Journal of Hazardous Materials xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Journal of Hazardous Materials

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

Molten thermoplastic dripping behavior induced by flame spread over wire insulation under overload currents

Hao He[a], Qixing Zhang[a,*], Ran Tu[b], Luyao Zhao[a], Jia Liu[a], Yongming Zhang[a,*]

[a] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, PR China
[b] College of Mechanical Engineering and Automation, Huaqiao University, Xiamen, Fujian 361021, PR China

HIGHLIGHTS

- Overload current effects on the transient wire temperature profile were predicted.
- A relationship between molten loss and volume variation was proposed.
- The dripping frequency was obtained theoretically and experimentally.
- The flame width, height and spreading velocity presented different behaviors.

ARTICLE INFO

Article history:
Received 31 March 2016
Received in revised form 15 July 2016
Accepted 29 July 2016
Available online xxx

Keywords:
Dripping behavior
Molten insulation
Molten drip
Overload currents
Wire fire

ABSTRACT

The dripping behavior of the molten thermoplastic insulation of copper wire, induced by flame spread under overload currents, was investigated for a better understanding of energized electrical wire fires. Three types of sample wire, with the same polyethylene insulation thickness and different core diameters, were used in this study. First, overload current effects on the transient one-dimensional wire temperature profile were predicted using simplified theoretical analysis; the heating process and equilibrium temperature were obtained. Second, experiments on the melting characteristics were conducted in a laboratory environment, including drop formation and frequency, falling speed, and combustion on the steel base. Third, a relationship between molten mass loss and volume variation was proposed to evaluate the dripping time and frequency. A strong current was a prerequisite for the wire dripping behavior and the averaged dripping frequency was found to be proportional to the square of the current based on the theoretical and experimental results. Finally, the influence of dripping behavior on the flame propagation along the energized electrical wire was discussed. The flame width, bright flame height and flame spreading velocity presented different behaviors.

1. Introduction

The incidence of electrical fires has increased with urbanization and electrification. In China, a total of 115,599 electrical fires occurred in 2013, resulting in 745 deaths, 538 injuries and ¥1.9 billion in direct economic loss; 60.0% of the fires involved the failure of electrical wires [1]. In the United States, an estimated 25,900 residential building electrical fires were reported annually from 2009 to 2011; these fires caused an estimated 280 deaths, 1125 injuries and $1.1 billion in property damage. Electrical wire and cable insulation is the leading factor, igniting first in about 30% of incidents [2]. From accident statistics, most electrical fires are caused by short circuit, overheating and worn wire with the ignition of the insulation attached to the wires. Once ignited, fire propagates along the wire, releasing heat, soot particles, and toxic gases. If the wire burns fiercely with a fast propagation speed, the molten insulation accumulates over time. When the volume of molten insulation reaches a certain limit, dripping can occur. The hot molten or burning polymer may ignite nearby combustibles, expand combustion range and increase the fire risk.

Various standards and tests have been developed to evaluate the fire performance of electrical wires [3]. For example, NASA's standard test was used to study the effects of wire gauge and insulation thickness, internal wire temperature, and sample orientation on the wire insulation flammability [4]. Hasegawa et al. experimentally studied the ignition delay time and the upward flame-spread rate over the surface of insulated electrical cables under an externally

* Corresponding authors.
E-mail addresses: qixing@ustc.edu.cn (Q. Zhang), zhangym@ustc.edu.cn (Y. Zhang).

http://dx.doi.org/10.1016/j.jhazmat.2016.07.070
0304-3894/

Nomenclature

d	Diameter (m)
δ	Insulation thickness (m)
A	Area (m^2)
α	Thermal diffusion coefficient (m^2/s)
ρ	Density (kg/m^3)
λ	Thermal conductivity (W/m/K)
c	Specific heat (J/kg/K)
$\dot{m}$	Mass loss rate (g/s)
$\dot{q}''$	Heat release rate per unit length (kW/m)
I	Current (A)
T	Temperature (K or °C)
ρ	Density (kg/m^3)
f	Frequency (Hz)
g	Gravity (m/s^2)
B	Mass transfer number
Nu	Nusselt number
r	Radius (m)
t	Time (s)
v	Flame spreading velocity (m/s)
w	Bright flame width (m)
ε	Emissivity
σ	Stefan-Boltzmann constant

Subscripts

c	Core
p	Insulation
g	Gas
o	Outer surface
f	Flame
∞	Ambient

applied radiation heat flux [5]. Leung et al. formulated a mathematical model to study the effect of the inert central core on thermal pyrolysis of the insulation layer, without flame, during the heating process [6]. Based on the heat transfer between the hot gases and burning surface, Umemura et al. proposed a physical model to explain self-sustained burning in flame propagation of electrical wires in microgravity [7]. For fire safety in space, Fujita and Nakamura et al. have focused on flame propagation along electrical wires in microgravity. They conducted a series of experiments to study the influence of both internal and external parameters, including wire initial temperature, core diameter, ambient oxygen concentration [8], low external flow [9], opposed-wind [10], sub-atmospheric pressure [11], and dilution gas on wire combustion under normal gravity and microgravity. They also studied the effect of alternating current (AC) electrical fields on the flame spread over electrical wire [12] and the ignition of electrical wire with short-term excess electric current [13]. Huang developed a model to explain ignition and the following transition to spread [14]. Takahashi performed several tests to examine the influence of flow velocity on the dependent volume change of molten insulation under varying external opposed flow conditions in microgravity [15]. Hu explored the effect of a high thermal conductivity metal core at different inclinations on flame spread over electric wire [16]. Lim et al. investigated the effect of electrical fields on the characteristics of flame spread along a polyethylene (PE) insulated electrical wire by varying the AC frequency and voltage [17]. Recently, several works examined the thermoplastic properties of the dripping melt. Zhang et al. explored the effect of the melting behavior of thermoplastic polymers on the mass loss rates during the steady burning stage [18]. Y. Wang investigated the thermal stabilities of eight thermoplastic materials (PE etc.) as well as their melting

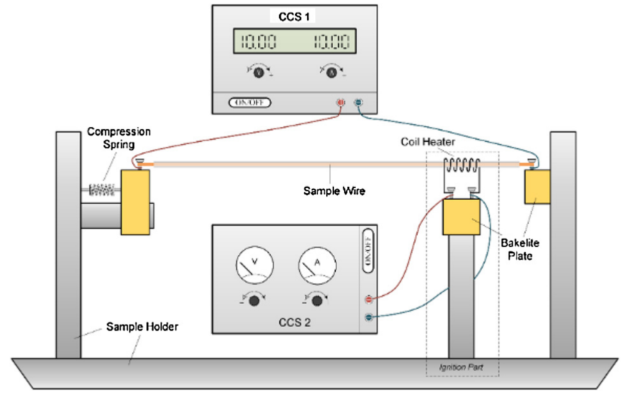

Fig. 1. Schematic of the experimental apparatus.

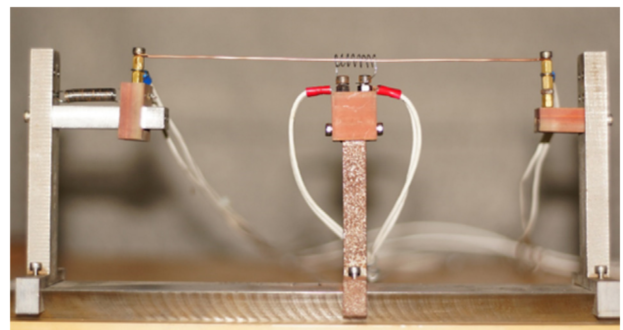

Fig. 2. Photo of the wire sample holder.

drops generated under the UL 94 vertical burning test conditions [19]. Kandola et al. presented a methodology to record the real-time melting, burning, and dripping behavior of thermoplastic polymers [20]. A heat-transfer model was developed to compute the surface temperature of the polymer samples at various furnace temperatures [21]. N. Wang conducted several medium-scale experiments on the thermal hazard induced by melting and dripping of thermoplastics [22]. Xie et al. studied the loop mechanism between the wall fire and pool fires induced by the melting and dripping of thermoplastic based on a T-shape trough [23], and by comparing the polymers' faster flowing burning the results suggested that the fire hazard of polyethylene (PE) is clearly higher than polystyrene (PS) [24].

In general, although previous works have focused on the ignition and flame spread of electrical wire and the thermoplastic properties, there are limited studies of the dripping of molten insulation especially that induced by strong electrical currents, which are more common and could be more dangerous. Therefore, in this paper, the effect of electrical current on the molten dripping insulation was investigated. Two theoretical relationships were developed to determine the temperature and dripping behavior of molten insulation under strong electrical currents. An experimental study has been performed using several wires, to validate these theoretical relationships. The results of this study could be useful for the fire safety design of electrical wires.

2. Experimental

Fig. 1 shows the experimental apparatus, which consisted of three parts: a wire sample holder, two constant current sources (CCS), and an ignition part. As shown in Fig. 2, the sample holder consisted of a base, holder, Bakelite plates, compression spring, wiring terminal, coil heater, and sample wire. The dimensions of the base were 300 mm (L) × 60 mm (W) × 15 mm (H). The base and