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Opposed-flow flame spread and extinction in electric wires: the effects of gravity, external radiant heat flux, and wire characteristics on wire flammability

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Opposed-flow flame spread and extinction in electric wires: the effects of gravity, external radiant heat flux, and wire characteristics on wire flammability

Abstract:

Combustion of electric wires is the most probable cause of fire in human space activities. Therefore, the fire performance of electric wires in microgravity conditions must be thoroughly analyzed. This study investigates the opposed-flow flame spread and its limits in electric wires preheated by external radiation, under both normal gravity and microgravity, to understand their fire performance when exposed to external heat sources in such gravity conditions. The experiments were performed on low-density polyethylene (LDPE)-insulated copper (Cu) wires having an outer diameter of 4 mm and differing in core diameter (2.5 and 0.7 mm, corresponding to insulation thicknesses of 0.75 and 1.65 mm, respectively). Both standard and black LDPE insulations were used to study the effect of radiation absorption on the wire preheating and subsequent flame spread. The comparison of the flame spread limits revealed that the wire with the thicker Cu core was less flammable under both normal gravity and microgravity; in particular, its flammability further decreased in the case of microgravity, in contrast with thinner electric wires (~1 mm outer diameter), which exhibited higher flammability in the same gravity condition. These results suggest that different mechanisms, for thicker and thinner wires, determining the critical conditions to sustain flame spread under microgravity. This study provides valuable information about the fire performance of electric wires in space gravity.

Keywords:

Electric-wire combustion, Opposed-flow flame spread, Flammability limit, External radiant heat flux, Microgravity

1. Introduction

Investigating the combustion characteristics of solid fuels in a microgravity environment is essential to improve fire safety in human space activities; it is well known that gravity affects combustion processes, especially because of the buoyancy-induced flow that influences several heat and mass transport processes. Flammability is often used to characterize the fire risk of a solid fuel since it is a measure of fire potential and hazard. The fire risk of a material is normally determined by the ease of ignition, flame spread rate (FSR), heat release rate, and toxicity; the flame spread is frequently considered in flammability studies and material fire testing due to its strong influence on the fire after its ignition. To improve the scientific understanding of flame behavior over solid materials under microgravity, the flame spread and extinction phenomena have been investigated in such gravity condition by several researchers. Cellulose or polymethylmethacrylate (PMMA) sheets have been often used as representative solid fuels in the microgravity combustion research because they burn cleanly and their physicochemical properties are well known [1–11] and, therefore, they are widely accepted as testing materials to study the fundamentals of flame spread. However, a real fire usually involves diverse types of materials, such as fire-retardant fabrics, polymers, and electric wire insulations, and also their fire performance needs to be investigated as related to spacecraft fire safety; in particular, studies on the electric wire combustion are very important since this is the most probable cause of fire in human space activities.

Electric wire combustion has the unique feature that the heat transfer through the metal conductor affects the fire performance of the insulation material during the burning event. Some researches on electric wire combustion under both normal gravity and microgravity have revealed that the role of the metal conductor in the flammability of the insulation material depends on the wire geometry [12–15] and surrounding ambient conditions such as O_2 concentration [16], airflow velocity [17–20], pressure [21], external radiative heat flux [15,22,23], and gravity [23–26]. Fujita et al. [27–29] investigated the ignition limit and delay time of low-density polyethylene (LDPE)-insulated nichrome wires subject to short- and long-term excess electric current; they observed that the ignition limit dramatically expands in microgravity compared with normal gravity due to the absence of the buoyancy-induced flow. Kim [30] and Lim et al. [31,32] examined, under normal gravity, the effect of the alternating current (AC) electric fields on the flame spread over the same sample wires used by Fujita et al. and reported that the flame spread over the wire and the flammability of the insulation material are varied, respectively, by the presence of the AC electric field and by the AC frequency and voltage. Citerne et al. [33] analyzed the interaction among flames spreading over three parallel wires under microgravity, finding that the heat exchange between wires enhances their spread. Osorio et al. [23] studied the effect of external radiation on the flame spread limit of thin ethylene tetrafluoroethylene (ETFE)-insulated copper wires under both normal gravity and microgravity; they demonstrated that the introduction of external radiation extends the flame spread limit of the wire that, moreover, becomes more flammable under microgravity compared with normal gravity. This effect was investigated also by Miyamoto et al. [15] on thick samples of polyethylene (PE)-insulated wires through a downward flame spread test under normal gravity. They suggested that the metal core may act as a heat sink, cooling the insulation material during the flame spread event.

Despite these multiple studies, the effect of the wire geometry (i.e., outer diameter, core diameter, and insulation thickness) on the electric wire combustion under microgravity has not been well studied yet; in particular, the influence of the wire dimensions in the presence of external radiation, which is a typical external factor affecting the material performance in real fire events [34–37], has not been investigated in such gravity condition.

In the present study, we investigated the opposed-flow/downward flame spread over LDPE-insulated wires and its extinction under a varied external radiant heat flux, in both normal gravity and microgravity conditions. The experiments were performed with copper wires of several sizes to study the effect of the wire dimensions on their combustion. First, the FSR and the limiting oxygen concentration (LOC), as an indicator of material flammability limit, in normal gravity were determined as a function of the external radiant heat flux. Then, similar experiments were conducted under microgravity. Based on the results, the effect of the wire dimensions on the flame spread limit in different gravitational conditions was successively discussed. Since the amount of heat absorption under a varied external radiant heat flux could be a controlling factor in the wire combustion, the LDPE color was also changed in the experiment as a problem parameter.

2. Experimental

2.1. Experimental setup

Figure 1 shows a schematic of the experimental apparatus, developed in a previous work [38], used to investigate the wire flammability under an external radiant heat flux. The combustion chamber was made of aluminum, 390 mm long in the streamwise direction, and 80 mm in inner diameter, nearly identical in configuration to the standard tube size for the ISO 4589-2 Oxygen Index Test [39]. A mixture of O_2 and N_2 was injected at the bottom of the chamber with a flow rate determined by mass flow controllers; it was supplied uniformly to the test section through a bed of glass beads and a honeycomb at the bottom of the chamber. A forced airflow was also supplied at a fixed velocity of 10 cm/s in all experiments. The pressure inside the chamber was kept at 100 kPa via a back pressure regulator at the chamber outlet. A testing wire was supported vertically along the centerline of the chamber by a sample holder. The top end of the wire was ignited with an electrically heated Kanthal wire coil and the burning event was recorded by both a digital video camera and an infrared (IR) camera. Four halogen lamps were installed inside the chamber at intervals of 90° and at 30 mm from its centerline; they supplied radiant heat flux up to 16 kW/m^2 to the wire surface.

Figure 2 shows a photo of the tested wires, composed of an outer LDPE insulation and a copper core. The samples were “laboratory wires” specially manufactured for our experiments to ensure that their dimensions were of the desired values. Although they were not actual electrical wires, their use allowed a detailed study of the interaction between core and insulation under the effect of external radiation. Two types of wires were tested, with the same outer diameter (d_o = 4 mm) but different core diameter (d_c = 2.5 and 0.7 mm, corresponding to an insulation thickness τ = 0.75 and 1.65 mm, respectively) (Table 1). The copper core and LDPE insulation were 175 and 130 mm long, respectively; the core was made longer so to hold the wire at both core ends. Each wire type was manufactured in two different insulation colors, standard LDPE and black LDPE, to evaluate the flammability under different radiation heat absorptance values.

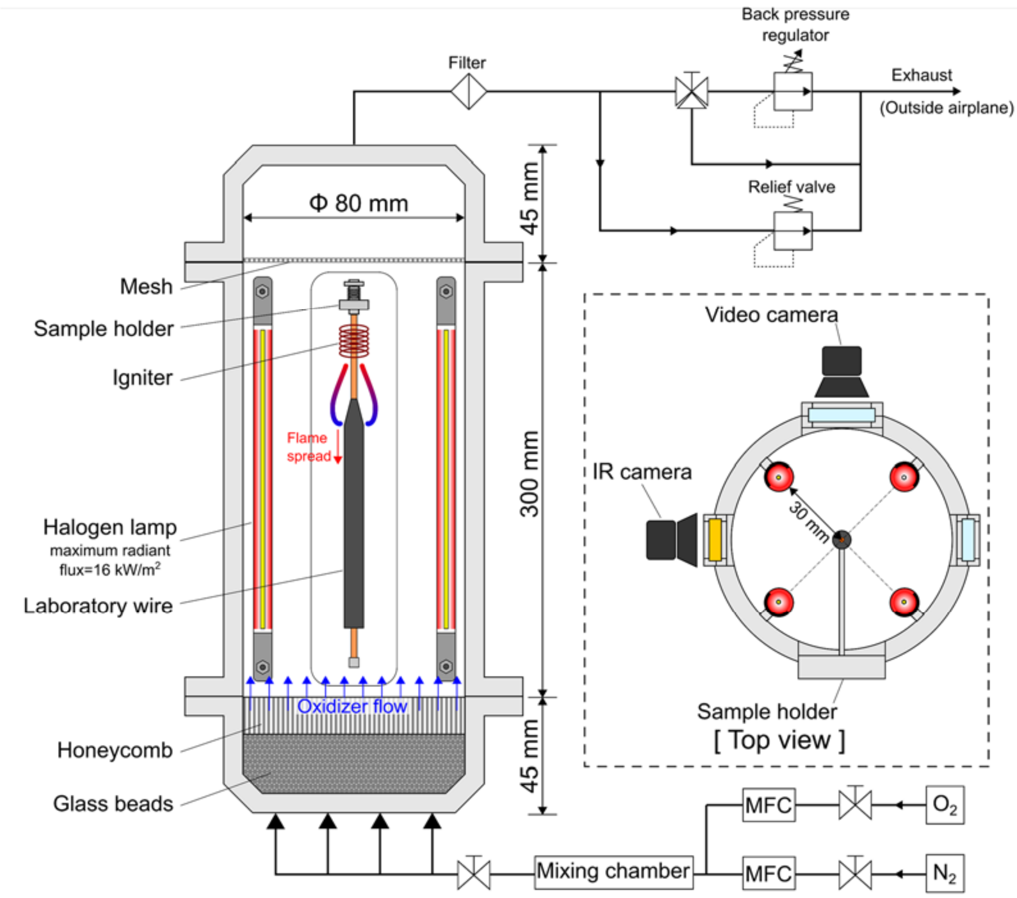

Fig. 1. Schematic of the experimental apparatus.

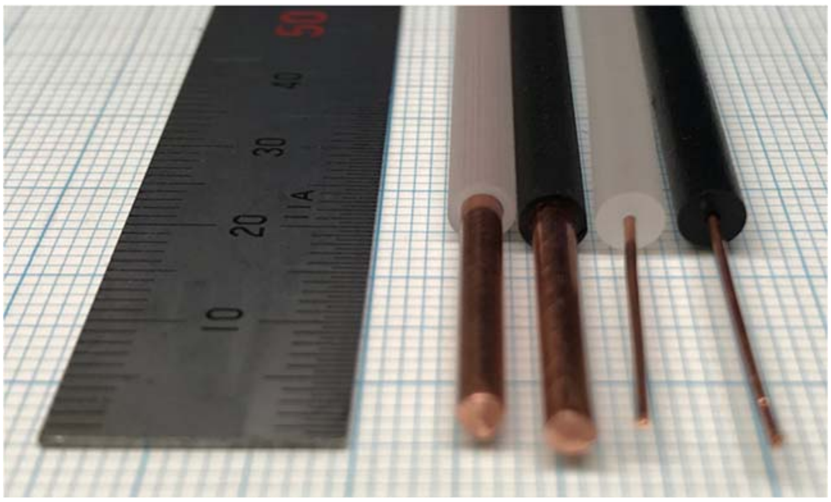

Fig. 2. Photograph of the tested wires. From left to right, outer diameter (d_o)/core diameter (d_c) = 4.0 mm/2.5 mm and standard low-density polyethylene (LDPE), d_o/d_c = 4.0 mm/2.5 mm and black LDPE, d_o/d_c = 4.0 mm/0.7 mm and standard LDPE, and d_o/d_c = 4.0 mm/0.7 mm and black LDPE.

Table 1. Geometrical configurations of the two wire types tested.

Name	Outer diameter (d_o) [mm]	Core diameter (d_c) [mm]	LDPE thickness (τ) [mm]
Type I	4	2.5	0.75
Type II	4	0.7	1.65

*5 wt% carbon particles were doped for the black low-density polyethylene (LDPE) samples.

2.2. Microgravity experiments

The microgravity experiments were conducted in parabolic flights, on board of a Gulfstream-II aircraft, operated by the Diamond Air Service Inc. in Japan. Parabolic flights provide about 20 s of 3×10^{-2} g_0. The experiments were performed based on the sequence illustrated in Fig. 3 and a programmable logic controller was used to control their timing. Prior to ignition, the samples were preheated for 15 s under halogen lamps, which were turned off during the flame spread to visualize the flame and avoid the insulation melting and thermal shrinkage in the preheating.

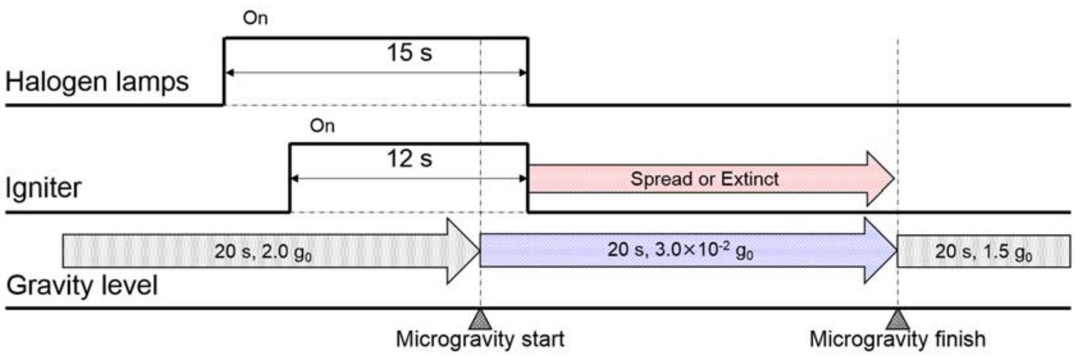

Fig. 3. Experimental procedure for the microgravity experiments.

3. Results and discussion

3.1. Overall characteristics of flame spread and extinction under normal gravity

The downward flame spread and extinction behaviors of each sample wire were first investigated without exposure to external radiation. Figures 4 and 5 illustrate representative flame behaviors and time histories of the flame front position, respectively, during flame spread. During the experiments, molten LDPE dripped down along the unburned insulation surface; under such condition, flashes were often observed at the flame front during the flame spread and they might have been caused by the flammable gas pyrolyzed from the solid and molten dripping LDPE. The results in Fig. 5 shows that, in the experimental conditions adopted, the downward flame spread was not steady but accelerated with time. When the ambient O_2 concentration was sufficiently high, the flame length continuously grew with time and the downstream of the spreading flame turned into a sooty flame due to the excess fuel burning. Under near-extinction conditions, the spreading flame exhibited two kinds of instability depending on the wire dimensions, flamelet spreading (Fig. 4(B)) and oscillatory flame spreading (Fig. 4(C)); when d_c was 2.5 mm, the first type was observed. The flamelet movement is also presented in Fig. 5(A) as a green and blue curve, showing a nearly steady state in contrast with the flame spread under high O_2 concentration. Once a flamelet was formed over the sample wire, it exhibited two types of behavior: it became gradually weaker during the flame spread, eventually quenching (see Fig. 4(B) at +60 s), or, as an upstream flamelet, it ignited the unburned LDPE left behind and then turned into an envelope flame (Fig. 4(A)). Thus, in the second case, both upward and downward flame spread from the flamelet were simultaneously observed. When d_c was 0.7 mm, still under near-extinction conditions, the oscillatory flame spreading was observed (Fig. 4(C)) and the time history of the corresponding flame front (Fig. 5(B)) revealed such behavior in a wide range of O_2 concentration (around 2% higher than the flame spread limit). In the insulation melting process, a large globular molten LDPE was formed at the wire burning region and its size continuously grew during the flame spread due to an unbalance between the melting and gasification rates; furthermore, the thinner copper core supported it to prevent downward dripping. This molten LDPE formed a wake region downstream and maintained the oscillating flame by anchoring it there. The appearance of such oscillatory flame spreading over plastic materials under near-extinction conditions has been reported, and its mechanism explained, by some researchers [40–42].

The abovementioned instabilities of flame spread in near-extinction conditions have not been previously reported in case of thin wires [16,18,19,21,24,25,43] and are considered to be a unique feature of thick insulation ones. In addition, the wire dimensions influenced the extinction mechanism of the flame spreading over the sample wires even in the same experimental conditions.

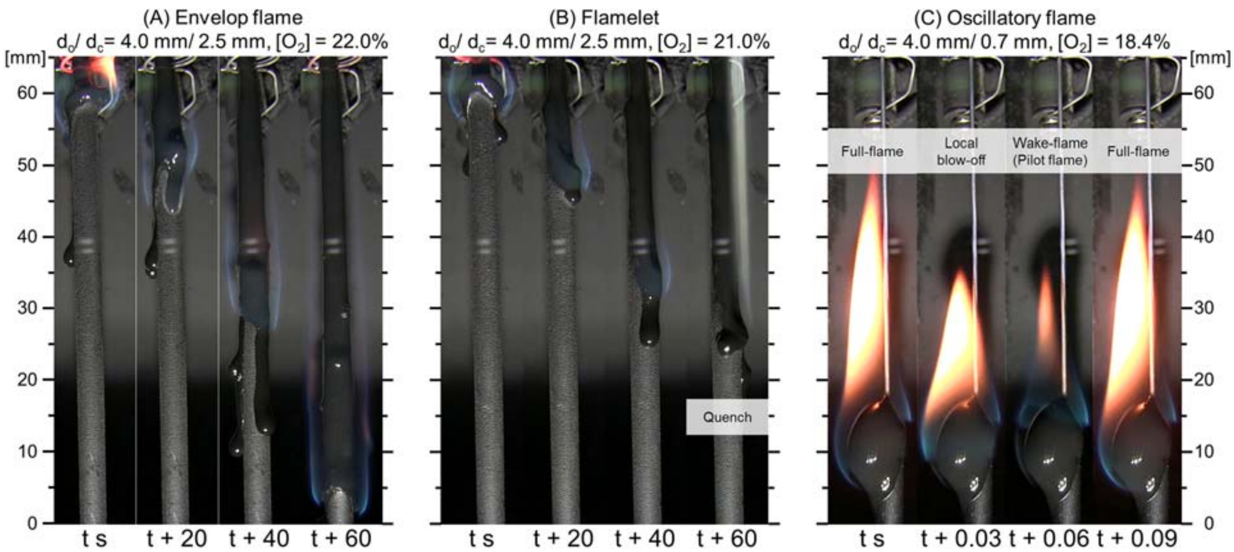

Fig. 4. Photographs of representative downward flame spread behaviors during time under normal gravity and without external heating. The opposed-flow velocity was 10 cm/s.

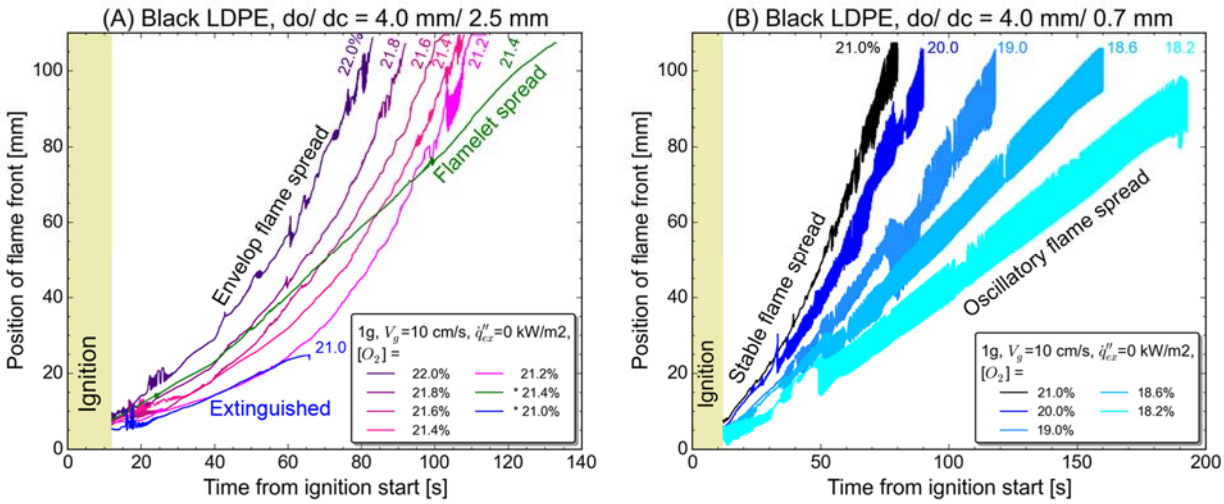

Fig. 5. Time history of the flame front position during downward spreading over black low-density polyethylene (LDPE) wires under normal gravity without external heating; the opposed-flow velocity was 10 cm/s.

3.2. Flame spread limits of the tested wires under normal gravity

The flame spread boundary maps for the four different sample wires are presented in Fig. 6, where each scatter indicator represents five repeated experiments and the burn probability scale indicates the flame spread occurrence in the experiments (100% = flame spread observed in all tests; 0% = flame spread never observed). The black LDPE-insulated samples exhibited an approximately linear relationship between flame spread limits and external radiant heat flux, while standard LDPE-insulated ones showed flame spread limits monotonically decreasing for heat fluxes up to 8 kW/m^2 and then turning into a weak dependency on them in the 8–16 kW/m^2 range. This effect of the insulation color could be explained by the difference in absorbance and transmittance for the external radiation between standard and black LDPE.

Figure 7 presents photographs of the burning wire appearances and the corresponding diagrams of radiative heat flux absorption and transmission in the LDPE insulations. Figs. 7(A) and (B) clearly show that, when the wires were heated by the flame, the standard LDPE became transparent, while the color of the black LDPE did not change because of its carbon particles doping. A similar result was observed during the sample preheating with the halogen lamps. Therefore, the transmittance of standard LDPE increased due to the change in transparency with the external heat flux intensity and the exposure time to the radiant flux increased; then, a major part of the radiative heat was transmitted into the insulation layer and reflected at the interface with the metal core (Fig. 7(D)), resulting in flame spread limits without a clear dependency on the increase in external radiant heat flux when this exceeds 8 kW/m^2. On the other hand, the radiant heat flux was selectively absorbed near the surface of the black LDPE samples and, thus, directly contributed to extending the flame spread limits, resulting in the observed monotonic decreasing trend as a function of the external radiation intensity.

As regards the effect of the copper core size on the flame spread limits, the flammability decreased when d_c increased with a corresponding reduction of the insulation thickness. This implies that a thicker copper core acts as a heat sink, reducing the flammability of the insulation material in near-extinction conditions. These results are consistent with previous works on the flammability of LDPE-insulated copper rods and stainless steel hollow tubes [15,20,44]. Furthermore, as shown in Fig. 6, the flame spread limit of the wire having the thicker core reached a higher O_2 concentration at 16 kW/m^2 compared to that at 0 kW/m^2 of the sample with the thinner core, for both black and standard LDPE cases. This means that the heat sink effect of a thicker copper core cannot be compensated by insulation surface preheating in the tested range of radiant flux. More discussion about the dimension effects on the electric wire flammability will be made in a later section.

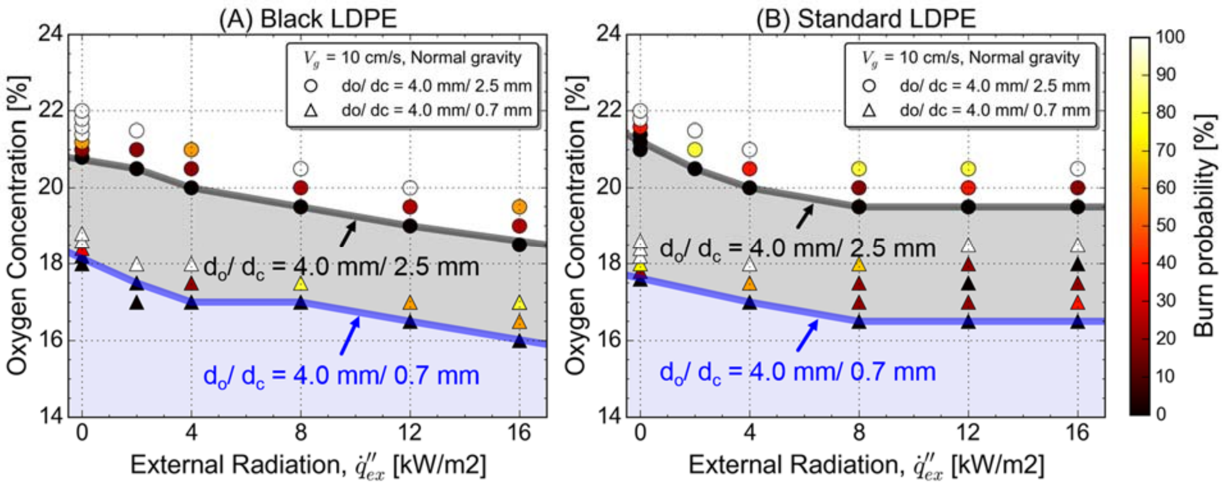

Fig. 6. Flame spread boundary maps as a function of the external radiant heat flux under normal gravity in case of (A) black and (B) standard low-density polyethylene (LDPE) as insulation; the opposed-flow velocity was 10 cm/s. The burn probability scale (on the right) is referred to the scatter indicator colors.

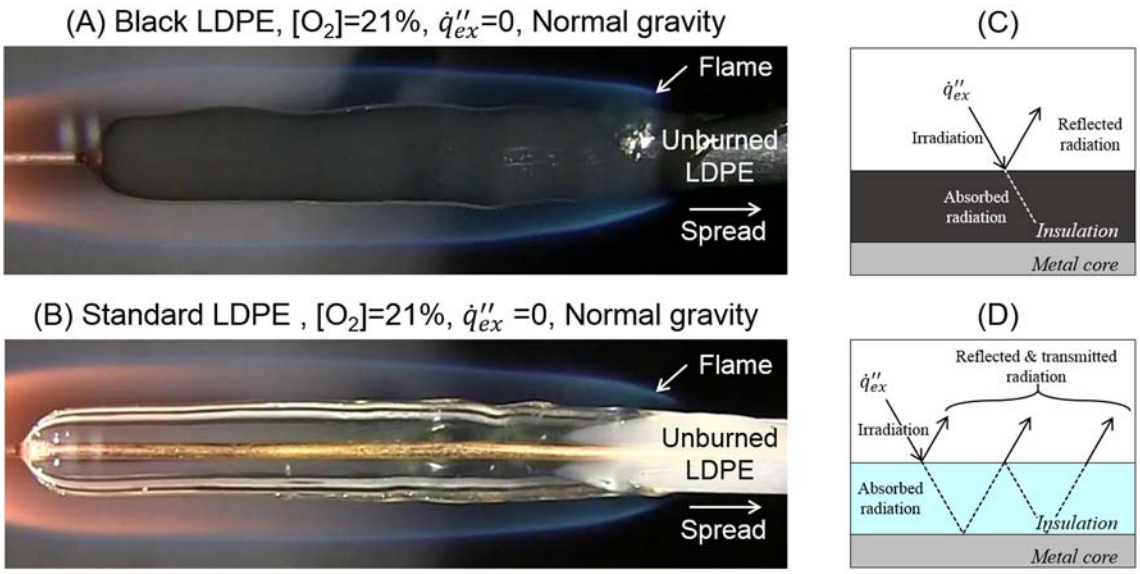

Fig. 7. Photographs of the burning (A) black and (B) standard low-density polyethylene (LDPE)-insulated wires and the corresponding conceptual diagrams ((C) and (D), respectively) of radiative heat flux absorption and transmission in the insulation layer.

3.3. Flame spread under microgravity

Photographs of the flame spread behaviors observed under microgravity are shown in Fig. 8. When the sample wires were heated with the coil igniter, a large bright flame was initially formed and, then, propagated downwardly without dripping of the molten insulation. Moreover, the flame luminosity was significantly lower than under normal gravity even at a 25% O_2 concentration. In addition, oscillation of the flame leading edge was observed on both samples under near-extinction conditions as done under normal gravity.

Figure 9 illustrates the measured FSR as a function of the O_2 concentration in microgravity; it was smaller for the thick core samples than that of the thin one. Thus, the flammability ranking of the tested wires under microgravity is consistent with the results obtained under normal gravity.

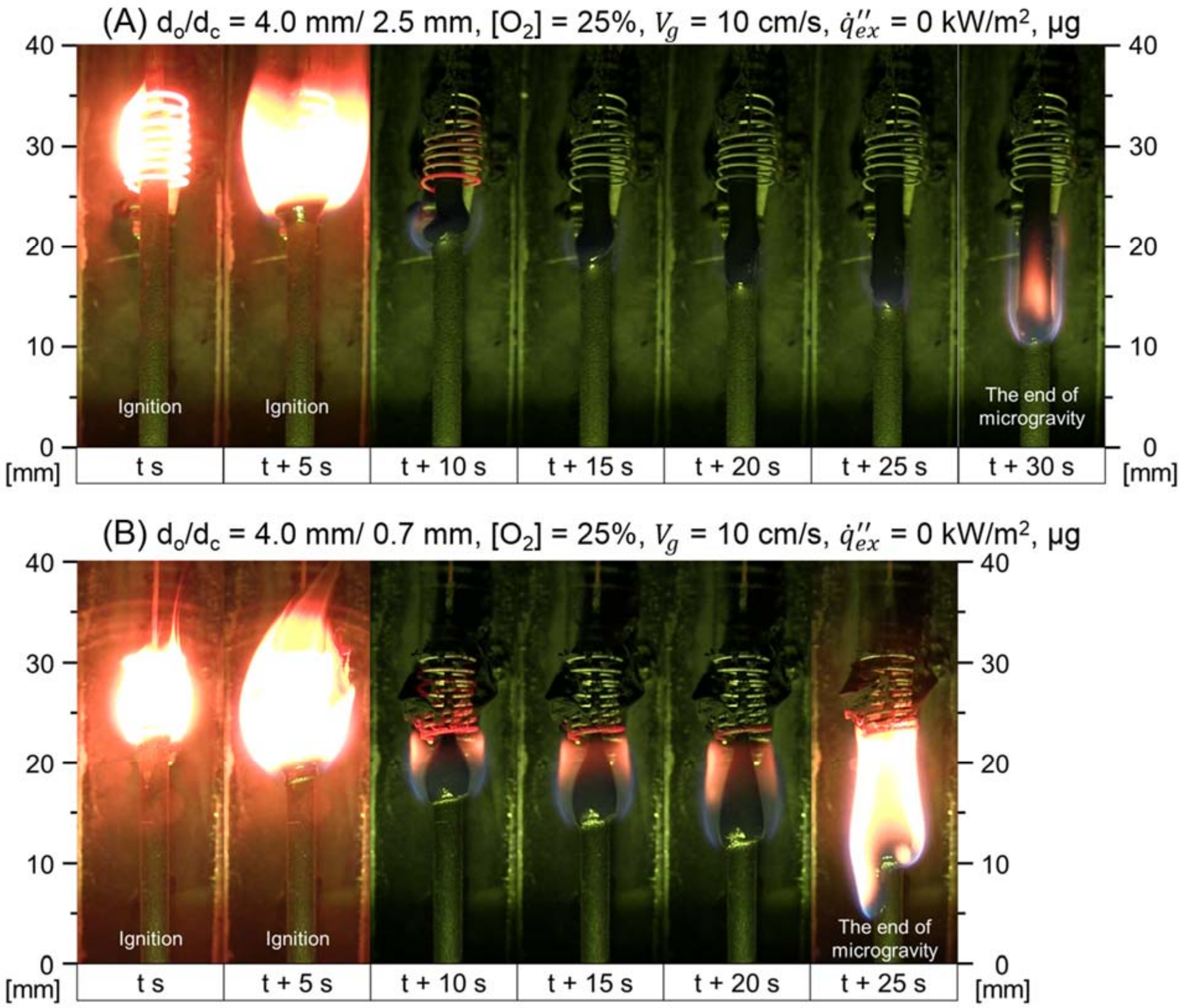

Fig. 8. Photographs of flame spread over black low-density polyethylene-insulated wires, with (A) thick and (B) thin copper core diameter (d_c) and same experimental conditions, under microgravity.

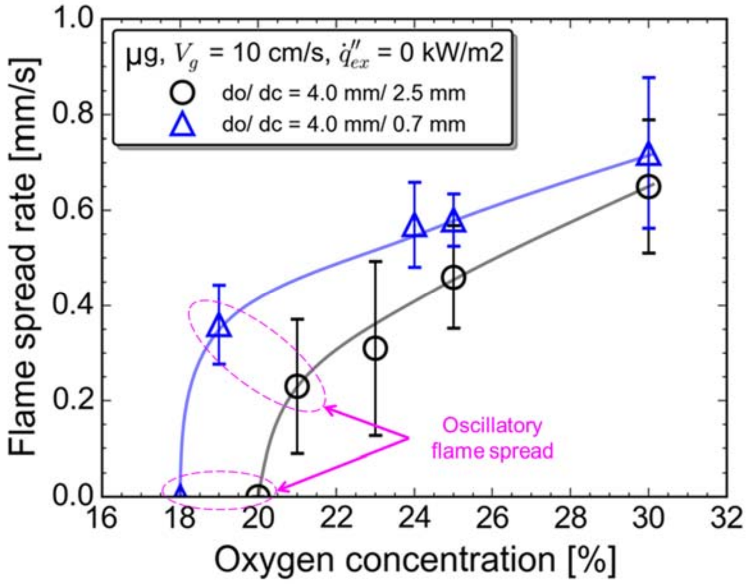

Fig. 9. Flame spread rate on the black low-density polyethylene-insulated wires as a function of the O_2 concentration under microgravity without external heating; the opposed-flow velocity was 10 cm/s.

3.4. Comparison of the flame spread limits under microgravity and normal gravity

Figure 10 compares the flame spread boundary maps obtained under microgravity and normal gravity. There were some scattered data in the microgravity results that were basically caused by the stochastic extinction due to the inherently unsteady flame spread over thick sample wires and the unstable external effect during parabolic flight (there were non-negligible g-jitter and airplane vibrations during the microgravity tests). The normal gravity flame spread boundaries followed a continuous line (see Fig. 6), and, although the number of experiments conducted under microgravity was limited, the dependence of the flame spread limits on the external radiant flux exhibited a similar trend, namely, they expanded to lower O_2 concentrations with the increase in the external radiant heat flux. Compared to normal gravity, limiting O_2 concentration increases for both wires under microgravity, that is, the flammability of the tested wires was reduced. The gravity effect on the flame spread limits of thinner (~1 mm) electric wires has been investigated by several researchers [23–25], which reported that the wires become more flammable under microgravity in low-forced airflow velocity conditions (V_g = 5–20 cm/s).

Since the residence time of the combustion gases in the reaction zone could basically be longer under microgravity than under normal gravity due to the absence of the buoyancy-induced flow, a microgravity environment allows longer chemical reaction times. Therefore, a flame could be sustained at lower O_2 concentrations with a resulting longer reaction time resulting. On the other hand, the oxygen transport to the reaction zone decreases under microgravity low-flow velocity conditions, leading to a large stand-off distance of the flame spread because of the reduced convective flow. Hence, the heat transfer from the flame to the solid surface and also FSR are reduced. The comparison between the present work and previous studies suggests that thicker and thinner wires may have different controlling mechanisms to sustain the flame spread under microgravity even with the same forced flow velocity and O_2 concentration. From our results, we can infer that the flame spread over the tested wires might have been dominated by the latter mechanism at the airflow velocity used in this study (V_g = 10 cm/s) due to the wire thickness. When the LDPE layer is thick or the core acts as a significant heat sink, there is a temperature gradient in the insulation. In such case, the decrease in the heat transfer from the flame to the preheated sample zone under microgravity causes a heat imbalance relative to the inward heat conduction from sample surface to core; consequently, the FSR and wire flammability are lower compared to normal gravity conditions.

Although the effects of the LDPE melting, dripping, and deformation on the flame spread and its limits are hard to quantify, there were clear differences in the behaviors observed under normal gravity and microgravity since dripping and deformation are results of gravity. Their impact on the flame spread over thermoplastic materials has been examined by several previous works and the effect of fuel type, size, and orientation and the surrounding ambient conditions have also been discussed [12,13,20,44–47]. The change of the dripping behavior associated with that of the gravity condition would have a non-negligible effect on the difference in the flame spread limits between normal gravity and microgravity because it not only carries away the enthalpy from the downstream burning region but also transports energy to the upstream unburned area. Further investigations are necessary to understand the role of the dripping on the flame spread over thermoplastic materials.

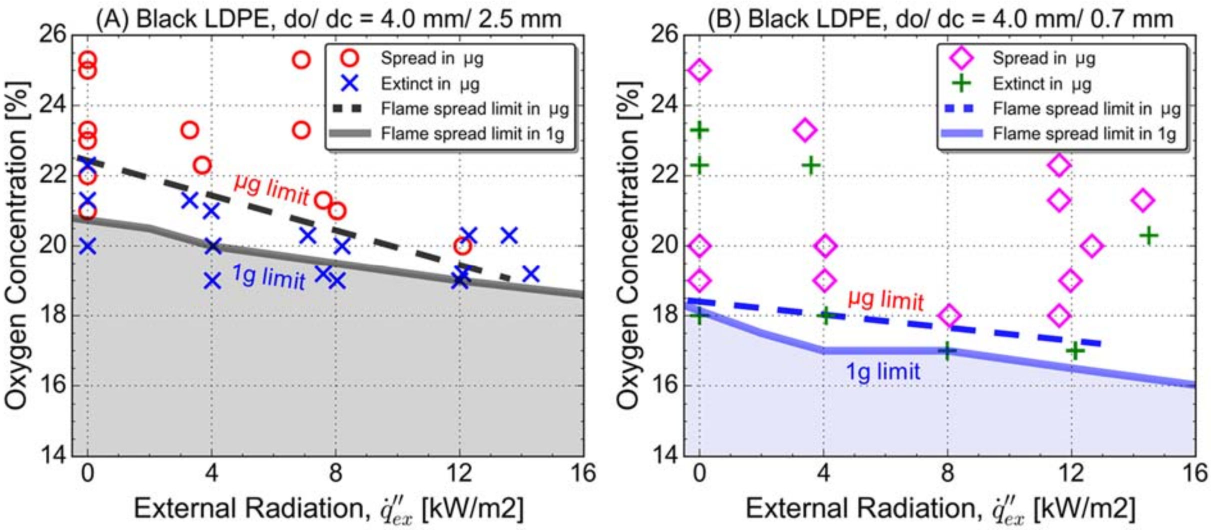

Fig. 10. Flame spread boundary maps as a function of the external radiant heat flux for black low-density polyethylene (LDPE)-insulated wires, with (A) thick and (B) thin copper core diameter (d_c), under microgravity (dashed lines) and normal gravity (solid lines); the opposed-flow velocity was 10 cm/s.

3.5. Effects of wire dimensions on electric wire flammability

The effects of the wire dimensions on the flammability of electric wire have been studied by several researchers [12–14] and identified as a quite complex problem that requires considering the impacts of many parameters, such as follows:

(1) the insulation thickness controls the in-depth heat losses toward the wire center, including the heat transfer to the metal core;

(2) the core diameter controls the temperature distribution along the wire and the contact area between its core and insulation;

(3) the outer diameter varies the curvature of the electric wire surface.

The present study experimentally demonstrated that, for a given wire outer diameter, the flammability of wires having a larger core diameter is lower than that of those with smaller d_c, under both normal gravity and microgravity; in addition, the insulation preheating in the tested range of external radiant heat flux cannot compensate the wire flammability reduction due to a d_c increase. However, the flammability ranking obtained is judged by the flame spread limits in the limited sample wire length (130 mm) and microgravity time (~20 s). Therefore, we can reasonably state that the ranking defined in the present study is based on experimental observations during the early transient stage of wire combustion, from the initial ignition state to the stable flame spread one. A previous work has revealed that the role of the copper core transits from a heat sink that cools the insulation to a heat source that heats the insulation during this transient process [22]. Furthermore, other works reported that the transient effect depends on the thermal conductivity of the core material as well as on the wire dimensions [15,20]; this effect should be an important study subject so to better clarify the wire dimension effects on the flammability of electric wires.

4. Conclusion

The dimension effect on the electric wire flammability in opposed-flow configuration was investigated by evaluating the flame spread limits over the wire insulation under various external radiant heat fluxes, in both normal gravity and microgravity conditions. Although the samples were laboratory wires, their analysis provided detailed information about the effects of gravity, preheating, and wire characteristics on electric wire flammability. The experimental results obtained under normal gravity indicated that the copper core size influences the extinction mechanism of the flame spread over the wire. As regards the flame spread limit as a function of the external radiant heat flux, black LDPE insulations exhibited an approximately linear relationship, whereas the standard LDPE ones showed a weak dependency when the flux exceeded 8 kW/m^2, which may be attributed to the change in their transparency of standard LDPE (i.e., from non-transparent to transparent) while heated by the external radiation. Further, the sample wire with the larger copper core (2.5 mm) was less flammable than that with the smaller one (0.7 mm) in both the gravity conditions examined due to the significant heat sink role played by the thick core, which could not be compensated within the tested range of external radiant heat flux. As for the gravity effect on the wire flammability, both tested sample wires were less flammable under microgravity. This leads the most significant conclusion of this paper: thicker and thinner wires may exhibit different controlling mechanisms to sustain the flame spread under microgravity. It also suggests that the comprehension of the wire dimension effects on the electric wire flammability requires understanding the transient process from the initial ignition stage to the stable flame spread one because the flame spread limits seem to appear during the transient process. The presented results provide a lot of variable information and could be used for validation to improve the fundamental understanding of electric wire combustion under not only microgravity but also normal gravity.

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