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低重力環境下における被覆電線の過負荷着火に及ぼす制限空間径の影響

Effects of confined space size on overload ignition of polymer-insulated wire in reduced gravity: A numerical study

郭峰 [1], 橋本望 [1], 藤田修 [1],
Feng GUO[1], Nozomu HASHIMOTO[1], Osamu FUJITA[1]
[1] 北海道大学工学研究院，Hokkaido University, Faculty of Engineering

1. Introduction

Overload ignition of electric wires is one of the most probable causes of fires in spacecraft[1)]. To improve the fire safety of manned space exploration activities and further to the moon and Mars, more insights on the ignition characteristics of polymer insulated wires with an excess electric current in microgravity and partial gravities are expected. Previously, a series of experimental and 1-dimensional (1D) numerical studies have been carried out in an identical combustion chamber for the overload ignition of electric wires[2-5)]. It was found that the ignition limit can be greatly extended in microgravity (0*G*) than that in normal gravity (1*G*). To distinguish the difference in ignition characteristics caused by gravity, an updated 2-dimensional (2D) numerical model was established using Fire Dynamics Simulator (FDS)[6,7)]. However, electric wires are always located in a confined space, like narrow channels or protective sleeves. Such confinement may affect the flammability/ignitability of the wire regardless of gravity. In addition, Since the experimental space for microgravity experiments is often limited, we also need to understand how the chamber design affects the experimental results. In this work, we performed a numerical study by utilizing the 2D numerical model to investigate the effect of the confined space size on the overload ignition of the wire under varied gravities.

2. Methods

As shown in Figure 1 (a), the original 2D model was taken from the cross-section of the experimental chamber (140 mm × 170 mm) under a Cartesian coordinate system which is identical to the previous works[6-8)]. We selected five confinement variations with different diameters (10, 20, 40, 80, and 120 mm) to simulate scenarios in varied tube sizes. All the confinement walls were set as inert boundaries at 293 K. Same to the previous study[8)], the wire was assumed as infinitely long with the outer layer of Low-density-polyethylene (LDPE) and the inner layer of Nichrome (NiCr) with reasonable choices of material properties and pyrolysis parameters. The overloading was modeled as the volumetric Joule heat from the inner layer, which is controlled by the applied current value. The single-step reaction of ethylene combustion was employed [9)], and the ignition criterion was set as the critical local volumetric heat release of 32 MW/m^3. The ignition delay times were simulated in 0*G* and 1*G* under the chamber-sized confinement as shown in Figure 1(b), which have good agreement with available experimental results [2,5)]. Therefore, the results of chamber-sized confinement in 0*G* will be used as the baseline for comparing with further simulations with varied confined space sizes.

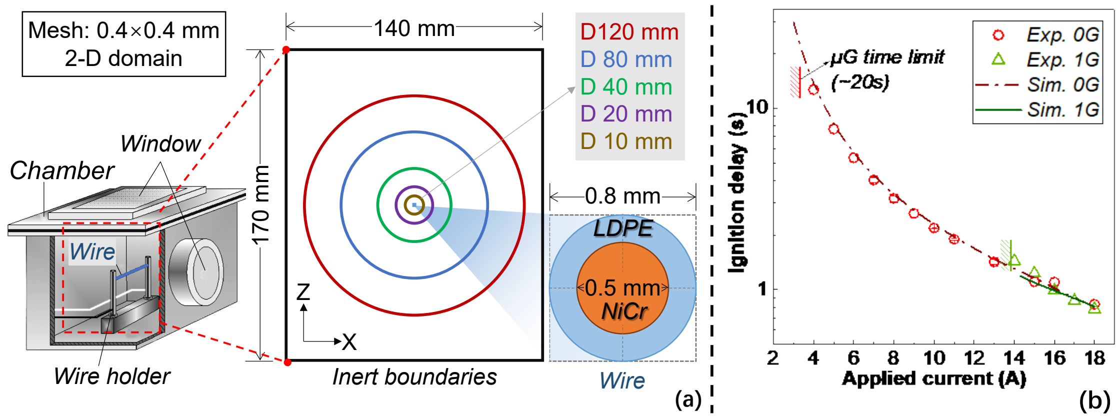

Figure 1. (a) Schematic of 2-dimensional numerical model with different sizes of confined space; (b) Validated ignition delay times with chamber-sized confined space in 0*G* and 1*G*.

3. Results and discussion

3.1. Ignition delay time

Ignition delay times under continuous current supply have been recorded as a function of electric current value. In order to more clearly compare the difference of ignition delay time of the wire under different confined space sizes and different gravity levels, the normalized ignition delay time was utilized, which is defined as the ratio of ignition delay time with a certain current (t_{ig}) over the ignition delay time with the same current under the chamber-sized confinement in 0*G* ($t_{ig,chamber,0G}$). Figure 2 compares the normalized ignition delay times as a function of applied current with different sizes of confinement at gravity levels of space, the moon, Mars, and the earth.

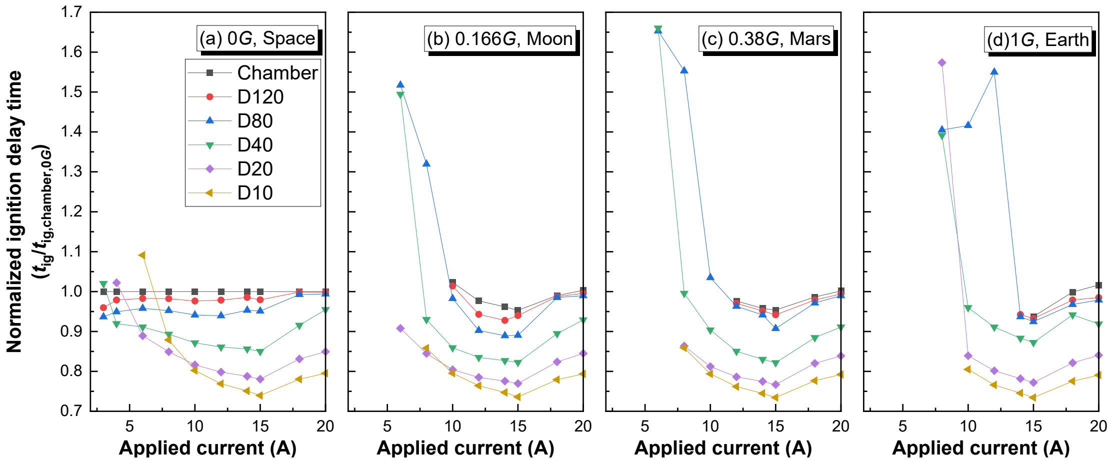

Figure 2. Comparison of normalized ignition delay times as a function of applied current with different sizes of confined space under gravity levels of: (a) 0*G* for space, (b) 0.166*G* for the moon, (c) 0.38*G* for Mars and (d) 1*G* for the earth.

Overall, when a higher electric current was applied, the ignition occurs earlier in the smaller confined space. However, when the applied current decreases, the ignition delay time in smaller confinement became longer. For the cases at 0*G* (Figure 2(a)), due to large heat loss from the hot inner gases to the confined boundaries (large radial temperature gradient), the delay time increased in very small confinements (D10, D20) at lower current. On the other hand, for the cases at partial-*G* and 1*G* (Figure 2 (b-d)), the intermediate sizes of confinement (D20-D80) gave much longer delay times to ignition, which is also much longer than the corresponding pyrolysis times. It was found that such highly delayed ignition is equivalent to the piloted ignition (explosion) of partially premixed gases in the intermediate confinements that allow the pyrolyzed fuel and inner air to mix in the flammable range.

3.2. Ignition position

The ignition positions in Z-direction have been recorded as a function of electric current value, as shown in Figure 3. In 0*G*, transitions from the "spontaneous ignition" to the "wire-assisted ignition" with applied current increase can be found for the cases under larger confinements; while for the smaller confinements, the ignition mode tends to spontaneous ignition even with a high current supply. The confined space limits the diffusion range of rapidly released pyrolyzed gases reducing the local heat loss due to mixing. In addition, the pressure increases faster in the smaller confinement with the same amount of pyrolyzed gas release, which may promote spontaneous ignition with a higher current supply as well. In 0.166*G* and 0.38*G*, the ignition modes have a similar manner to cases in 0*G* with a high current supply. However, with a lower current supply, the wire-assisted ignition mode for the intermediate sizes of confinement (D20-D80) in partial-*G* and 1*G* implied the piloted ignition of the partially premixed gas mixtures.

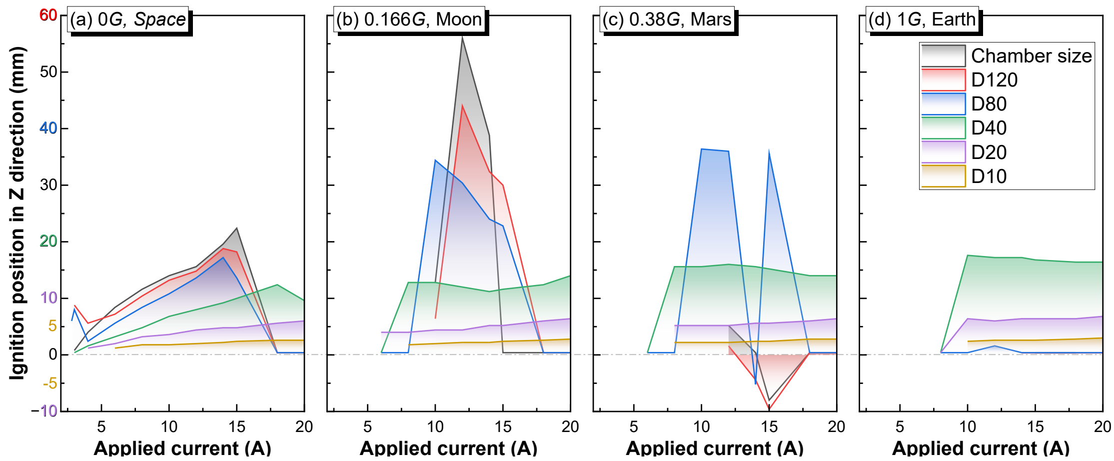

Figure 3. Comparison of Ignition positions in Z-direction as a function of applied current with different sizes of confined space under gravity levels of: (a) 0*G* for space, (b) 0.166*G* for the moon, (c) 0.38*G* for Mars and (d) 1*G* for the earth.

3.3. Ignition limits

The overload ignition limit can be considered from two aspects: Minimum Ignition Energy (MIE) and limiting current to the ignition. The MIEs with different confined space sizes under varied gravities were plotted in Figure 4(a). Overall, the MIEs in 0*G* are lower than the partial-*G* and 1*G*, and they all decrease with the confinement size decrease. For the very small confinement (D10), MIEs at different gravities tend to converge around 1kJ/m. The circle size indicates the current value that gave the MIE, which is not always the same as the limiting current. The limiting currents with different confined space sizes under varied gravities were plotted in Figure 4(b). In 0*G*, the MIE can be found with a current around 5.5-6A which is slightly higher than the limiting currents around 3A. For the partial-G and 1G, the limiting current can be drastically decreased with the confinement size decrease due to the delayed piloted ignition of flammable partially premixed gases. From the perspective of the MIE, smaller confinement diameters (10, 20 mm) pose a higher ignition threat in all gravities. While, from the perspective of the limiting current, the intermediate sizes (40, 80 mm) of confined space present a risk of ignition at a lower current supplied continuously.

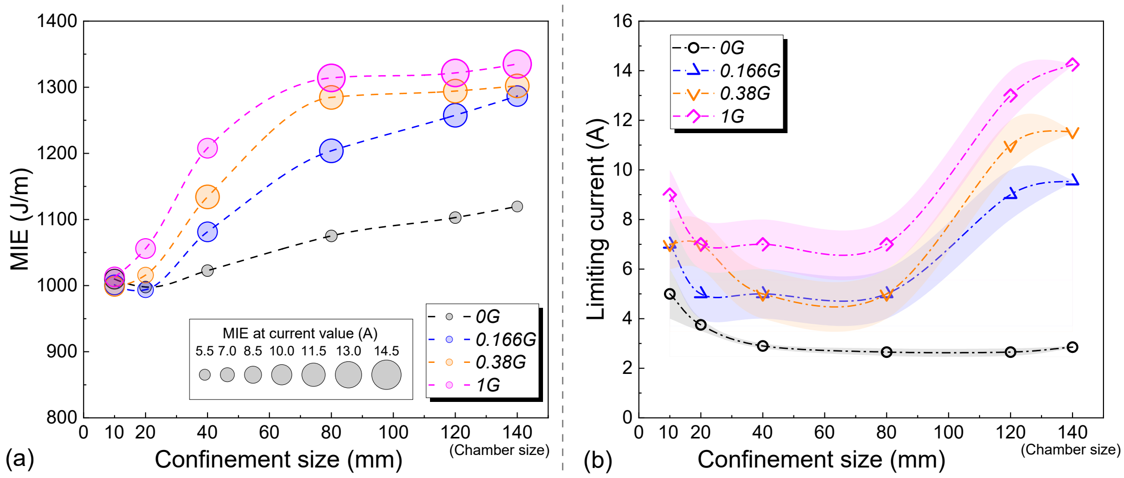

Figure 4. (a) Minimum ignition energy and (b) limiting current for ignition with different confinement sizes under varied gravity levels of space, the moon, Mars, and the earth.

4. Concluding remarks

In this paper, the effects of confined space size on ignition characteristics of overloaded electric wire were investigated numerically. After validation with experimental results under the chamber-sized confinement, the 2-D numerical model was then extended to simulate the overload ignition phenomena under varied confined space sizes and different gravity levels (0*G*, 0.166*G*, 0.38*G*, and 1*G*). The ignition delay time, ignition position, minimum ignition energy, and limiting current were predicted and compared. The smaller confinement sizes lead to a lower MIE at all gravities. While, the intermediate diameters of the confinement (40~80 mm) pose a noticeable risk of ignition with a lower limiting current at all gravity levels.

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