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Laser piloted ignition of electrical wire in microgravity

Yoshinari Kobayashi [a,*], Yusuke Konno [b], Xinyan Huang [c], Shinji Nakaya [d], Mitsuhiro Tsue [d], Nozomu Hashimoto [b], Osamu Fujita [b], Carlos Fernandez-Pello [e]

[a] *Department of Mechanical Engineering, Gifu University, 1-1 Yanagido, Gifu City 501-1193, Japan*

[b] *Division of Mechanical and Space Engineering, Hokkaido University, Kita 13 Nishi 8, Kita-ku, Sapporo, Hokkaido 060-8628, Japan*

[c] *Department of Building Services Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong*

[d] *Department of Aeronautics and Astronautics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*

[e] *Department of Mechanical Engineering, University of California, Berkeley, CA 94720, USA*

Abstract: This work studied the piloted ignition of electrical wires in both normal gravity and microgravity using the laser-induced spark. Unique experiments were conducted in the microgravity parabolic flight with laboratory wires under the oxygen concentration of 14 ~ 21% and external radiation of up to 15.9 kW/m^2. The wire sample consists of a 2.5-mm thick core, using the solid copper (Cu) or the hollow stainless steel (SS) tube, and a 0.75-mm thick black polyethylene (PE) insulation. This is the first piloted-ignition experiment on solid fuel in microgravity with the laser-induced spark as the pilot. Experimental results show that regardless of the oxygen level, the ignition delay time is always smaller in microgravity than in normal gravity, indicating a higher fire risk in the microgravity space environment. As the heat flux and the oxygen concentration increase, auto-ignition is observed. Moreover, if the core is exposed to the external heating source, it can heat the insulation to promote the ignition, different from the heat sink found in past ignition research. This unique research provides valuable information about the fire risk of electrical wire in microgravity and future long-term space travel.

Keywords: Ignitability, Auto-ignition, Oxygen concentration, Polyethylene (PE) wire, Microgravity

1. Introduction

Space exploration activities have reached new heights in recent years, including worldwide collaborations in the International Space Station (ISS), space transportation businesses by private space companies, or startup for space development in multiple developing countries. In these manned space activities, safety is the most important requirement. One fatal accident expected in spacecraft is the fire. In fact, fire in an isolated habitat such as spacecraft cabin has been identified as a significant risk factor, since the Apollo 1 fire claimed lives of three astronauts in 1967 [1,2]. Planned long-term missions bring more concerns about the possibility of accidental fire in space facilities or vehicles. Since a space facility such as ISS is designed with a life expectancy of 20 to 30 years, and it has many combustible materials and sources of fire, the probability of fire is high. Among these combustible materials, electrical wires and harnesses have been identified as a potential fire source in spacecraft because they are easy to ignite due to short-circuiting, poor contact, external heating, and ground fault [3–5]. Therefore, understanding their combustion characteristics can improve the fire safety management in space.

Many past researches have studied a variety of combustion phenomena for thin research wires (diameter of ~ 1 mm), such as the ignition of overloaded electrical wires, flame spread over wire under various flow conditions and the extinction of wire fire. For example, Bakhman *et al.* [6,7] first studied the flame spread over polymer coatings on copper wires with both horizontal and vertical orientations. Fujita *et al.* [8–10] studied the effect of wire configuration, pressure, temperature, environmental flow, oxygen (O_2) concentration, and dilution gas on wire combustion under both normal gravity and microgravity. Nakamura *et al.* [11,12] showed that the flame spread over polyethylene (PE)-insulated wire was faster with the larger size and thermal conductivity of core, so that core acted as a heat source in the flame spread. Huang *et al.* [13] revealed that high-conductance wire core acted as a heat sink during the piloted ignition and the transition to flame spread. Umemura *et al.* [14] presented a detailed numerical model to describe combustion characteristics of a copper-core wire, and showed a heat sink effect of copper core near the extinction, which was confirmed experimentally in [15]. Recently, Kobayashi *et al.* [16] observed a simultaneous dual effect, i.e., a heat source in the preheating region and a heat sink in the burning region. In normal gravity, the dripping flow of molten insulation acts as an additional heat source to facilitate the downward flame spread, but such dripping effect will disappear in microgravity.

So far, no piloted ignition experiment on the electrical wire has been conducted in microgravity, and there is also no laser piloted ignition experiment on any fuel in microgravity. Many studies focused on piloted ignition of pyrolysates from combustible materials. For example, Delichatsios [17] measured the ignition time, the critical heat flux, and mass loss rates for two types of plywood at reduced O_2 concentrations. The piloted ignition of PMMA in sub-atmospheric pressures and elevated O_2 concentrations has been explored experimentally and numerically [18–20]. Dai *et al.* [21] developed a numerical model to determine critical mass fluxes at ignition or extinction and discussed them regarding the Damköhler number and the igniter power. Kashiwagi [22] studied the laser introduced autoignition and laser heated ignition (piloted by a hot wire) of PMMA and red oak under the high radiant heat flux between 40 and 180 kW/m^2. Nakamura *et al.* [23,24] studied the critical ambient pressure and O_2 concentration for direct laser ignition of thin fuel sample and found the sample orientation had a strong effect on the ease of ignition.

The piloted-ignition of electrical wire under external heat flux has not been studied in the past. Also, there is no experiment on the piloted ignition of any solid fuel in microgravity yet. Fire behaves differently in between normal gravity and microgravity because of buoyancy. This work, therefore, has an important implication for improving fire safety for wires with flammable insulation in a spacecraft environment.

2. Experiment

2.1. Laboratory wire samples

In this experiment, "laboratory" wire samples which consist of PE insulation and metal core were used. The length of the core (175 mm) was larger than the length of insulation (130 mm). Two different wire configurations were tested, specifications of which are listed in Table 1. Two core-to-wire diameter ratios d_c/d_o were (I) 0.75/4.0 and (II) 2.5/4.0 (Fig. 1). The wire was five times thicker than those used in [8–13] and almost the same as [15,16].

A black low-density polyethylene (B-LDPE) was selected as the wire insulation because the black sample can absorb most of the irradiation and avoid the influence of transmitted irradiation. Two core materials were tested to investigate the core effect: (i) high-conductance solid copper (Cu) rod and (ii) a low-conductance hollow stainless steel (SS) tube with wall thickness of 1 mm. The thermo-physical properties of insulation and core materials can be found in [15,16]. The SS tube was selected not only as a low-conductivity core but also as a mechanism to simulate the insulation without a core. Without a core, PE insulation would become soft and bent when heated by external radiation and flame, and a dripping flow inside the insulation would be produced. Note that SS core wire was only used in the type II configuration.

Table 1. Configurations of PE insulation tubes and metal cores, and $\sum(\rho cA)$ is calculated using PE and Cu.

	d_c (mm)	d_o (mm)	δ_p (mm)	A_c/A_o (-)	$\Sigma(\rho cA)$ (J/m-K)
I	0.75	4.0	1.625	3.5%	19
II	2.5	4.0	0.75	39%	29

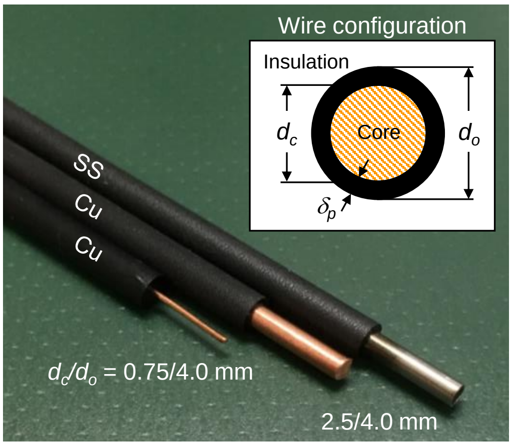

Fig. 1. Wire samples (insulation and core) and wire configuration.

2.2. Combustion chamber and flow line

A schematic diagram of the experimental apparatus is presented in Fig. 2. Laser piloted ignition tests were conducted inside an aluminum cylinder chamber which had a length of 300 mm, an inner diameter

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of 80 mm, and a wall thickness of 5 mm as shown in Fig. 2(a). At 30 mm distant from the centerline of the chamber, four IR lamps were placed concentrically at intervals of 90°. The radiant heaters were quartz infrared halogen lamps with a lit length of 154 mm and a total length of 276 mm (same as those in [15]). The radiant heat flux to the wire sample was measured by a radiometer under different supplied powers to be uniform and calibrated with supply power, like that in [15]. Therefore, it was the averaged heat flux, the maximum value of which was 15.9 kW/m^2. The tested wires were vertically placed inside the chamber by a wire holder in both normal gravity and microgravity.

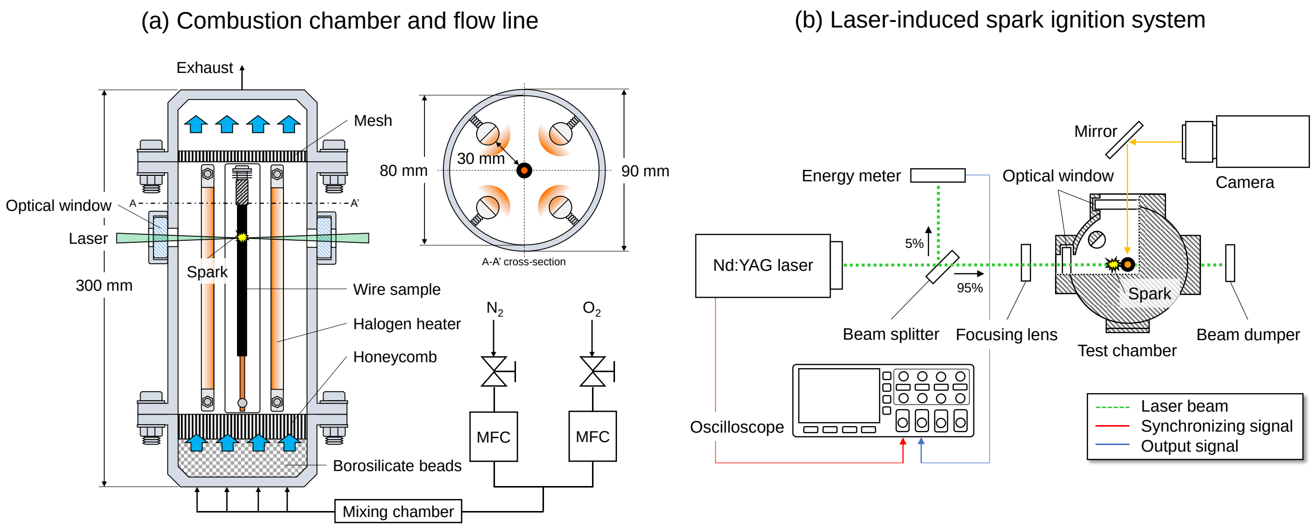

Fig. 2. Schematic diagram of experiment: (a) combustion chamber, and (b) laser-induced spark ignition system.

Pure O_2 and nitrogen (N_2) gases from gas cylinders were passed through mass flow controllers (Bronkhorst, F-202AV) with an accuracy of ± 0.5%. The pressure inside the chamber was fixed at 1 atm by a back-pressure regulator at the outlet of the chamber. The O_2 concentration and flow velocity were controlled by the flow rate of O_2 and N_2. After passing through a mixing chamber, borosilicate beads and meshes were used to homogenize further and straighten the flow. The O_2 concentration of flow varied between 14% and 21% by volume (balancing N_2) at a fixed flow velocity of 10 cm/s. Note that in normal gravity, the actual flow velocity around wire should be larger than 10 cm/s due to buoyancy induced by the heated wire (see calculation in Section 4.1).

2.3. Laser-induced spark ignition (LSI) system

Laser-induced spark ignition (LSI) was adopted in this work. Compared to conventional electrical spark ignition, LSI has no wall effects, no heat-loss through electrodes, and adaptable ignition location and timing [25–27]. Also, the piloting intensity will not change with the environment, and is more consistent than other pilots of small flame and electrical heater. Figure 2(b) shows the diagram of LSI system. A second harmonic generation of a Q-switched Nd:YAG laser (EKSPLA, NL232) was used, and its output specifications are listed in Table 2. The laser beam first passed a beam splitter. The energy fraction of the reflected laser beam was measured to be 5% by an energy meter to identify the incident energy. Then, the laser beam was focused by a focusing lens with focal length of 100 mm, and breakdown occurred to induce spark at 1 mm distant from the surface of the insulation. The energy intensity acquired from the energy meter was converted to digital signal and stored in an oscilloscope (Tektronics, MDO3104). The incident energy was fixed at 100 mJ/pulse in all ignition tests. During the tests, pyrolysis process and successful/failed ignition were recorded with a digital video camera (Canon, iVIS HF G20, 30 fps).

Table 2. Laser output specifications

Item	Value
Wavelength	532 nm
Pulse energy	100 mJ/pulse
Energy stability (standard deviation)	± 2%
Pulse duration	5.9 ns
Pulse reputation rate	30 Hz
Beam diameter	4mm

2.4. *Microgravity test procedure*

Microgravity experiments were conducted in parabolic flights onboard Gulfstream-II aircraft operated by Diamond Air Service (DAS) Inc. in Japan. Microgravity environment of 10^{-2} g was simulated for about 20 s in each parabolic flight. In flight, the 3-D gravity variations, chamber pressure, and radiant lamp power were recorded in a data logger (Graphtec, midi LOGGER GL900). Because of the limited flight number, only wire with d_c/d_o = 2.5/4.0 and Cu core was tested in microgravity. The microgravity experiments were conducted based on the sequence shown in Fig. 3, and the normal-gravity experiments followed the same manner except for no change in gravity throughout the test. Before ignition, the prescribed airflow first flowed through the chamber, and the radiant lamps were turned on to preheat wire samples for 15 s. Then, the laser beam was busted at an interval of 2 s for five times in total. That is, the maximum heating time was 25 s. For microgravity experiments, the radiant heating period includes 5 s in 2g and 20 s in microgravity.

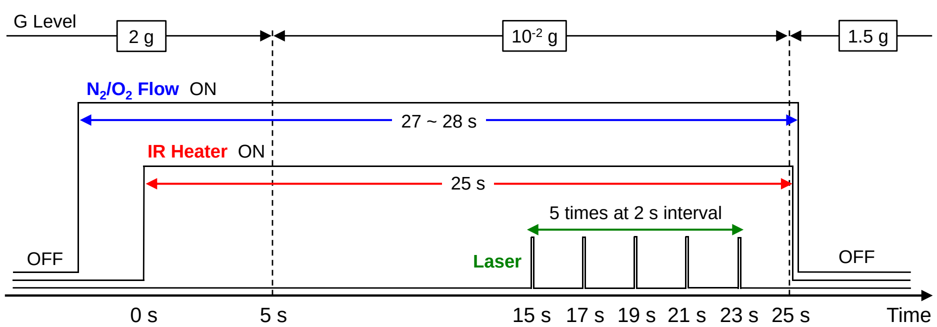

Fig. 3. The test sequence for microgravity experiments.

3. Results

3.1. Ignition phenomena

Figure 4 shows a group of snapshots of laser piloted ignition at 16% O_2 under 14.6 kW/m^2 in microgravity. Once heated, the wire insulation began to shrink and pyrolyze. Such process became more manifest as the heating time was increased. After heating for about 15 s, a layer of pyrolysis gas (i.e., smoke) near the surface of insulation appeared, and the entire chamber became blurred. After the 5th spark discharged at $t = 23$ s, a short-term flash of spark occurred within 1 s, which was defined as the flashpoint or ignition. Then, a flame quickly wrapped the entire wire and was sustained until the burnout of insulation, i.e., the fire point ($t = 25$ s). Similar ignition phenomenon was also observed in the normal-gravity experiments.

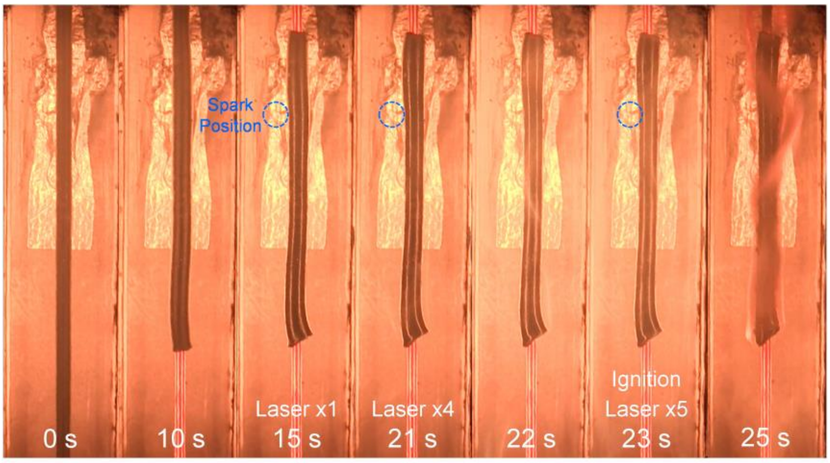

Fig. 4. The ignition-to-flame transition under 16% O_2 and 14.6 kW/m^2 in microgravity where the 5th spark ignited the wire.

As confirmed by the video, the gas-phase ignition (spark) occurred at the focal point of laser 1 mm away from the insulation, which was inside in the flow boundary layer. To verify that the ignition was initiated by the laser rather than the auto-ignition, experiments with and without the laser ignition were conducted under normal gravity for comparison. As expected, under the same heating duration, heat flux, and O_2 concentration, ignition occurred with laser pilot, while did not occur without laser pilot. On the other hand, continuously increasing the heating duration, auto-ignition may occur even without the laser pilot.

3.2. Ignition delay time

The ignition delay time (t_{ig}) observed in the experiment, should include the pyrolysis time (t_p), mixing time (t_{mix}), and chemical time (t_{chem}), as

$$t_{ig} = t_p + t_{mix} + t_{chem} \tag{1a}$$

For the piloted ignition, the gas-phase chemical time (t_{chem}) is negligible because the temperature of the pilot (e.g. laser spark, electrical spark or flame) is very high. If the pilot source is close to the fuel surface, the mixing time (t_{mix}) will be much less then 1 s [28]. The pyrolysis time (t_p) is usually the longest unless fuel is directly heated by the strong laser and hot gases [29] or the external flow speed is very large [30]. For auto-ignition, the gas-phase mixing and chemical processes may be important.

Because the wire is relatively thin, the classical piloted ignition theory for the thermally-thin fuel may be adopted to estimate the pyrolysis time [28]. Then, the ignition delay time may be expressed as

$$t_{ig} = \frac{\sum(\rho c A)_i \left(T_p - T_\infty\right)/(\pi d_o)}{\dot{q}''_{rad} - \dot{q}''_{conv} - \dot{q}''_{rr}} + t_{mix} + t_{chem} \qquad (1b)$$

where $\sum(\rho c A)$ is the thermal inertia of the wire, T_p is the pyrolysis temperature of PE, T_∞ is the ambient temperature, subscript $i = p$, c indicates the polymer insulation and core, respectively, A is the cross-section area, d_o is the outer diameter of the wire, $\dot{q}''_{conv}$ is the convective heat loss, and $\dot{q}''_{rr}$ is the re-radiation heat loss.

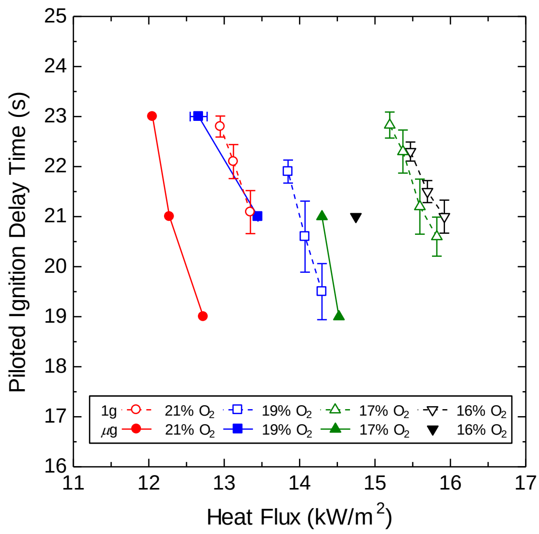

Fig. 5. Ignition delay time of B-LDPE-insulated wires with Cu core (d_c/d_o = 2.5/4.0 mm) under different oxygen concentrations. Hollow symbols are for normal gravity, and solid symbols are for microgravity.

Figure 5 shows the measured piloted ignition delay time (t_{ig}) as a function of heat flux under different O_2 concentrations in normal gravity and microgravity. First, the measured ignition delay time decreases with increasing radiant heat flux ($\dot{q}''_{rad}$), which was similar to those obtained with a flame or a hot wire as a pilot [18–20]. Both the long ignition delay time and the strong dependence on external heat flux suggest that the pyrolysis time dominates the ignition delay and is much larger than the time for mixing and chemical processes, like most other piloted ignition experiments.

Moreover, the ignition delay time increases as the O_2 concentration is decreased. For example, under the radiation of 12.8 kW/m^2 and microgravity, the ignition delay time increases from 19 s to 23 s, as the O_2 concentration decreases from 21% to 19%. According to the thermogravimetric analysis, the O_2 concentration has a strong effect on the pyrolysis temperature of PE [31,32]. Specifically, as the O_2

concentration decreases from 21% (normal air) to 0% (pure N_2), the pyrolysis temperature of PE (T_p) increases significantly from 250°C to 450°C. As seen from Eq. (1b), for larger pyrolysis temperature under the lower O_2 concentration, a larger radiant heat flux is required for achieving the same ignition time.

3.3. Ignitability map

The ignition limit is defined if no piloted ignition occurred after five laser pulses or 25 s heating, i.e. $t_{ig,c} = 25$ s. Figure 6 shows the ignitability map, as a function of radiant heat flux and O_2 concentration, for Cu-core wire with $d_c/d_o = 2.5/4.0$ [mm]. The double circle symbols indicate the auto-ignition. The solid (no ignition) and hollow (ignition) symbols are used to help identify the ignition boundary.

In normal gravity, auto-ignition was observed within the limit of piloted ignition. Specifically, the critical O_2 concentration for auto-ignition is about 2% higher than that for piloted ignition, or the critical heat flux is about 1 kW/m^2 higher. The auto-ignition experiments in microgravity were not conducted because of the limited number of microgravity experiments.

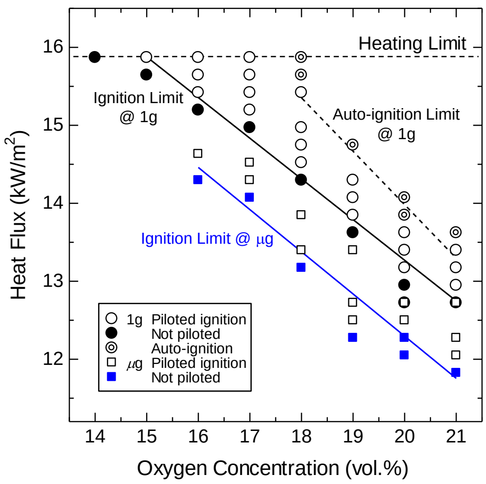

Fig. 6. Ignitability map of B-LDPE-insulated wires with $d_c/d_o = 2.5/4.0$ mm and Cu core. The radiant heating time is fixed to be 25 s.

Using the same thermally-thin theory, for a given ignition delay time ($t_{ig} = 25$ s), the critical radiant heat flux ($\dot{q}''_{rad,crt}$) can be expressed as

$$\dot{q}''_{rad,crt} = \frac{\Sigma(\rho c A)_i \left(T_{p,O_2} - T_\infty\right)/(\pi d_o)}{t_{ig} - t_{mix} - t_{chem}} + \dot{q}''_{conv} + \dot{q}''_{rr} \qquad (2)$$

As the O_2 concentration is increased, $\dot{q}''_{rad,crt}$ should decrease because of the decreased T_p. The linear fit between the limiting heat flux and oxygen concentration is also provided in Fig. 6 as the boundary line. For piloted ignition, the slopes of boundary lines in normal gravity and microgravity are close to each other, although the gravity or oxygen concentration can change the mixing time. Based on Eq. (2), the same slope further suggests that the mixing time is negligible for the current laser piloted ignition.

On the other hand, the auto-ignition requires the occurrence of gas-phase thermal explosion before turning off the heater, so that gas-phase mixing and chemical processes may not be overlooked. Considering a 2nd-order gas-phase chemical reaction rate ($\dot{\omega}$) given by the Arrhenius expression, it increases with O_2 concentration as

$$\dot{\omega} = Z\exp\left(-\frac{E}{RT_g}\right)[O][F] \tag{3}$$

where Z is the pre-exponential factor, E is the activation energy, R is the gas constant, $[O]$ and $[F]$ are the concentrations of oxidizer and fuel, respectively. The temperature (T_g) is the gas temperature, which is much lower than the temperature of the pilot source, so the reaction rate is much slower.

If there is a critical reaction rate for auto-ignition to occur, a lower O_2 concentration is required at a higher gas temperature, i.e., under a larger heat flux. Thus, the boundary line for auto-ignition shows a similar trend to the laser piloted ignition in Fig. 6, but its larger slope shows the larger sensitivity to the O_2 concentration. A similar trend should also be expected for auto-ignition in microgravity.

4. Discussions

4.1. Effect of gravity

Figure 5 also shows that the wire is easier to ignite in microgravity than in normal gravity. Specifically, under a fixed radiant heat flux, the wire in microgravity can be ignited in a shorter heating time or a lower O_2 concentration. There are two major mechanisms, related to the level of gravity, affecting the critical radiant heat flux, (i) the change in convective heating ($\dot{q}''_{conv}$), and (ii) the change in mixing time (t_{mix}).

In general, the convective heat loss increases with the free stream velocity (U) as

$$\dot{q}''_{conv} = h\Delta T \sim Nu \propto U^n \qquad (U_{1g} > U_{\mu g}) \tag{4}$$

where h is the convective coefficient, and index $n > 0$. In normal gravity, the buoyancy accelerates the external flow, so the values of h and $\dot{q}''_{conv}$ should be larger than those in microgravity. Because of the small convective heat loss in microgravity (seen Eq. (2)), a smaller critical radiant heat flux is required, i.e., the piloted ignition becomes easier in spacecraft.

The mixing time can be estimated as

$$t_{mix} \approx \frac{\delta_{BD}^2}{D_g} \approx \frac{(\rho ck)_g}{h^2} \tag{5}$$

where D is the diffusivity, k is the thermal conductivity, and subscript g represents the gas. Because of a smaller h in microgravity, the required mixing time is larger, making the ignition more difficult.

Therefore, these two mechanisms should compete with each other on the ease of ignition. Experimental results in Fig. 5 shows that the ignition is easier in microgravity; thus, the mechanism of reducing the convective cooling is dominant. This is also supported by the same slope of the boundary line between normal gravity and microgravity found in Fig. 6. Nevertheless, if the pyrolysis time becomes smaller under a larger radiant heat flux, the change in mixing time may become more important, that is, the ignition risk in microgravity may become lower than that in normal gravity (to be verified in future work).

4.2. *Effect of core*

Figure 7a compares the ignitability of Cu-core wire and SS-core wire of the same dimension. As expected for SS-core wire, i.e., the critical heat flux of both piloted-ignition and auto-ignition decreases as the O_2 concentration is increased, the same trend as Cu core. However, the critical heat flux for wire with a hollow SS core was higher than with a solid Cu core. In other words, the Cu-core wire is easier to ignite. This result goes against our intuition because the metal core was found to be a heat sink in ignition [13]. Based on Eq. (2), the wire with larger thermal inertia should be more difficult to ignite, and the cross-section area of a solid Cu core is much larger than a hollow SS core.

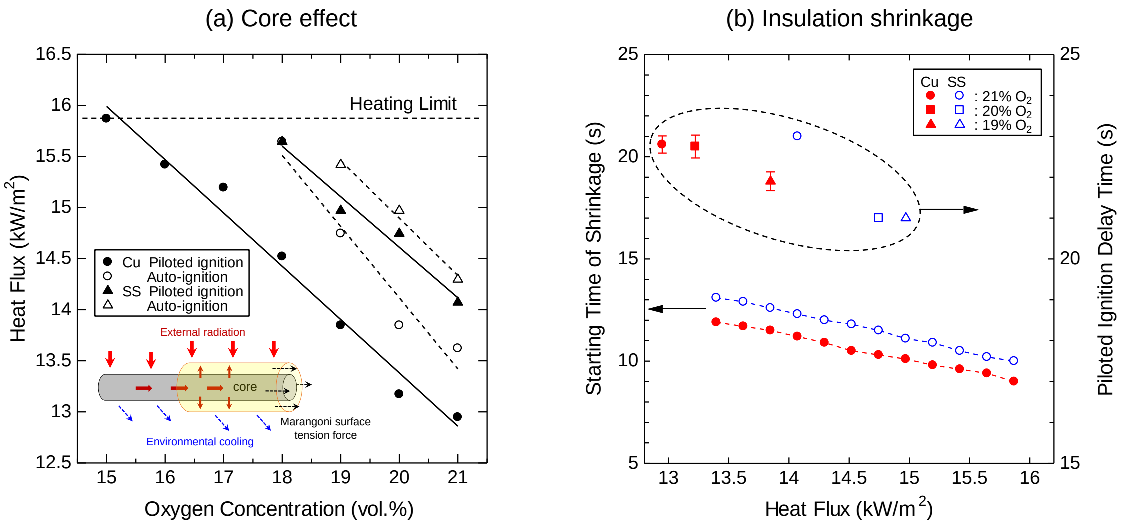

Fig. 7. Effect of the core on the wire ignitability and insulation-shrinkage behavior in normal gravity where the size of B-LDPE insulated wire is d_c/d_o = 2.5/4.0 mm.

A close look at the experiment reveals that because the core was longer than the insulation, both core ends were directly heated by the external radiation. Then, part of the heat ($\dot{q}''_{cond}$) was conducted towards the cooler core covered by the insulation (see diagram in Fig. 7a), and its magnitude was larger for the high-thermal-conductivity solid Cu core. Therefore, the overall effect of Cu core on this ignition process became a heat source. Also, thermocouple measurements in normal-gravity experiments confirmed that the Cu-core temperature was higher than the SS-core temperature.

The shrinkage of insulation found during the heating (see Fig. 4) is driven by the Marangoni surface-tension force, that is, the surface tension is smaller if the insulation is hotter. The heat source effect of the core is also supported by different shrinking times between two cores where the molten insulation shrank more and faster in Cu core than in SS core, as shown in Fig. 7b. Because the surface tension of molten insulation decreases with the increased temperature, the larger surface tension in the cool center will pull the hot insulation on both sides. As the hot Cu core helped heat the insulation, it melted faster, and then shrank faster.

Note that the direct heating to the core and the consequent assisted heating to insulation are highly possible in a real fire, if there is a nearby fire or hot smoke. Therefore, caution is needed when considering the effect of the core (heat source or heat sink) on the ignition.

4.3. *Effect of insulation thickness*

Figure 8 shows the ignitability of a thick-insulation wire with d_c/d_o = 0.75/4.0 mm and Cu core. Under the current test matrix, this thick-insulation can only be ignited at 21% O_2 and near the maximum heat flux. Specifically, at 21% O_2, the critical heat flux increases from 12.8 kW/m^2 to 15.5 kW/m^2 as the insulation thickness increases from 0.75 mm to 1.625 mm. In other words, as the insulation becomes thicker, the wire is more difficult to ignite. For this thick-insulation wire, its thermal inertia $\sum(\rho c A)$ is much larger, as compared in Table 1.

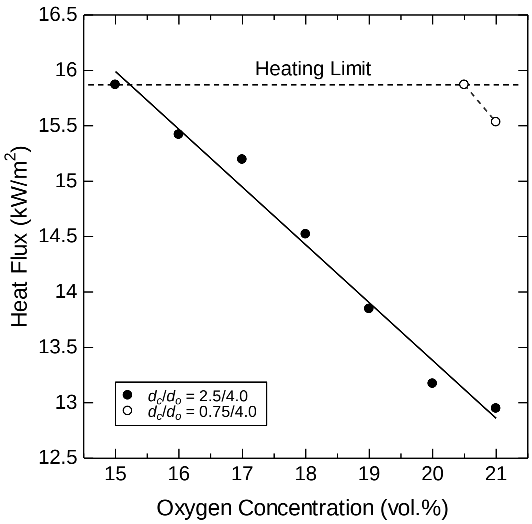

Fig. 8. Ignitability of B-LDPE-insulated wires d_c/d_o = 0.75/4.0 mm and Cu core in normal gravity.

Based on Eq. (2), the critical heat flux should increase under the same heating duration, and the increment could be estimated as

$$\Delta\dot{q}''_{rad,crt} \approx \frac{\Delta[\sum(\rho c A)_i]}{t_{ig}(\pi d_o)}\left(\frac{T_p - T_\infty}{2}\right) \approx 3\ \mathrm{kW/m^2} \qquad (6)$$

where a linear temperature profile is assumed in the wire radial direction. This estimation agrees on the experimental result. This result shows the importance of thermal inertia in wire ignition, which was also observed in previous tests on thinner wires (about 1-mm diameter) ignited by a short coil heater [13]. Note that despite of low ignitability, once ignited, wires of thicker insulation have larger fuel density, so that it may have a larger fire hazard in terms of the heat release rate and the dripping.

5. Conclusion

This work studied the first ever piloted ignition of solid fuel (using electrical wires) in both normal gravity and microgravity (parabolic flight). It is also the first time that the laser-induced spark is used as the pilot. Experimental results show that the ignition delay time is always smaller in microgravity, regardless of the oxygen level. In other words, in microgravity, the reduced pyrolysis time due to a weak cooling overcomes the increment in mixing time. For a given heating duration, ignition can be achieved under lower external radiation and a lower oxygen concentration in microgravity than those in normal gravity. Both results indicate a higher fire risk in the microgravity space environment.

As the heat flux and the oxygen concentration increase, auto-ignition is also observed. Moreover, wire of a solid Cu core is found to be easier to ignite, compared to that of a hollow SS core, because the part of the core is directly exposed to external radiation. This result indicates that core acts a heat source for ignition, different from the heat sink found in [13]. In other words, depending on the ignition scenario, the core can be either a heat sink or heat source in the ignition of wire. Also, thicker insulation wire was found to be more difficult to ignite, because of the larger thermal inertia. This unique research provides valuable information about the fire risk of electrical wire in microgravity and future long-term space travel.

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References

[1] Friedman R. Fire Safety in Spacecraft. Fire Mater 1996;20:235–43. doi:10.1002/(SICI)1099-1018(199609)20:5<235::AID-FAM580>3.0.CO;2-Y.

[2] Lange KE, Perka AT, Duffield BE, Jeng FF. Bounding the Spacecraft Atmosphere Design Space for Future Exploration Missions. NASA/CR 2005:213689.

[3] Fujita O. Solid combustion research in microgravity as a basis of fire safety in space. Proc Combust Inst 2015;35:2487–502. doi:10.1016/j.proci.2014.08.010.

[4] Friedman R. Fire Safety in the Low-Gravity Spacecraft Environment 1999. doi:10.4271/1999-01-1937.

[5] NASA-STD-6001B, Flammability, Offgassing, and Compatibility Requirements and Test Procedures. 2016.

[6] Bakhman N, Aldabaev L, Kondrikov B, Filippov V. Burning of polymeric coatings on copper wires and glass threads: I. Flame propagation velocity. Combust Flame 1981;41:17–34. doi:10.1016/0010-2180(81)90036-5.

[7] Bakhman N, Aldabaev L, Kondrikov B, Filippov V. Burning of polymeric coatings on copper wires and glass threads: II. Critical conditions of burning. Combust Flame 1981;41:35–43.

doi:10.1016/0010-2180(81)90037-7.

[8] Fujita O, Kikuchi M, Ito K, Nishizawa K. Effective mechanisms to determine flame spread rate over ethylene-tetrafluoroethylene wire insulation: Discussion on dilution gas effect based on temperature measurements. Proc Combust Inst 2000;28:2905–11. doi:10.1016/S0082-0784(00)80715-8.

[9] Fujita O, Nishizawa K, Ito K. Effect of low external flow on flame spread over polyethylene-insulated wire in microgravity. Proc Combust Inst 2002;29:2545–52. doi:10.1016/S1540-7489(02)80310-8.

[10] Takahashi S, Takeuchi H, Ito H, Nakamura Y, Fujita O. Study on unsteady molten insulation volume change during flame spreading over wire insulation in microgravity. Proc Combust Inst 2013;34:2657–64. doi:10.1016/j.proci.2012.06.158.

[11] Nakamura Y, Yoshimura N, Matsumura T, Ito H, Fujita O. Opposed-wind Effect on Flame Spread of Electric Wire in Sub-atmospheric Pressure. J Therm Sci Technol 2008;3:430–41. doi:10.1299/jtst.3.430.

[12] Nakamura Y, Yoshimura N, Ito H, Azumaya K, Fujita O. Flame spread over electric wire in sub-atmospheric pressure. Proc Combust Inst 2009;32:2559–66. doi:http://dx.doi.org/10.1016/j.proci.2008.06.146.

[13] Huang X, Nakamura Y, Williams FA. Ignition-to-spread transition of externally heated electrical wire. Proc Combust Inst 2013;34:2505–12. doi:http://dx.doi.org/10.1016/j.proci.2012.06.047.

[14] Umemura A, Uchida M, Hirata T, Sato J. Physical model analysis of flame spreading along an electrical wire in microgravity. Proc Combust Inst 2002;29:2535–43. doi:10.1016/S1540-7489(02)80309-1.

[15] Miyamoto K, Huang X, Hashimoto N, Fujita O, Fernandez-Pello C. Limiting Oxygen Concentration (LOC) of Burning Polyethylene Insulated Wires under External Radiation. Fire Saf J 2016;86:32–40. doi:10.1016/j.firesaf.2016.09.004.

[16] Kobayashi Y, Huang X, Nakaya S, Tsue M, Fernandez-Pello C. Flame spread over horizontal and vertical wires: The role of dripping and core. Fire Saf J 2017;91:112–22. doi:10.1016/j.firesaf.2017.03.047.

[17] Delichatsios MA. Piloted ignition times, critical heat fluxes and mass loss rates at reduced oxygen atmospheres. Fire Saf J 2005;40:197–212. doi:10.1016/j.firesaf.2004.11.005.

[18] Mcallister S, Fernandez-pello C, Urban D, Ruff G. Piloted ignition delay of PMMA in space exploration atmospheres. Proc Combust Inst 2009;32:2453–9. doi:10.1016/j.proci.2008.05.076.

[19] McAllister S, Fernandez-Pello C, Urban D, Ruff G. The combined effect of pressure and oxygen concentration on piloted ignition of a solid combustible. Combust Flame 2010;157:1753–9. doi:10.1016/j.combustflame.2010.02.022.

[20] Rich D, Lautenberger C, Torero JL, Quintiere JG, Fernandez-Pello C. Mass flux of combustible solids at piloted ignition. Proc Combust Inst 2007;31 II:2653–60. doi:10.1016/j.proci.2006.08.055.

[21] Dai J, Delichatsios MA, Yang L, Zhang J. Piloted ignition and extinction for solid fuels. Proc Combust Inst 2013;34:2487–95. doi:10.1016/j.proci.2012.07.021.

[22] Kashiwagi T. Radiative ignition mechanism of solid fuels. Fire Saf J 1981;3:185–200. doi:10.1016/0379-7112(81)90043-6.

[23] Nakamura Y, Aoki a. Irradiated ignition of solid materials in reduced pressure atmosphere with various oxygen concentrations – for fire safety in space habitats. Adv Sp Res 2008;41:777–82. doi:10.1016/j.asr.2007.03.027.

[24] Nakamura Y, Kashiwagi T. Effects of sample orientation on nonpiloted ignition of thin poly(methyl methacrylate) sheet by a laser1. Theoretical prediction. Combust Flame 2005;141:149–69. doi:10.1016/j.combustflame.2004.12.014.

[25] Ronney PD. Laser versus conventional iginition of flames. Opt Eng 1994;33:510–521.

[26] Phuoc T, White F. Laser-induced spark ignition of CH 4/air mixtures. Combust Flame 1999;2180:203–16. doi:10.1016/S0010-2180(99)00051-6.

[27] Phuoc TX. Laser-induced spark ignition fundamental and applications. Opt Lasers Eng 2006;44:351–97. doi:10.1016/j.optlaseng.2005.03.008.

[28] Quintiere JG. Fundamental of Fire Phenomena. New York: John Wiley; 2006.

[29] Kashiwagi T. Experimental observation of radiative ignition mechanisms. Combust Flame 1979;34:231–44. doi:10.1016/0010-2180(79)90098-1.

[30] Fernandez-Pello C. The Solid Phase. In: Cox G, editor. Combust Fundam Fire, New York: Academic Press; 1994, p. 31–100.

[31] Peterson JD, Vyazovkin S, Wight C a. Kinetics of the Thermal and Thermo-Oxidative Degradation of Polystyrene, Polyethylene and Poly(propylene). Macromol Chem Phys 2001;202:775–84. doi:10.1002/1521-3935(20010301)202:6<775::AID-MACP775>3.0.CO;2-G.

[32] Takashi Kashiwagi TJO. A study of oxygen effects on nonflaming transient gasification of PMMA and PE during thermal irradiation 1982:815–23.