Title

Necessary ignition condition to determine correct extinction limit of spreading flame over electrical wire under opposed air flow in microgravity

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keyword

Limiting Oxygen Concentration(LOC), Microgravity, Polyethylene insulated wire, Ignition, Spreading flame,

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Effect of ignition condition on the extinction limit for opposed flame spread over electrical wires in microgravity

Abstract

Flame spread over wire insulation plays a crucial role in spacecraft fire safety. To quantify the effect of the initial ignition condition on the Limiting Oxygen Concentration (LOC) of spreading flame over wire insulation, opposed flow flame spread experiments with wire insulation were conducted in microgravity (parabolic flights). Both ignition power (32.7 to 71.8 W) and heating time (5-15 s) were varied for an external flow of 100 mm/s. The sample wires were made of Polyethylene-coated Nickel-Chrome (NiCr) and Copper (Cu), respectively, both with inner core diameter of 0.50 mm and insulation thickness of 0.30 mm. A 0.50 mm diameter coiled Kanthal wire wrapped around the sample wire 6 times with 8 mm length was used as the igniter. The experimental results show that the LOC gradually decreases as the ignition power or heating time increases and eventually it reaches a constant value. Also, the effect of ignition condition on LOC was more pronounced for Cu wires than for NiCr wires. The variation range of LOC in the tested ignition condition in microgravity was larger than that of horizontal flame spread in normal gravity. This conclusion can have implication for future experiment in the International Space Station to avoid the wrong LOC value because of the insufficient initial ignition energy and will eventually lead to an improved fire safety in spacecrafts.

Keywords

Limiting Oxygen Concentration (LOC), Microgravity flame spread, Polyethylene insulated wire, Ignition

1. Introduction

A fire accident is one of the most severe events in a spacecraft due to its completely enclosed environment and because there are basically no available evacuation options [1]. Therefore, fire safety is an essential requirement for future manned space missions. To ensure the fire safety, numerous studies have been conducted on solid combustion in microgravity [2–4]. Also, many electrical devices and cables are installed in the spacecraft, and ignition of electrical wire is the most likely cause of fire accidents because of overloading or short circuiting [1]. Materials intended to be used in spacecraft are generally screened by National Aeronautics and Space Administration's (NASA) fire safety standard STD-6001B to reduce the fire risk [5]. In this standard, Test 4 addresses fire safety of electrical wires [5]. This test is used for evaluating electrical wire flammability in an environment similar to that in the spacecraft. In fact, this standard has contributed much to reduce the fire risk in a spacecraft for several decades [6]. However, it is still unclear whether this standard can evaluate the material flammability in microgravity environment properly because this test is conducted on the ground and it does not consider the effect of gravity on the flame behavior. Although natural convection is almost absent in microgravity, low flow velocities still exist due to Heating, Ventilation, and Air Conditioning (HVAC) system operation and the movement caused by astronauts' activities [7]. This leads to the reduction of heat loss from the combustible material to the ambient microgravity environment. Thus, the flammability of the materials is changed between microgravity and normal gravity environments. According to Takahashi et al. [8], the most flammable condition of electrical wires do not exist in normal gravity, but rather in microgravity because of the reduction of buoyancy. Based on this fact, various aspects related to burning of wire insulation in microgravity have been studied, such as the ignition limit [9–11], flame spread rate [12–21], and extinction limit [8, 22, 23]. These studies have been carried out for numerous materials and under various conditions and have provided ample understanding of the physics of flammability characteristics of wires in microgravity. In these studies, the Limiting Oxygen Concentration (LOC) is often used as an index for a fire safety standard on the ground and could be extended to material flammability evaluation in spacecraft. The project called "Flammability Limits at Reduced Gravity Experiment (FLARE)" aims to make a formula to predict the LOC in microgravity as the following sequence [7]. The first step is to get the LOC of spreading flame over the wire insulation under various conditions using parabolic flight experiments. In the second step, the formula predicting the LOC value from the results obtained in parabolic flights is built up and assessed. The final step consists in conducting the experiments to get the LOC in long-term microgravity environment using the International Space Station (ISS) and contrasting the outputs with the results given by the formula. In this sequence, getting correct LOC values from parabolic flights is important to establish the correct formula. In the past experiments, to obtain the LOC values in experiments, the sample wire was first ignited by external heating such as a coil heater. However, there is limited research about the initial ignition condition itself even though it potentially affects the subsequent spreading flame and especially short duration experiment like those conducted in parabolic flights. Huang et al. [24] investigated that the ignition-to-spread transition of externally heated electrical wire by using a coil heater and found that the additional amount of heat is required after flash occurs to sustain a flame in the transition to the steady state, especially for a higher conductance wire. However, the effect of this external heating on LOC has not been reported. Mitsui et al. [25] reported some experimental data on the effect of initial ignition condition on LOC using parabolic flight experiments. Moreover, further experimental data and discussion are needed to understand the role of the initial ignition condition in order to establish the correct LOC value.

In the current study, flame spread tests were conducted using parabolic flight experiments to investigate the effect of initial ignition condition on the extinction limit of spreading flame over wire insulation in terms of oxygen concentration. It is important to understand this effect in order to obtain the correct LOC value and also to design the ignition procedure for the future experiments in the Japanese Experiment Module (JEM, also called "Kibo") on the ISS, which is planned in 2019 within the framework of the FLARE project led by the Japan Aerospace Exploration Agency (JAXA). In addition to its contribution towards improved spacecraft fire safety, this research is providing important data to guide future experiment in the ISS, because it ensures that the correct LOC is established.

2. Experiments

2.1. Experimental apparatus

In the current study, two experimental apparatuses that have similar design concepts were used: 1) the Detection of Ignition and Adaptive Mitigation Onboard for Non-Damaged Spacecrafts (DIAMONDS) rig developed by Sorbonne Université (Paris, France) and the French Space Agency (CNES), and 2) the FIRE WIRE setup developed by Hokkaido University (Sapporo, Japan) and JAXA.

2.1.1 DIAMONDS

Figure 1 (a) shows the experimental setup for the parabolic flight experiments.

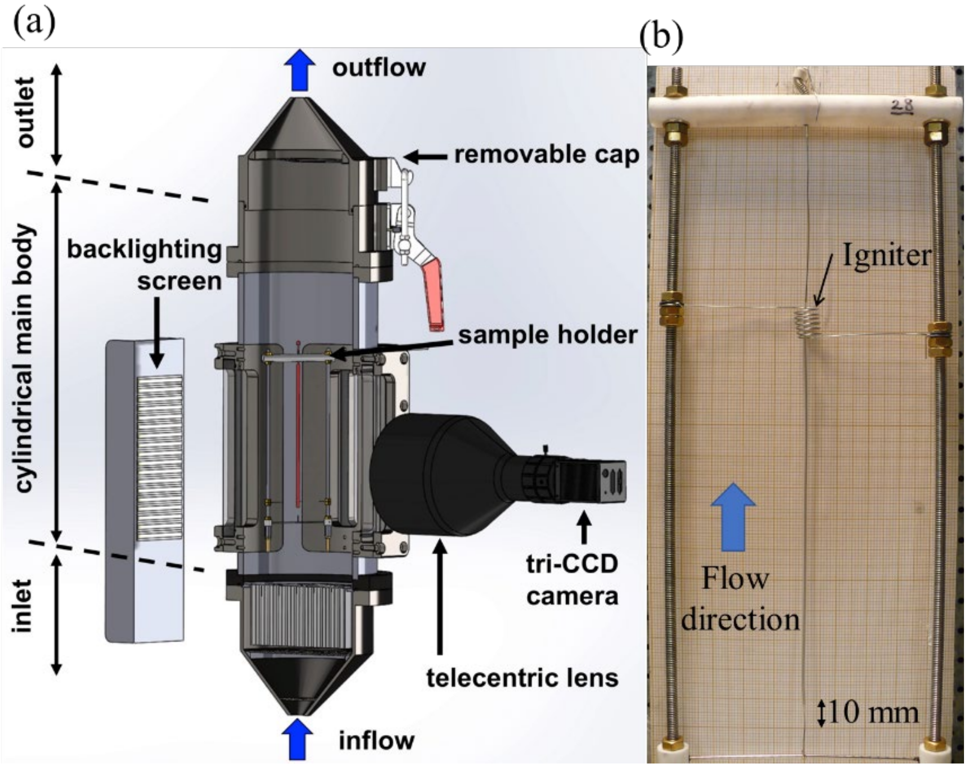

Fig. 1 Experimental set up of apparatus A: (a) schematic cut of the combustion chamber [21]**;**

(b) picture of a sample on a sample holder with a millimeter paper in the background.

The cylindrical part of chamber has an inner diameter of 190 mm. In the combustion chamber, the oxidizer flow entered from the bottom and was vented at the top. The oxidizer flow was produced by mixing air (O_2/N_2 =21/79 % by volume) with pure nitrogen and controlled by mass flow controllers. The airflow was made uniform using a honeycomb, and the uniformity was confirmed through one-component hot wire measurements. A detailed description of the air flow and other experimental design and method and further information are available in the work by Citerne et al. [14]. The backlight was turned on/off at fixed intervals. As a result, the camera not only captured the direct visible flame emission, but also the image with a backlight, which was used to visualize the behavior of molten insulation and the soot distribution in the flame. Further research to measure the soot volume fraction and temperature using this camera and backlight is ongoing [26]. Figure 1 (b) shows a picture of sample holder. Every sample holder had a wire coated with polyethylene over a length of 130 mm. Each sample holder was placed along the center line of the chamber. The microgravity experiment was carried out during parabolic flights (on board of the Novespace A310 airplane), which enabled microgravity conditions for about 22 s with a gravity level lower than 10^{-2} g_0 (g_0 = 9.81 ms^{-2}) for each parabola. In the following, this apparatus is identified as apparatus A.

2.1.2 FIRE WIRE

Figure 2 shows a schematic of the experimental setup for the parabolic flight and ground experiments.

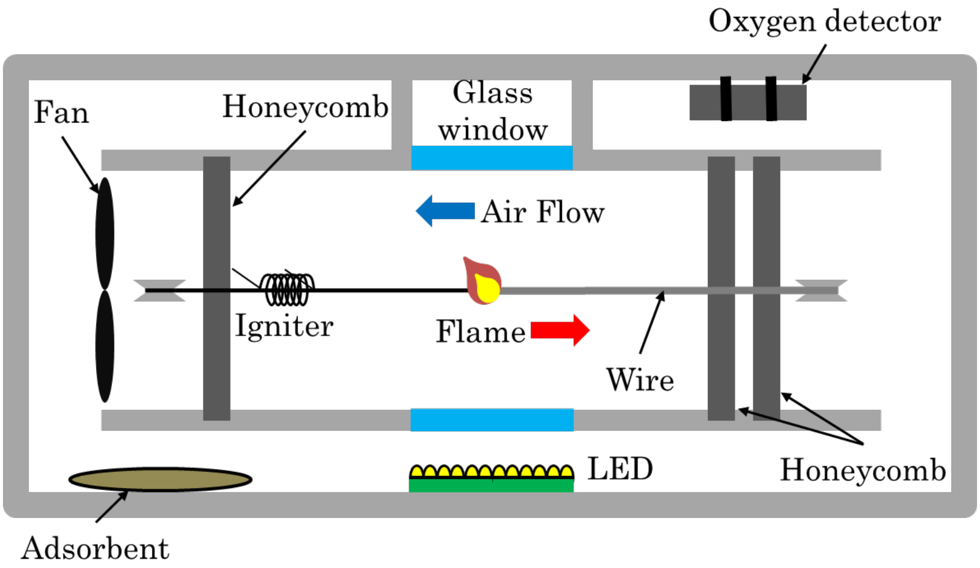

Fig. 2 Schematic of the experimental setup of apparatus B

This is the same apparatus used in previous studies by Fujita and co-workers [8, 18]. The setup is composed of a 500 mm long combustion chamber of square cross-section (260 mm × 260 mm), a digital video camera (Canon IVIS HF-G10), a pressure meter (VALCOM, VPRN-A4- 266 kPa), two current supply sources (Takasago, EX-375L), a programmable controller (MELSEC, FN2N-16MR), a data logger (GRAPHTEC, midi LOGGER dual GL-500), and an oxygen detector (JIKCO, JKO-25LII). Inside the combustion chamber, there is a 380 mm long rectangular flow duct with a rectangular cross section of 140 mm by 150 mm. The duct has an air suction fan (globefan, X1402512M) at the left end, which imitates the ventilation flows in a spacecraft. The opposed flow velocity, ranging from 0 to 250 mm/s, is controlled by the electric voltage powering the fan. The airflow was made uniform using a honeycomb, and the uniformity was confirmed through Laser Doppler Anemometer measurements before the experiments. A sample wire is installed at the center of the flow duct parallel to the external flow. The microgravity environment was attained by parabolic flights operated by DIAMOND AIR SERVICE in Japan, which provide duration of about 20 s with a gravity level lower than 10^{-2} g_0. In the following, this apparatus is identified as apparatus B.

2.2 Ignition procedure

Figure 3 show the igniters used for these experiments in apparatus A (Fig. 3 (a)) and B (Fig. 3 (b)).

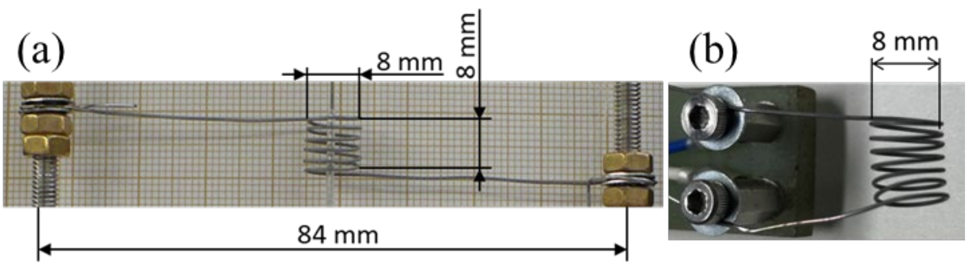

Fig. 3 the shape of igniter: (a) for apparatus A; (b) for apparatus B.

These igniters were made of Kanthal wire (Kanthal AF) with a diameter of 0.5 mm. The diameter of the coil was 8 mm and this coil was made of 6 turns wrapped around the sample wire over a length of 8 mm. Electric current was applied to the coil, which then could ignite the sample wire by external heating (there was no direct contact between the ignitor and the sample wire). As parameters of the series of experiments, both the ignition power at coil of igniter and the igniter heating time were varied, ranging from 34 W to 74.8 W, and from 5 s to 15 s, respectively. To provide the desired power, the electric current was controlled. For instance, a current of 5.4 A was supplied for the igniter (namely identical resistance of ignition coil is 1.18 Ω) to give 34 W at ignition coil.

2.3 Experimental conditions

In both apparatuses, the pressure inside the chamber was set to 1 atmosphere and the flow velocity was fixed at 100 mm/s (which is a typical flow velocity on the ISS) during the experiments. In this research, Nickel-Chrome (NiCr) and Copper (Cu) wire with low density polyethylene (LDPE) were used as sample wires. The specification of the sample wires is listed in Table 1.

Table 1. Specifications of sample wires

Sample No.	Core material	Coating material	Core diameter	Coating Thickness
#1	NiCr	Low density polyethylene	0.5 mm	0.3 mm
#2	Cu			

The physical properties of sample materials are shown in Table 2.

Table 2. Properties of LDPE, NiCr, and Cu

	LDPE	NiCr	Cu
Density [kg/m^3]	920	8670	8880
Specific heat [kJ/kg/K]	2.3	0.444	0.386
Thermal conductivity [W/mK]	0.38	17.4	398
Thermal diffusivity [m^2/s]	0.38	0.0045	0.177
Pyrolysis temperature [K]	673	-	-

3. Results and discussion

3.1 Results of microgravity experiments

In the parabolic flight experiments, when the flame spread could be sustained during the whole microgravity (μg) period of each parabola, it was considered a "Flammable" scenario. When the flame spread could not be sustained during the whole period of μg, it was considered an "Extinction" scenario. As a result, the LOC is assumed to lie between the maximum oxygen concentration that systematically leads to extinction and the minimum oxygen concentration that systematically enables the propagation case. The number of tests that could be performed in microgravity was small due to the limited availability of parabolic flights. However, enough data were obtained to reach conclusions about the trend of LOC as a function of initial ignition condition.

3.1.1 Microgravity results for the NiCr wire

Figure 4 shows a series of pictures for typical flame spread scenarios in microgravity for various ignition powers and constant heating time.

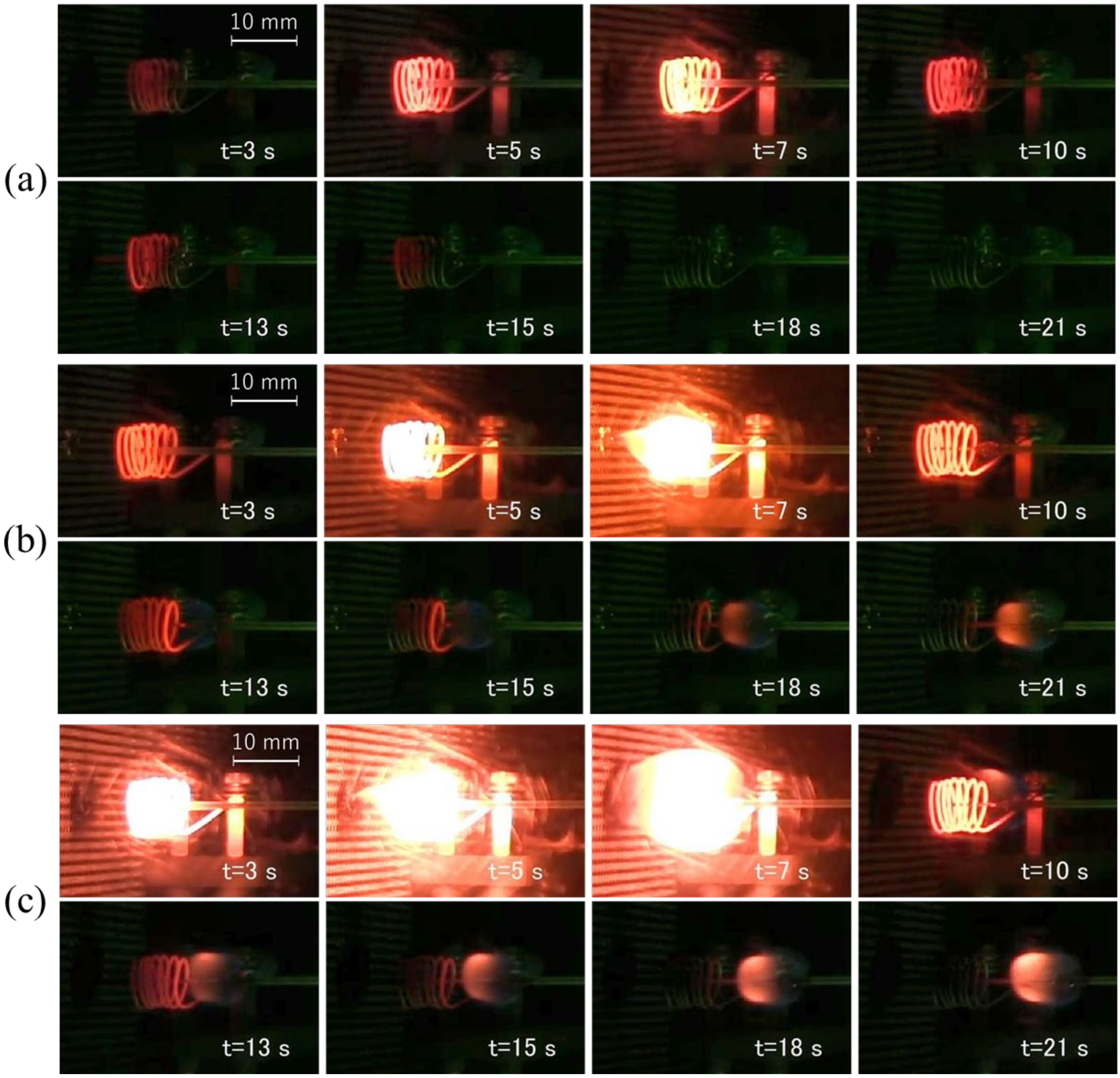

Fig. 4 Frames showing the evolution of the visible flame shape using #1 wire with time after the start of the ignition (O_2 concentration: 16%, flow velocity: 100 mm/s, heating time: 8 s, Microgravity): (a) 34 W (b) 47.6 W (c) 74.8 W

In Fig. 4, the external flow direction is from the right to the left, and the flame propagates from the igniter to right hand side, i.e. it is an opposed flow case. According to these pictures, when the ignition power is higher than 47.6 W, the flame can be sustained until the end of the microgravity period for an oxygen concentration of 16%. However, the flame could not be sustained for an initial ignition power of 34 W for the same oxygen concentration, even though the heating time was constant. Also, as the initial ignition power is increased, the diameter of the initial flame in the igniter is increased.

Figure 5 shows a series of pictures for typical flame spread scenarios in microgravity for various ignition heating times with a constant ignition power.

(a)

(b)

(c)

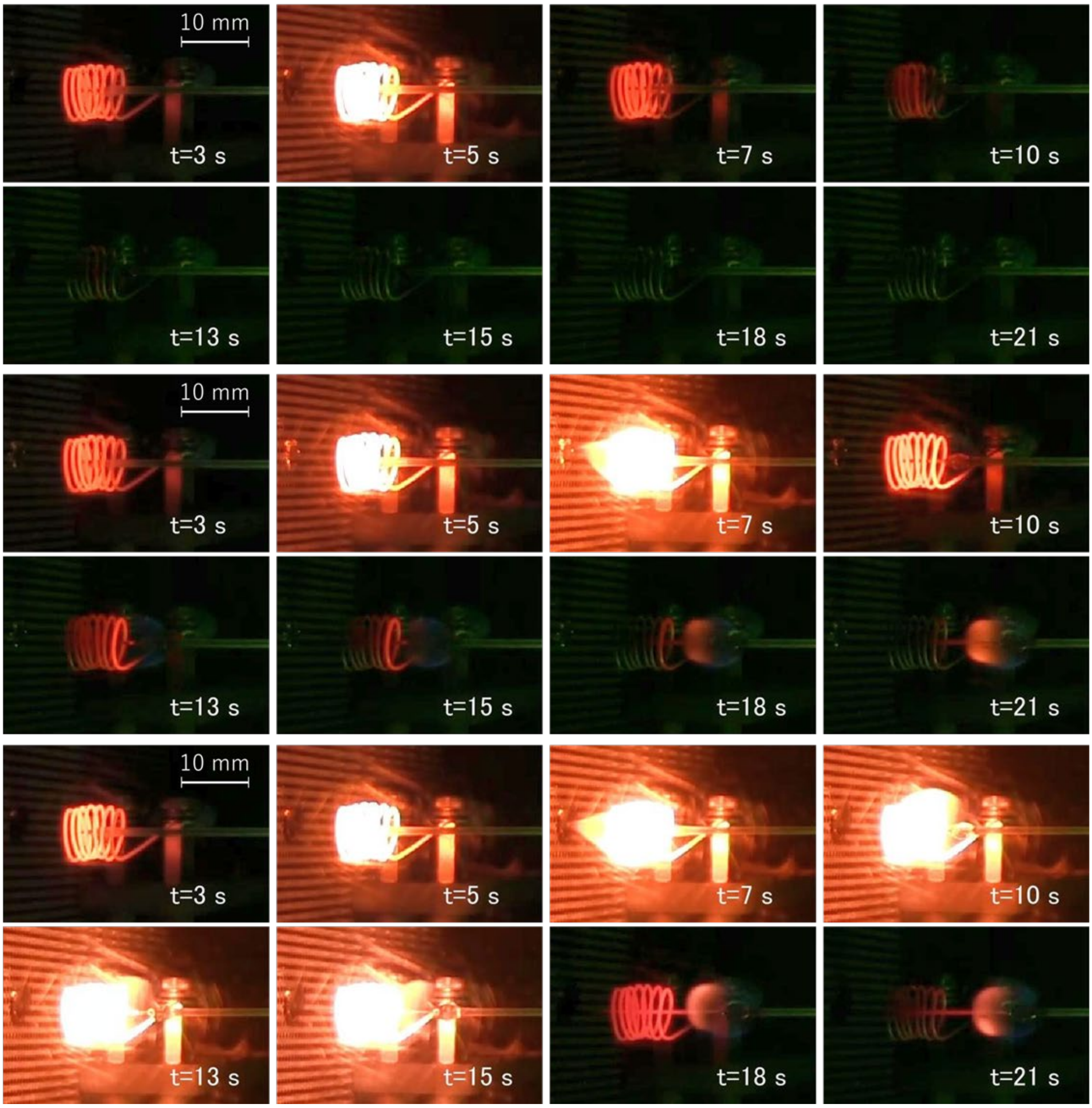

Fig. 5 Frames showing the evolution of the visible flame shape using #1 wire with time after the start of the ignition (flow velocity: 100 mm/s, ignition power: 47.6 W, Microgravity): (a) 5 s, O_2 concentration: 17% (b) 8 s, O_2 concentration: 16% (c) 15 s, O_2 concentration: 16%

The configuration of the flow and flame spread direction are the same as in Fig. 4. According to these pictures, when the heating time is longer than 8 s, the flame can be sustained until the end of the microgravity period for an oxygen concentration of 16%. However, the flame cannot be sustained if the initial ignition time is 5 s for an oxygen concentration of 17% even though the ignition power is constant. Also, Fig. 5 (c) (t = 21 s) shows that the bare core wire glows after the flame spread is over as the heating time increased.

Figure 6 shows the results extracted from these experiments as a function of heating time and ignition power.

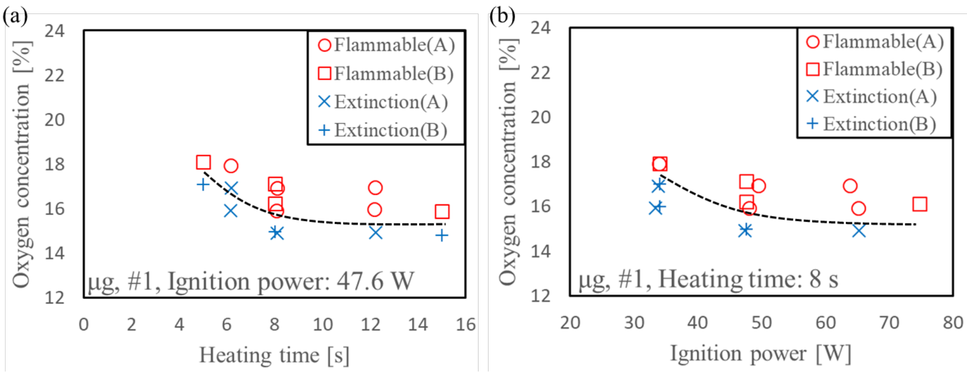

Figure 6. LOC of NiCr wire vs. heating time and constant ignition power: 47.6 W (a) and ignition power and constant heating time: 8 s (b) in μg and external flow velocity: 100mm/s. The data obtained in apparatus A is referred to as (A) and the ones from apparatus B as (B). Each symbol is based on single experiments while the line indicates the expected LOC based on the experimental result.

As seen in Fig. 6, the results from the two apparatuses are very similar, and this provides strong support for the high quality of the data. The dotted lines in Fig. 6 show the expected LOC curve as a function of the initial ignition condition based on the experimental results. In Fig. 6, the LOC gradually decreases as the ignition power or the heating time increases, and eventually it reaches an almost constant value when the heating time is 12 s or longer, or the ignition power is 47.6 W or higher. The variation range of LOC within the ranges of ignition power and heating time investigated is about 2%. Nagachi et al. have investigated the effect of flow velocity and direction on LOC of spreading flame over the wire insulation in microgravity [27]. According to their work, this past LOC of #1 wire in opposed flow was shown to appear around 15-16 % of oxygen concentration and this LOC is consistent with the current LOC results when the ignition power or time was sufficient.

3.1.2 Microgravity results for the Cu wire

Figure 7 shows a series of pictures for typical flame spread scenarios in microgravity for various ignition powers and constant heating time.

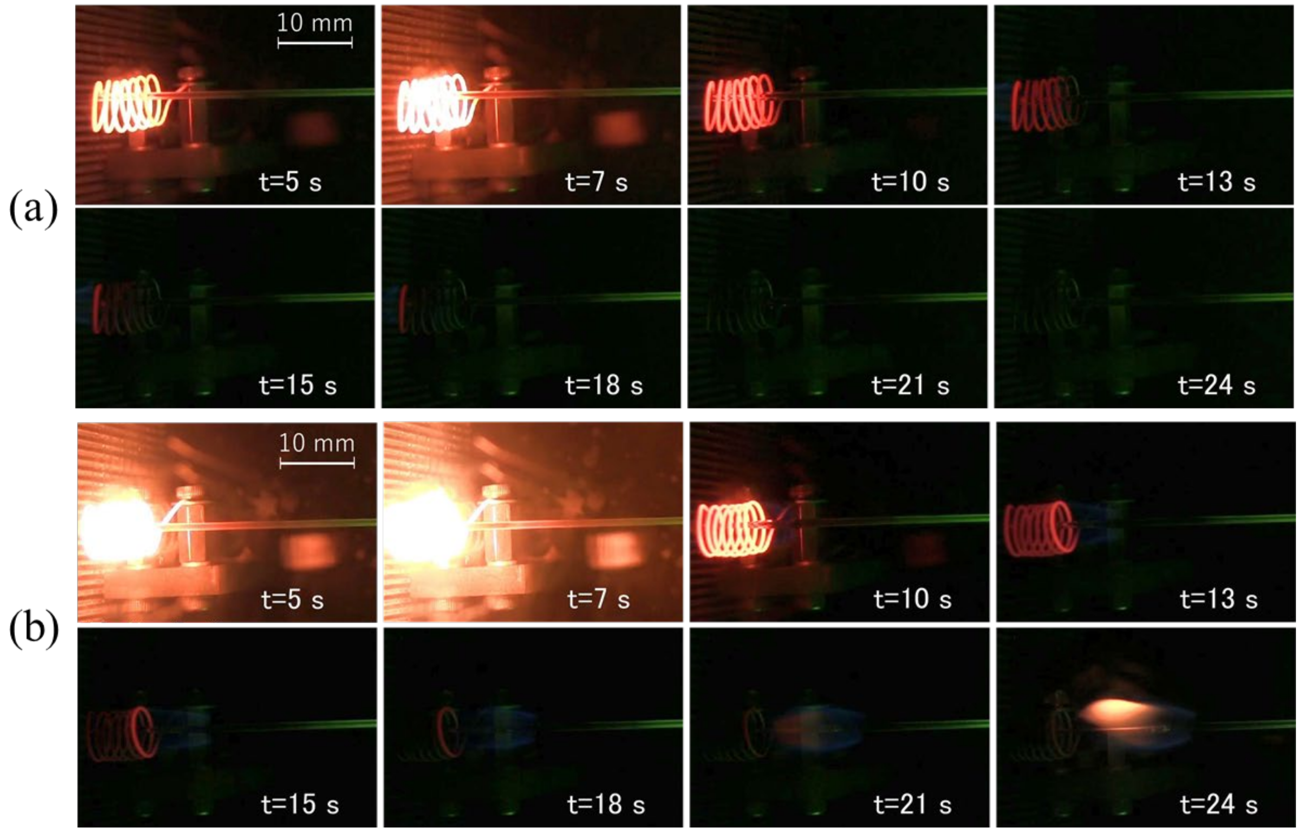

Fig. 7 Frames showing the evolution of the visible flame shape using #2 wire with time after the start of the ignition (O_2 concentration: 17%, flow velocity: 100 mm/s, heating time: 8 s, Microgravity): (a) 47.6 W (b) 74.8 W

The configuration of the flow and flame spread direction are the same as in Fig. 4. According to these pictures, when the ignition power was 74.8 W, the flame spread could be sustained until the end of the microgravity period for an oxygen concentration of 17%. However, when the ignition power was 47.6 W, the flame spread could not be sustained, even though the oxygen concentration and heating time was the same as before.

Figure 8 shows the LOC in microgravity of the Cu wire as a function of ignition power and heating time under constant ignition power.

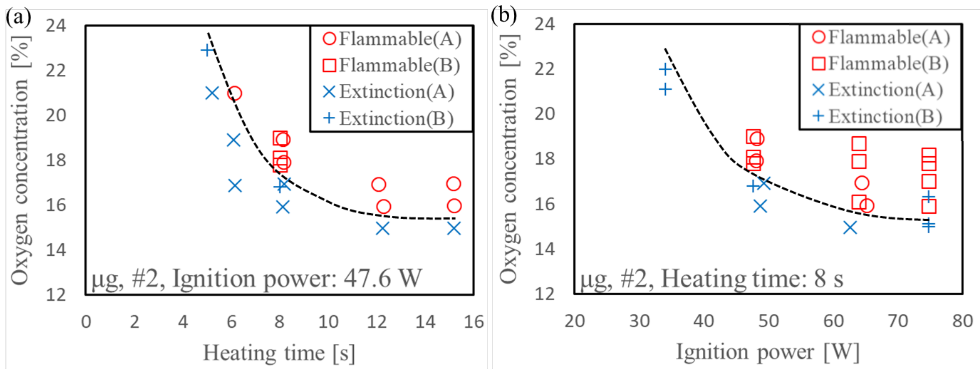

Figure 8. LOC of Cu wire vs. heating time and constant ignition power: 47.6 W (a) and ignition power and constant heating time: 8 s (b) in μg and external flow velocity: 100mm/s. The data obtained in apparatus A is referred to as (A) and the ones from apparatus B as (B). Each symbol is based on single experiments while the

line indicates the expected LOC based on the experimental result.

In contrast to the results for the NiCr wire, ignition could not be achieved for the Cu wire when the ignition time was shorter than 5 s or the ignition power is less than 34 W. In Fig. 8, the LOC for the Cu wire decreases as the heating time or the ignition power is increased and finally tends towards a constant value, just as for the NiCr wire. According to Nagachi et al. [27], the LOC of this wire stands around an oxygen concentration of 15-16% and this past LOC is consistent with the LOC results in the present study, provided that the heating current and the heating time is sufficient.

Figure 9 shows the LOC in microgravity of the NiCr and Cu wire as a function of the total energy. In this study, the total energy was defined as the product of the ignition power and the heating time.

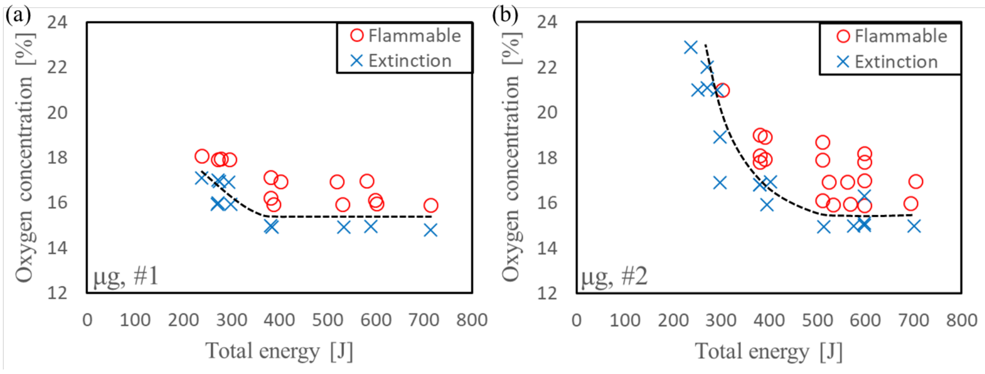

Figure 9. LOC vs. Total energy (Ignition power×heating time) (a) NiCr wire (b) Cu wire in μg and external flow velocity: 100mm/s. Each symbol is based on single experiments while the line indicates the expected LOC based on the experimental result.

For both wires, the LOC decreased initially and eventually reached a steady value as the total energy increased. Also, within the ignition power levels investigated, the variation of the LOC of the Cu wire was more significant than for the NiCr wire. Moreover, the NiCr wire was found to be more flammable than the Cu wire for small total energies. However, the discrepancy in the LOC between both wires collapsed when the total energy increased.

3.2 Results from normal gravity experiments

The ground experiments were conducted using apparatus B in order to compare with the parabolic flight experiments. In this study, data from horizontal configuration in normal gravity was chosen as the comparable data with microgravity because the horizontal configuration is the case where the phenomenon is most affected by the gravitational field and could give clearer difference attributed to the presence of gravity on the flame spreading phenomenon. Another study has already been conducted on the effect of inclination on spreading flame over wire insulation and pointed out that phenomenon of flame spread changed as wire inclination changed [28]. Figure 10 shows a series of pictures of typical flame spread scenarios in normal gravity (1g) using NiCr wire. Part (a) of the figure shows a case of flame spread (referred to as “Flammable”), while part (b) shows a case of no flame spread (referred to as “Extinction”).

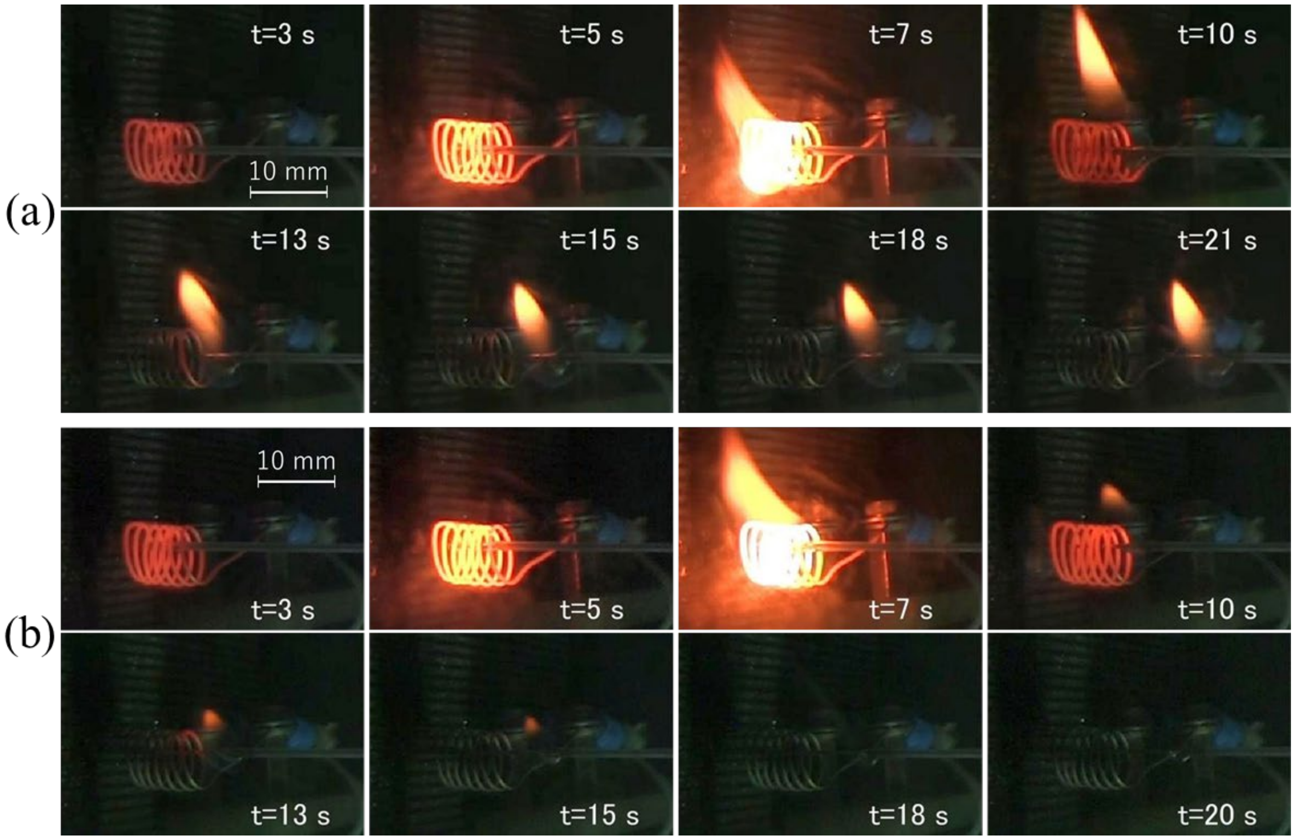

Figure 10 Frames showing the evolution of the visible flame shape using #1 wire with time after the start of the ignition using #1 wire (100 mm/s, ignition power: 47.6 W, heating time: = 8 s, Normal gravity): (a) O_2 concentration: 17.0% (b) O_2 concentration 16.7%.

In the ground test, the flame looks vertically stretched because of the natural convection during the ignition sequence, while the flame looks like an envelope along the wire in microgravity. Figures 11 and 12, respectively, show the LOC of the NiCr wire and the Cu wire in normal gravity as a function of the ignition power for a constant heating time and as a function of heating time under constant ignition power.

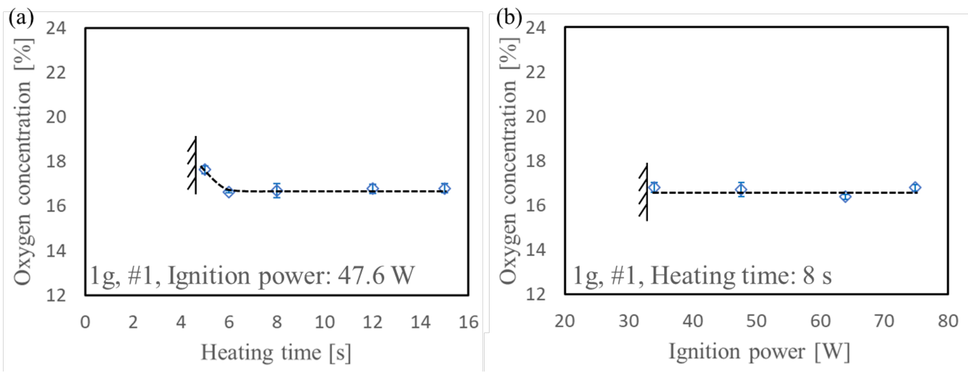

Figure 11. LOC of the NiCr wire vs. heating time and constant ignition power: 47.6 W (a) and ignition power and constant heating time: 8 s (b) in 1g and external flow velocity: 100 mm/s.

All symbols represent average values of 3-6 experiments. The error bars indicate the standard deviation of the experiment results and the line indicates the expected LOC from the experimental results.

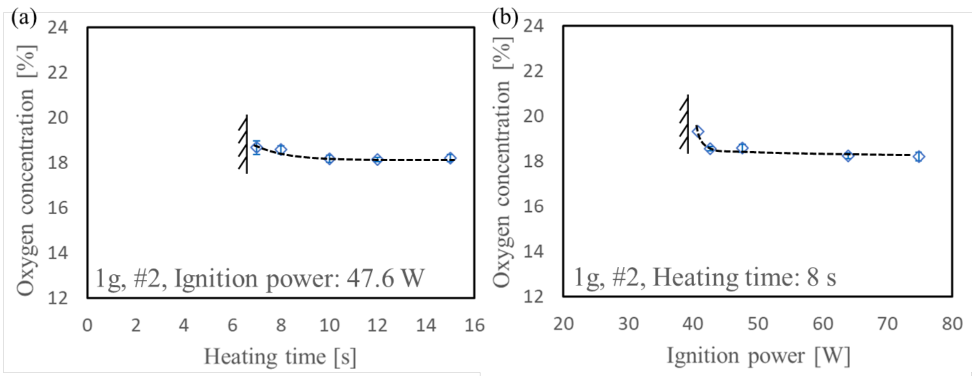

Figure 12. LOC of the Cu wire vs. heating time and constant ignition power: 47.6 W (a) and ignition power and constant heating time: 8 s (b) in 1g and external flow velocity: 100 mm/s.
All symbols represent average values of 3-6 experiments. The error bars indicate the standard deviation of the experiment results and the line indicates the expected LOC from the experimental results.

In normal gravity, the LOC was defined as the minimum oxygen concentration allowing the flame to be sustained and propagate over a distance longer than 100 mm along the wire, whereas the distance covered by the flame in microgravity is about 20-40 mm depending on the oxygen concentration and the core materials. Also, all plots were the average of at least 3 repeated tests and error bars indicate the standard deviation of the experiment results. For the case of 5 s long heating time in Fig. 11 (a), 3 out of the 6 experiments could not ignite because this condition is close to ignition limit, and the plot in the figure is based on the 3 experiments that led to ignition. Also, ignition did not occur when the heating time was shorter than 5 s or the current was lower than 34 W (minimum current to achieve ignition in Fig. 11 (b)), even when the oxygen concentration was increased to 21%. For the case of 40.7 W ignition power in Fig. 12 (b), 2 out of 3 experiments did not lead to ignition because this condition is close to ignition limit, and the plot was based on the remaining single experiment. Also, if the heating time is shorter than 7 s in Fig. 12 (a) or the current is lower than 40.7 W in Fig. 12 (b) the ignition of #2 wire was no longer achieved even though the oxygen concentration is increased up to 21%. In Fig. 11, the LOC was almost constant around 16.7% oxygen concentration and the LOC was almost constant around 18% oxygen concentration, as seen in Fig. 12. The difference of LOC is attributed to the difference of the thermal conductivity of core wires. In case of Cu wire, because of high thermal conductivity, the energy easily passes through the core and the unburned wire is preheated over a longer characteristic length by the core wire than in the case of NiCr wire. However, the wire was cooled down by natural convection and more energy was lost in the Cu wire than in the NiCr wire. Consequently, the LOC of the Cu wire is larger than that of NiCr wire. Also, there is a less influence of the initial ignition condition in normal gravity as compared with that in microgravity. In other words, once ignition firmly occurred, extinction limit in terms of oxygen concentration is properly given under normal gravity.

4. Discussion

4.1 The effect of initial ignition condition and core material

According to the last section, LOC decreased and became almost constant as the initial ignition power or the time increased in microgravity. When the initial ignition condition, i.e. current and time, is not high enough, the igniter cannot preheat the wire to attain the temperature distribution in the wire for the steady flame spread. However, when the initial ignition condition is high enough, igniter can preheat the wire to attain the temperature distribution in the wire for the steady flame spread. As seen in Fig. 9, the Cu wire was more sensitive to the initial ignition condition than the NiCr wire. Due to difference in thermal conductivity of core wire, the temperature distribution for steady spreading are different. Finally, the temperature distribution under a given ignition condition affects the LOC, that is, when preheating is less than the steady temperature distribution, higher O_2 concentration required to made up the lack of energy for steady propagation and higher LOC is appeared. To discuss the preheating effect, the development of the temperature distribution was considered based on Huang et al. [24]. In their model, the wire is long enough and the partial length (L_h), exposed to an external heat flux $\dot{q}''_{in}$ from an igniter. Because of the symmetry of the wire and heating zone, only half of the wire is considered, with an adiabatic boundary condition at the heated center. Also, the wire is assumed as thermally thin. From these assumptions, the temperature distribution can be obtained from the following equations.

$$\left(\sum \rho cA\right)\frac{\partial T}{\partial t} = A_c\lambda_c\frac{\partial^2 T}{\partial x^2} + P_0\left(\dot{q}''_{in} - \sigma(T^4 - T_\infty^4)\right) \qquad \cdots\left(0 < x \le \frac{L_h}{2}\right)$$

$$\left(\sum \rho cA\right)\frac{\partial T}{\partial t} = A_c\lambda_c\frac{\partial^2 T}{\partial x^2} - P_0\left(h(T - T_\infty) + \sigma(T^4 - T_\infty^4)\right) \qquad \cdots\left(x > \frac{L_h}{2}\right) \tag{1}$$

$$\text{where } T_{L_h/2^-} = T_{L_h/2^+}, \left(\frac{\partial T}{\partial x}\right)_{L_h/2^-} = \left(\frac{\partial T}{\partial x}\right)_{L_h/2^+}$$

$$\left(\frac{\partial T}{\partial x}\right)_0 = 0, and\ T_\infty = T_a\ (t > 0)$$

and $\sum \rho cA = (\rho cA)_c + (\rho cA)_p$. Here, ρ, c, A, T, λ, P_0, σ, and h are the density [kg/m^3], heat capacity [kJ/kgK], cross-section area [m^2], temperature [K], thermal conductivity [W/mK], Stefan-Boltzmann constant [W/m^2K^4], and the heat transfer coefficient [W/Km^2], respectively. The subscript c indicates the core, p the insulation, and a the ambient surrounding. The value of h corresponds to the condition where air flow is parallel to the cylinder surface according to Kase et al. [29]. Using Eq. (1), a one-dimensional temperature distribution along the wire is obtained under the arbitrary various initial $\dot{q}''_{in}$. To assess the development of preheating along the wire, preheating length by the igniter (L_{ig}) is introduced. L_{ig} is defined as the length from the center of heating region to the temperature point to be θ=1/e, where

$$\theta = \frac{T - T_\infty}{T_p - T_\infty} \tag{2}$$

Here, T_p is the pyrolysis temperature of the wire insulation.

Also, the preheat length of steady flame (L_s) is assume as following equation.

$$L_s \sim \frac{\overline{\alpha}}{V_f} \tag{3}$$

Here, V_f is the flame spread rate along the wire based on the experimental results and $\overline{\alpha}$ is the average thermal diffusivity of the wire in the axial direction, as derived from the following equation.

$$\overline{\alpha} = \frac{A_c\alpha_c + A_p\alpha_p}{A_c + A_p} \tag{4}$$

where, α is the thermal diffusivity [m^2/s].

If L_{ig} could be larger than L_s, we can assume the preheating by a given ignition condition exceeds that of steady flame.

Figure 13 shows the calculated result of L_{ig} and L_s using the NiCr and the Cu wires. To calculate the L_{ig}, $\dot{q}''_{in}$ of 150, 200, and 250 kW/m^2 are chosen. This is because the calculated ignition delay time using those values assumes that the ignition temperature as the pyrolysis temperature of the insulation material, T_p, is close to the experimental one. (200 kW/m^2 in the simulation is equivalent to 63.4 W in the experiment)

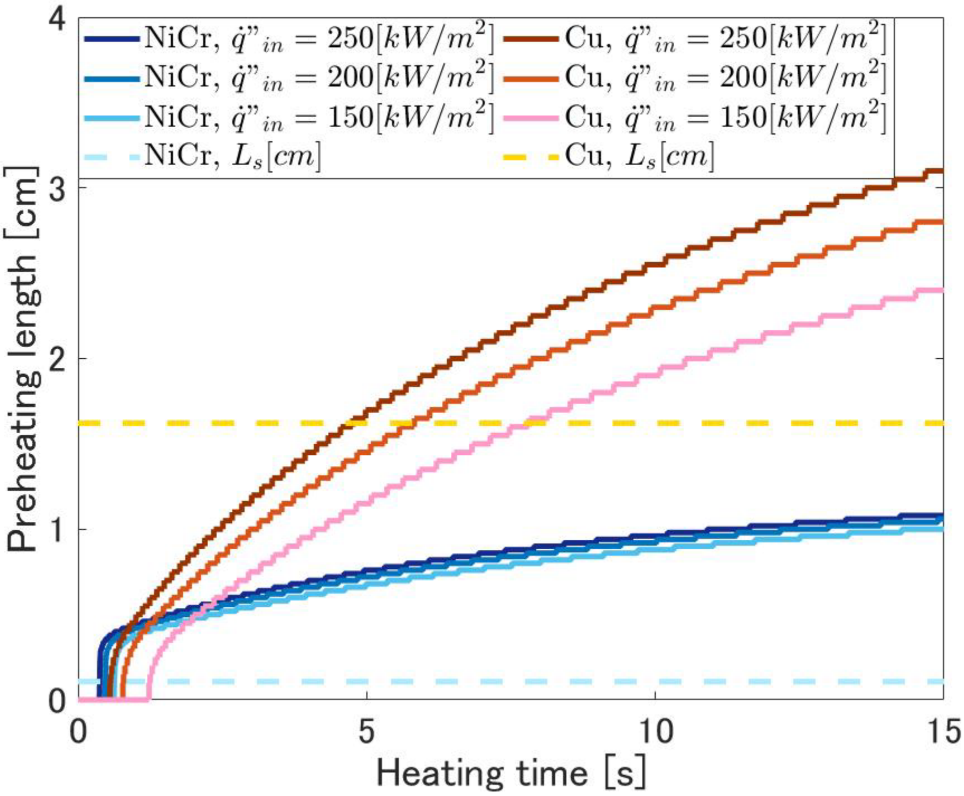

Figure 13. Calculated preheating length by the igniter for NiCr and Cu wires

The solid lines in Fig. 13 show the results for L_{ig}, while the dashed lines the results for L_s. According to these results, L_{ig} increases as $\dot{q}''_{in}$ or heating time increases. Furthermore, the Cu wire is more sensitive to the ignition condition than the NiCr wire, which could be an explanation why the LOC of the #2 wire from experiments is more sensitive to the initial ignition condition than that of #1 wire. Also, in terms of #2 wire, L_{ig} cannot reach the value L_s when the initial ignition power or heating time was small. In this case, the flame cannot achieve a steady flame spreading and higher oxygen concentration than the correct extinction limit is required during the transition period from ignition to the steady spreading. However, if the heat input or heating time is large enough, L_{ig} becomes longer than L_s. In this case, the temperature distribution for steady flame spread is achieved only by the preheating from the igniter and, therefore, the correct LOC value, extinction limit of steady spreading flame, is expected by the experimental determination of LOC. On the other hand, L_{ig} is always larger than L_s when heating time is 5 s and all $\dot{q}''_{in}$ condition for the NiCr wire. This means that the temperature distribution for steady flame spread is easily achieved only by the preheating from the igniter, and the determined LOC value becomes the actual extinction limit for steady spreading flame. However, in the actual experiments, igniter needs time to reach the maximum temperature and time to heat the wire up to the pyrolysis temperature, which causes the lack of heat input when heating time or heating current is very close to the ignition limit where LOC could be larger than the value for steady spreading flame.

4.2 The effect of gravity

According to the experiment, the variation range of limiting oxygen concentration in the tested ignition power in microgravity is larger than that of normal gravity case. It means that flame can be sustained in increased oxygen concentration in microgravity even though initial ignition power or time is not high enough. This is explained by the difference of flame shape. In microgravity, the whole flame covers the pyrolysis and burned regions of wire as an envelope flame along the wire (see Fig. 4 (c)). Then the heat feedback from the flame to the wire is enhanced in microgravity in comparison with normal gravity. Such an enhanced heat feedback assists the flame spreading during the period of transition to the steady spreading even though the initial ignition condition is close from the extinction condition. Especially, the enhanced heat feedback is more effective when the thermal conductivity of the wire core is higher such as the Cu wire, because the heat supplied to the burned region is effectively transferred to the unburned region through the core material.

The increased preheat length in gas phase is another important mechanism to increase heat feedback in microgravity in comparison with normal gravity. Disappearance of natural convection weakens the local approaching velocity to the spreading flame and characteristic length of preheat zone, L_{gx} (=α_g/V_g, where α_g is gas phase thermal diffusivity, V_g is the approaching air flow velocity), increases. The increased gas phase preheat length increases the heat supply to the unburned region of the wire because of surface curvature effect, so called logarithmic effect [13, 30]. Such a mechanism enhances the capability of microgravity flame to assist the combustion in the transient period from ignition to the steady spreading when ignition condition is not strong enough for steady combustion. On the other hand, in normal gravity, the flame shows an upward shape as seen in Fig. 10 (a) and, for sure, the preheat length becomes very short due to the increased approaching air flow velocity caused by the buoyancy induced flow. Therefore, the capability of the flame in normal gravity as an assistance of combustion in the transition period is very weak and the flame cannot be sustained even the oxygen concentration is increased. Then sustaining combustion or not essentially depends on whether the initial ignition condition can lead to the preheating required for steady spreading. The weak dependency of extinction limit on heating time and current in normal gravity as seen in Figs. 11 and 12 could be explained by such an understanding.

One of the concerns in the ISS experiments on orbit is to give incorrect LOC value. As discussed above, the flame could be sustained to reach steady rate spread with increased oxygen concentration even though the initial ignition condition is not strong enough. This situation leads to misreading of LOC in microgravity experiments and the resulting LOC could be larger than the correct value for extinction of steady spreading flame. To avoid such a situation, it is important to give enough preheating condition identical (or higher) to that required by the steady spreading flame.

5. Conclusions

This present study is the first study aimed at understanding the effect of initial ignition conditions on the LOC value for a flame spreading over electrical wires in microgravity was investigated experimentally. Then the necessary ignition condition to determine correct extinction limit in microgravity was discussed. The experimental results showed that the LOC was strongly affected by the ignition condition in microgravity. It gradually decreased as the ignition power or heating time increased and eventually reached an almost constant value. If the initial ignition condition is not strong enough, the preheat length given by the igniter is shorter than that from steady spreading flame, which could be an explanation of an increase in LOC with decreasing ignition power and time. Also, higher thermal conductivity wires such as the Cu wire was affected more strongly by the ignition condition than the lower conductivity wire (NiCr). This result can be explained by the fact that the temperature distribution given by the igniter is more sensitive to the ignition condition in high thermal conductivity core materials than in low thermal conductivity ones. Moreover, the variation range of LOC in the tested ignition power in microgravity is larger than that of normal gravity case. The difference was explained by the difference of capability of flames in normal and microgravity as an assistance for transient flame from ignition to the steady spreading. The shape of envelope along the wire and the increased gas phase preheat length in microgravity are proposed as mechanisms contributing to the higher capability to assist the transient flame towards the steady spreading.

These results suggest that importance of consideration of initial ignition energy because it effect on the LOC value, especially in microgravity. To obtain the correct LOC value in the future space experiment on the ISS, enough heating current and time by the igniter are necessary to ensure that the preheating of the wire is identical to the temperature distribution corresponding to the steady spreading flame. Otherwise, the LOC value determined in microgravity could be higher than the correct value because the capability of microgravity flame to assist the spread in the transient period is relatively high, while such a concern is limited on the ground.

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