory simulated electrical wires

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ABSTRACT

In electrical wires with insulations that burn and melt, the dripping of molten insulation can change the wire fire behavior, ignite nearby objects, and enhance the fire spread. Dripping is a result of gravity and depends on the insulation type of the wire and its orientation. In this work, the opposed flame spread over simulated electrical wires was studied with emphasis on the effect of the core and insulation type, and the melting and dripping of insulation. To facilitate the study, "laboratory" wires with polyethylene (PE) as insulation, were selected for the experiments. Horizontal and vertical wires of 8- and 9-mm diameter with soild copper (Cu) and hollow stainless steel (SS) cores and two types of PE insulations, low density and high density, were tested. The sizes of the laboratory wires were selected to facilitate the study of the effect of the type of insulation, the ratio of insulation to core thickness, or the thermal properties of the core, on the wire fire behaviors. Experimental results show a strong dependence of wire orientation on molten insulation dripping and flame spread. For horizontal wires, the flame spread is faster with Cu core than SS core because of a larger heat transfer ahead of the flame through the core. For vertical wires, the flame spread rate is dominated by the downward dripping of the molten insulation, but is comparatively not sensitive to the core material.

Increasing the opposed flow speed, the flame gets closer to the wire which enhances the heating from Cu core and locally increases the flame spread. The effects of other parameters such as oxygen concentration, wire diameter, and insulation material are also discussed. This work provides important support to a larger project aimed at studying the fire behavior of electrical wires in a spacecraft environment. Without gravity, the dripping of molten material will not occur in a spacecraft, thus, characteristics of the flame spread process over a wire insulation material that melts during the spread of the flame will be drastically different on Earth or in a spacecraft.

1. Introduction

Electrical wires are potential sources of fire ignition in residential and industrial structures, and in transportation [1–4]. The fundamental study of electrical wire combustion is complicated because of the interaction of the conductor core and the insulation, and the different fire characteristics of the insulation. For this reason, studies in the literature often use "laboratory" wires, assembled from a metal rod as the core and plastic tube as the insulation [5–14]. Bakhman et al. [5,6] first studied the flame spread over polymer coatings on copper wires with both horizontal and vertical orientations. Fujita and co-workers [7–10] conducted a series of experiments with thin wires (diameter ~ 1 mm) to investigate the influence of wire temperature, core size, ambient oxygen concentration, and opposed-wind on wire combustion. Leung et al. [11] studied the effect of the core under the external heating and non-flaming pyrolysis. Nakamura et al. [12,13] reported that the flame-spread rate over polyethylene (PE) insulated wires increased with decreasing pressure and increasing core size and thermal conductivity. Huang et al. [14] observed that wire core acted as a heat sink during the ignition and its transition to flame spread in PE insulations. Miyamoto et al. [15] found that the limiting oxygen concentration (LOC) for thick research wires (diameter ~ 1 cm) with PE insulation decreased with external radiation,

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Table 1
Physicochemical properties of (solid) PE insulations and cores, where thermal properties are evaluated near the room temperature, and $\Delta H > 0$ represents endothermic [15,16].

	ρ [26] (kg/m^3)	λ [26] (W/m/K)	c [26] (kJ/kg/K)	T_m [27] (°C)	ΔH_m [27] (MJ/kg)	T_p [27] (°C)	ΔH_p [27] (MJ/kg)
LDPE	927	0.23	1.55	105–110	0.50	387	1.8
HDPE	944	0.32	2.00	130–135	0.81	404	2.3
Cu [28]	8954	398	0.400	–	–	–	–
SS [28]	8000	13.8	0.384	–	–	–	–
Air [28]	1.18	0.026	1.07	–	–	–	–

while increased with the core conductance. Working also with PE insulated wires, Kobayashi et al. [16] recently showed that as the core conductance increased, the opposed flame spread increased in a horizontal wire while decreased in a vertical wire, because of the core's simultaneous dual effect as a heat source and heat sink.

Furthermore, in the presence of gravity, the dripping of molten insulation may affect the burning characteristics of wire and add a potential fire risk since it can ignite other objects and expand the fire size. This effect will be completely different in microgravity because molten insulation will not drip. There are only limited studies addressing the physical processes and fire hazards of the melting and dripping of wire's polymer insulation. For example, dripping of molten insulation was found in the first study on wire fire by Bakhman et al. [5,6] as well, but its processes or dynamics was not well discussed there. Zhang et al. [17] examined the effect of the melting behavior of thermoplastic polymers on the mass-loss rates during the steady burning stage. Cahill [18] tested the dripping behaviors of several commercial electrical wires for the aircraft safety. Kim et al. [19,20] simulated the melting and dripping of polymers subjected to external heating using the methods of the volume of fluid and enthalpy-porosity without a flame. He et al. [21] observed the enhanced melting and dripping of wire insulation under overload currents. Miyamoto et al. [15] found the dripping of melting insulation near LOC acted as a heat sink to reduce the wire flammability. Most recently, Kobayashi et al. [16] observed that as the core thermal conductance increased, the burning became enhanced while the dripping became deterred. Currently, materials to be used in spacecraft are tested in normal gravity to ensure fire safety. However, fire behaviors are significantly different in between normal gravity and microgravity [10,16,22]. Therefore, this work has an important implication for fire safety for electrical wires in a spacecraft environment because molten material will not dripped in microgravity.

In this work, the dripping behavior of molten insulation and its effect on the opposed flame spread over laboratory simulated electrical wires are studied. This is done by varying the wire orientation, horizontal or vertical, and varying opposed flow velocity and oxygen concentration with the objective of understanding the roles of these parameters on the wire fire.

2. Experiment

2.1. Laboratory wire samples

A task of interest is to study the effect of the type of insulation, the thermal properties of the core and insulation, and the relative size of insulation and core on the flame spread over the wires. Laboratory simulated wires consisting of a PE cylinder as insulation and a copper rod or a steel cylinder as the core were tested. The relatively large-diameter laboratory wires were selected to facilitate the interpretation of the experimental results, while they were not intended to reproduce actual electrical wires. These wires were the same as those in a previous work [15,16] to facilitate the comparison of the results. They are about 10 times thicker than those tested in Refs. [7–9,11,12,14,23,24], while thinner than the commercial power cables [25].

Two different "laboratory" wire insulations were tested: (1) a semi-transparent low-density polyethylene (LDPE) and (2) an opaque white high-density polyethylene (HDPE) both produced by DuPont. The physicochemical properties of the materials are presented in Table 1. Overall the HDPE has a higher thermal inertia and higher thermal requirements for melting and pyrolysis than the LDPE. Their physicochemical properties are also listed in Table 1 where ρ, k, c T_m, ΔH_m, T_p, and ΔH_p are density, thermal conductivity, specific heat, melting temperature, heat of melting, pyrolysis temperature, and heat of pyrolysis. The stainless-steel tube was selected not only as a low conductivity core, but also as a mechanism to simulate the insulation without a core. Without the SS core, the PE insulation would soften and bend when heated by the flame, and would also drip inside the PE tube. Three 1-mm holes were drilled in each core and the bead (about 0.5 mm diameter) of K-type thermocouple (TC) was accommodated to measure the core temperature. The

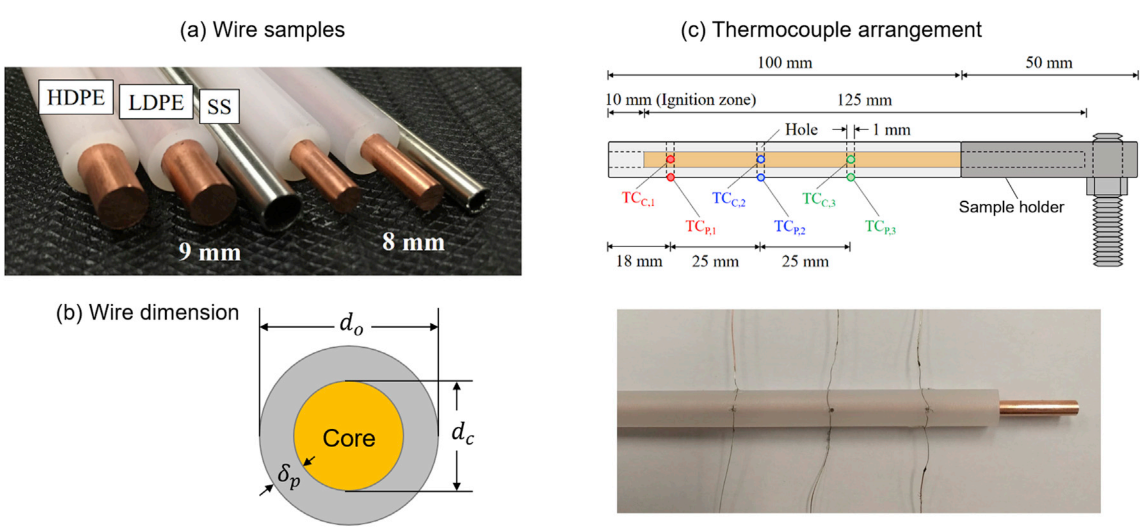

Fig. 1. (a) Photo of tested wire samples, (b) wire configuration, and (c) thermocouple arrangement in the wire.