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Flame spread over electric wire with high thermal conductivity metal core at different inclinations

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Abstract

This paper reveals experimentally the flame spread rate (FSR) [both upward (concurrently) and downward (opposed)] over electric wire with high thermal conductivity metal core at different inclination angles, which is new in view of that previous works about such inclination effect are mainly focusing on the material (wood, PMMA……) where the conductivity through media itself is not so important. Polyethylene (PE) insulated copper (Cu) wires with inner core diameter (d_c) of 0.30 mm, 0.50 mm 0.80 mm and insulation thickness (δ_p) of 0.15 mm, 0.30 mm are studied with inclination angles ranged from −90° to +90°. Their behaviors are examined in both naturally normal (Hefei city with altitude of 50 m; 100 kPa) and a reduced (Lhasa city with altitude of 3650 m; 64 kPa) ambient pressure atmosphere. Results show that with increase in inclination angles from −90° to 90°, the FSR first decreases and then increases ("U" trend) with its value being lowest at nearly horizontal condition (0°) in both pressures, which is quite different from what we normally know for other materials with low thermal conductivity. Two characteristic lengths, the flame base width (W_f) and the pyrolysis zone length (L_p), are found to account for this special variation behavior with their variation trend with inclination angle being consistent with that of FSR. A simplified heat balance analysis concerning core thermal conduction effect is performed to calculate the FSR in relation to these two characteristic lengths, thermal conductivity of the metal core as well as the effective convection heating of the wire by the flame base. The calculated FSR are shown to be in fairly good agreement with the measured values at different inclination angles for different inner core (wire) diameters in both ambient pressures.

Keywords: Flame spread rate; Electric wire; Inclination angle; Thermal conductivity; Reduced pressure

1. Introduction

Electric wire fire behavior is very important in safety of aircraft and space vehicle utilization, in which flame spread behavior is one of the key fundamental points as received focused attention in recent years [1–6]. Flame spread rate over electric

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wire in microgravity, where no inclination effect needs to be considered, has been investigated carefully by Fujita et al. in recent years for different insulation and core metal, wire (core) sizes [4], external flow speeds [5] and oxygen concentrations (LOC) [6], and compared with those in normal gravity at horizontal condition. The flame spread rate over horizontal electric wire in reduced ambient pressures has also been revealed by Nakamura [7], who proposed two modes, "wire-driven mode" (high conductivity, Fe-core) and "flame-driven mode" (low conductivity, NiCr-core), controlling the flame spread process. However, the flame spread test at inclination condition is important in fire safety evaluation of the electric wire material that is to be used in spacecraft, for example, in NASA's standard test [8], the inclination angle of 75° from horizontal is used. Such tests are usually taken in the normal gravity conditions, and then extended for microgravity condition applications. So, the flame spread rate over electric wire at different inclination angles in normal gravity needs to be investigated for a better understanding of this issue.

There are already extensive referable works on flame spread over solid media with inclinations, which is usually characterized as thermally-thick or thermally-thin [9]. Drysdale and Macmillan [10] performed upward spread experiments on both thermally thin computer cards and thermally thick PMMA (6 mm thickness) samples with 2–6 cm wide. They found that little change in the average spread rate substantially as the inclination angle changes from horizontal orientation to 75°, after which the spread rate increased substantially until the inclination angle reaches vertical orientation. Pizzo et al. [11] and Xie and Desjardin [12] also investigated the flame spread over the surface of PMMA from 0° to 90° experimentally and 2-D numerically. Quintiere [13] performed experiments on thermally-thin metalized polyethylene terephthalate (0.20 mm thick) and paper (0.17 mm thick) in both upward and downward orientations. More recently, Gollner et al. [14] performed upward flame spread experiments systematically at different orientations for thermally-thick slab of PMMA (1.27 cm thick, 10 cm wide and 20 cm tall) and found that flame spread rates are greatest at angles near vertical orientation while burning rates are maximized at angles near horizontal orientation. Inclination angle effect on flame spread has also been tested for whitewood (70 mm width, 3 mm thickness and 400 mm length, −50° to +20°) by Zhang et al. [15], and for EPS (4 cm thickness, 80 cm length, 0°, 15°, 30° and 90°) by An et al. [16] in normal (100 kPa) and a reduced (64 kPa) ambient pressures.

However, it is noted that the dominant heat supply mechanism to control the flame spread should be quite different for electric wire with metal core from those of above solid media, in which the thermal conductivity over the media base itself is quite different. Especially, for electric wire with high conductivity core metal (for example, Copper, thermal conductivity ~400 W/m K), the heat supplied through conduction along the core will act as an "extra" dominating heat source [7]. How its flame spread rate varies with inclination angle is remained to be clarified and characterized, as an important issue directly related to fire safety test for electric wires as performed in normal gravity.

So, in this paper, we investigated the effect of inclination angle [from −90° (downward, opposed) to +90° (upward, concurrently)] on flame spread rate over electric wire using high thermal conductivity metal core (Copper) to advance our understanding of above issue by following efforts:

(1) The variation trend of flame spread rate with inclination angle of electric wire is clarified (for different core and wire diameters), which is compared with previous data achieved for other solid media (thermally-thick or thermally-thin) without such "high-thermal-conductivity-core" as well as over electric wire with NiCr core of which the thermal conductivity is low (45 W/m K) (as found to be quite different as described later in the paper);
(2) Characteristic lengths to account for such variation trend behavior are found (to be the flame base surrounding width (W_f) and the pyrolysis zone length (L_p)), and based on which;
(3) A simplified heat balance analysis concerning core conduction effect is performed to calculate the FSR in relation to these two lengths, thermal conductivity of the metal core as well as the effective convection heating of the wire by the flame base, to collapse the FSR values at different inclination angles for different inner core and wire diameters.

The above efforts have been examined in naturally both normal- (Hefei city with altitude of 50 m; 100 kPa) and a reduced (Lhasa city with altitude of 3650 m; 64 kPa) pressure atmosphere.

2. Experimental

The experimental setup is shown in Fig. 1, which is mainly composed of a sample holder, a rotary supporter and an ignition system. Polyethylene (PE) insulated copper (Cu: thermal conductivity ~ 400 W/m·K) wires with inner core diameter (d_c) of 0.30 mm, 0.50 mm 0.80 mm and insulation thickness (δ_p) of 0.15 mm, 0.30 mm (as listed in Table 1) are studied with inclination angles ranged from −90° to +90°. The core