



HOKKAIDO UNIVERSITY

Title	Application of ISO 4589-4 to determine limiting oxygen concentrations for opposed-flow flame spread over thin electric wires and their comparison with microgravity data
Author(s)	Konno, Yusuke; Bin Zainal, Muhammad Zhaffri; Hashimoto, Nozomu et al.
Citation	Fire safety journal, 141, 103989 https://doi.org/10.1016/j.firesaf.2023.103989
Issue Date	2023-12
Doc URL	https://hdl.handle.net/2115/95976
Rights	© [2023]. This manuscript version is made available under the CC-BY-NC-ND 4.0 license http://creativecommons.org/licenses/by-nc-nd/4.0/
Rights(URL)	https://creativecommons.org/licenses/by-nc-nd/4.0/
Type	journal article
File Information	FSJ-H0I_test-manuscript-R2-v1-wo-marker.pdf



Application of ISO 4589-4 to determine limiting oxygen concentrations for opposed-flow flame spread over thin electric wires and their comparison with microgravity data

Yusuke Konno^{a*}, Muhammad Zhaffri Bin Zainal^a, Nozomu Hashimoto^a, Osamu Fujita^{a*}

^a Division of Mechanical and Space Engineering, Hokkaido University,

Kitaku, Kita 13, Nishi 8, Sapporo, Hokkaido 060-8628, Japan

* Corresponding authors

E-mail address: y-konno@eng.hokudai.ac.jp (Yusuke Konno); ofujita@eng.hokudai.ac.jp (Osamu Fujita)

Tel: +81-11-706-6388 (Yusuke Konno); +81-11-706-6385 (Osamu Fujita)

Highlights

- The validity of applying HOI test specified in ISO 4589-4 to thin wire specimens was examined.
- LDPE and ETFE insulated Cu and NiCr wire samples were tested.
- The relationship between the LOC acquired on the ground and in microgravity is well connected.
- All wire samples tested in this study are more flammable under microgravity than normal gravity.
- The modified HOI test method properly worked to determine LOCs of wire samples.

Abstract

High gas flow velocity oxygen index test, ISO 4589-4, for measuring the limiting oxygen concentration of flat specimens in opposed flow configuration is applied to electric wires and its applicability is examined. Furthermore, data obtained on the ground are compared with those obtained in microgravity to verify the validity of estimating the minimum limiting oxygen concentration from the high gas flow velocity oxygen index test. The wire samples used in this study consist of LDPE and ETFE insulation over metallic cores. The gas flow velocity is varied from 4 to 100 cm/s to obtain the flammability data in wide range of flow velocity. Limiting oxygen concentrations of wire samples are accurately determined by following ISO 4589-4. All samples tested in this study are more flammable under microgravity than normal gravity. It is also confirmed that the relationship between the limiting oxygen concentration acquired on the ground and in microgravity is well connected.

Keywords: Spacecraft fire safety; Electric wire; Limiting oxygen concentration; Opposed flame spread; Extinction, Blow-off

Nomenclature

Abbreviations

ETFE	Ethylene-Tetrafluoroethylene
HOI	High Gas Velocity Oxygen Index
LDPE	Low-Density Polyethylene
LOC	Limiting Oxygen Concentration
LOI	Limiting Oxygen Index
MLOC	Minimum Limiting Oxygen Concentration
OI	Oxygen Index

1. Introduction

To ensure the fire safety of spacecraft, it is important to correctly evaluate the flame retardant properties of materials used in spacecraft, considering the atmospheric conditions expected in space missions. The National Aeronautics and Space Administration (NASA) has its own fire safety standard (NASA-STD-6001B [1]), which determines the suitability of materials for use in spacecraft from various perspectives, including flammability, odor, and off-gas tests. Although NASA-STD-6001B has a long history of ensuring fire safety for manned space missions, and is reliable and track record, several issues have been raised by scientists and engineers in recent years [2,3]. One of these is that the effect of gravity on the flammability of materials is not considered with respect to fire safety standards. It is well known that gravity plays an important role in combustion phenomena that produce large density changes in the gas phase. Therefore, to ensure the fire safety of spacecraft, the effect of gravity on the flammability of materials should be considered on a scientific basis.

The flame spread tests are often applied to evaluate the flammability of materials. In fact, the NASA-STD-6001B (Test 1 and Test 4) [1], the limiting oxygen index (LOI) test [4], and UL94 for plastic materials [5] also evaluate the flammability of materials based on the results of the flame spread tests. This is because the actual fire growth is controlled by the flame spread phenomena after the material ignites. Therefore, determining the critical conditions under which a material turns to self-sustained combustion after forced ignition is very meaningful in evaluating the flammability of materials. Against this background, many researchers have studied the effect of gravity on the flame spread over solid materials and limit conditions for flame spread using various methods [6,7].

Olson et al. [8,9] have carried out microgravity experiments in the NASA Lewis Research Center's (now known as Glenn Research Center) 2.2 second Drop Tower and 5.18 second Zero Gravity Facility to observe opposed flame spreading over 76 μm thick thin cellulosic paper. They have clarified that the relationship between the oxygen concentration at which flame spread is extinguished (called as Limiting Oxygen Concentration, LOC [2]) and the opposed flow velocity shows a U-shaped curve. This means that the

flammability of the material is suppressed under both low and high flow velocity conditions, and that there exists a flow velocity condition at which self-sustained combustion of the material is maintained at the lowest oxygen concentration (called as Minimum Limiting Oxygen Concentration, MLOC [2]). The presence of U-shaped trend of LOC with respect to the gas flow velocity is explained by change in residence time of combustion gas [10,11]. Under low flow velocity conditions (long residence time), quenching extinction branch appears in which heat losses are dominant, while under high flow velocity conditions (short residence time), blow-off (stretch extinction) branch appears in which reactant leakage due to finite rate chemistry is dominant.

If the MLOC of the material exists at a gas velocity less than buoyant flow induced by gravity, the flame retardancy of the material may deteriorate under reduced gravity conditions. In this case, some additional considerations need to be made for the current fire safety standards evaluated under ground conditions. To address the problems with current spacecraft fire safety standards, the Japan Aerospace Exploration Agency (JAXA) is promoting the Flammability Limits at Reduced-g Experiment (FLARE) project [2,12–14]. The main objective of the FLARE project is to establish a method for estimating MLOC of the various materials and to propose it as a new option for fire safety standard in spacecraft environments.

Takahashi et al. [15–19] have successfully developed a semi-empirical model to estimate LOC as a function of the opposed flow velocity for thermally thin sheet specimens. Moreover, their studies revealed that various materials have MLOC under low flow velocity conditions in microgravity where the buoyancy-induced flow disappears. An overview of the MLOC prediction method developed by Takahashi et al. [17–19] is shown in Figure 1, along with a conceptual diagram of the flammability diagram for solid materials. As mentioned earlier, the flammability map consists of a quenching extinction branch for low flow velocity conditions and blow-off extinction branch for high flow velocity conditions and shows a U-shaped trend. MLOC is estimated using a mathematical model that describes the extinction limit of an opposed-flow flame spread over a thermally thin solid material, but they [17–19] proposed to utilize experimental data available on the ground to improve the quantitative prediction accuracy of MLOC. In fact, they [17–19] successfully predicted MLOCs for a variety of

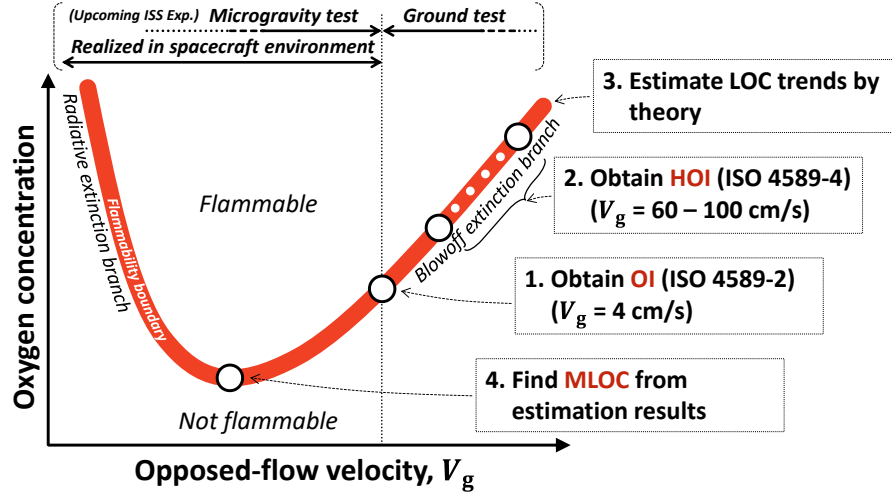


Figure 1: Conceptual diagram of flammability map for solid fuel and overview of MLOC prediction method proposed by Takahashi et al. [17–19].

materials by optimizing model parameters for which reference values are difficult to obtain, such as activation energy, pre-factor, and emissivity of solid materials, and by extrapolating ground data. For parameter tuning, it is recommended to use the Oxygen Index (OI) obtained under the low flow velocity condition (4 cm/s) which is standardized in ISO 4589-2 [4] and LOC obtained under the high flow velocity conditions (60 – 100 cm/s) where the flow field is controlled by forced convection rather than natural convection. The method for obtaining LOC under high flow velocity conditions is newly standardized as ISO 4589-4 [20] (called as a high gas velocity oxygen index (HOI) test). This may raise the question of why data at high flow velocity conditions are needed for MLOC predictions. The reasons are that the experimenter can control the effective flow velocity at flame extinction by providing extremely larger forced convection than the natural convection, and that extrapolation of LOC obtained under different flow velocity conditions improve the prediction accuracy of MLOC. Furthermore, by observing the trend of LOC over a wide range of flow velocities, it is possible to obtain a rough indication of whether LOC decreases or increases in microgravity conditions. It should be noted that, as a matter of course, natural convection induced by the flame dominates the flow field when the forced convection is small, it is recommended to use the HOI obtained at the larger flow velocity condition (60 – 100 cm/s) when predicting the MLOC.

At this stage, however, ISO 4589-4 has only been developed for thermally thin sheet specimens, and it is not clear whether the HOI test can be applied to a variety of materials, such as thermally thick materials and composite materials. As a next step we are currently working to develop an MLOC prediction method for electric wires which are identified as the most likely cause of fire in spacecraft. However, unlike the flat sheet specimens, there is no standard method for obtaining OI and HOI for wire specimens. Therefore, the present work attempted to examine the validity of applying the OI and HOI tests specified in ISO 4589-2 [4] and ISO 4589-4 [20] to thin electric wires. Furthermore, microgravity experiments were conducted using parabolic flight of airplane to obtain the relationship between LOC and opposed flow velocity over a wide range of flow velocities including the condition of MLOC. Experimental data from previous studies by Takahashi et al. [21] and Mizutani et al. [22] were also used to create flammability maps for wire samples. Then, discussion is made on whether the modified HOI test works to predict the MLOC of wire samples or not. In this study, copper (Cu) and nickel-chrome (NiCr) wire sample insulated with low density polyethylene (LDPE) and ethylene tetrafluoroethylene (ETFE) were used as experimental sample. ETFE is known as a flame-resistant polymer and has a high LOI value of 30% [23] while 18% for LDPE [24]. In this study, the wire samples with lower and higher OI than the oxygen concentration in air are purposely used to verify the validity of the HOI test method.

2. Experimental setup

2.1. Normal gravity experiments

In the ground test, the flame spread over the wire sample was observed with the HOI test apparatus (ISO 4589-4 [20]) developed by the FLARE project [2,12–14] for flat sheet sample. The ignition procedure and the determination method of the LOC are also in accordance with ISO 4589-2 [4] and ISO 4589-4 [20]. However, a new sample holder was developed in the present work because the target specimens were not flat sheet samples but electric wires.

Figure 2 shows the test apparatus used in this study which follows ISO 4589-4 [19]. It consists of a gas supply system and a test column. Mass flow controllers are installed in the gas supply system to adjust volume

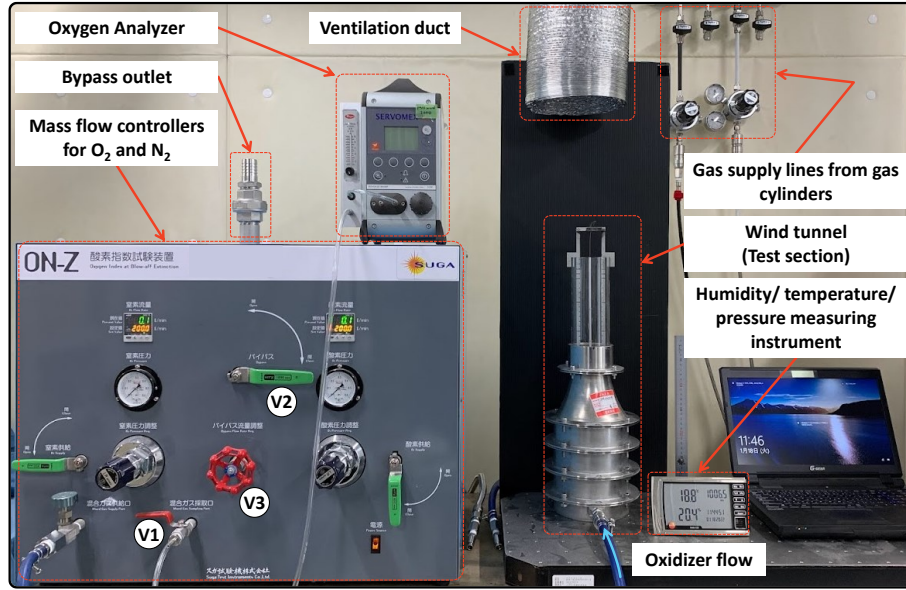


Figure 2: HOI test apparatus consisting of a gas supply system and a test column (wind tunnel). Details can be found in the reference [20].

flow rates of oxygen and nitrogen supplied from the gas cylinders to the test column. The gas flow velocity defined in the HOI test is the value measured by a hot-wire anemometer (not the bulk flow velocity in the test section). Therefore, the volume flow rate at which the gas flow velocity in the test section reaches the desired value has to be measured before the test and the volume flow rates of oxygen and nitrogen should be set based on the recorded volume flow rates. The gas supply line to the test column has two branches with shutoff valves (V1 and V2 in Figure 2). The one branch is for oxygen concentration measurement by paramagnetic oxygen analyzer (V1) and another branch is for bypassing part of the oxidizer flow to reduce the flow velocity in the test column during ignition (V2). The operating procedure of each valve during the test will be described later. The oxygen and nitrogen gas mixture was supplied from the bottom of the test column. A metal mesh and a honeycomb flow straightener are installed at the bottom of the test column to generate a uniform flow in the test section. The test section is a transparent glass tube with an inner diameter of 75 mm and a length of 230 mm. A sample holder was suspended from the top end of the glass tube and the wire sample was fixed to the sample holder as described below.

A sample holder designed in this study is shown in Figure 3. The holder was made of a stainless-steel plate with a thickness of 1 mm. The wire sample was fixed through the bottom and top holes in the sample holder. To

prevent deflection of the wire due to thermal expansion during the flame spread tests, a spring was used at the top end of the holder to maintain tension to the wire sample. The holder has F-shaped ledges on both sides to hang itself on the top end of the glass tube as seen in Figure 2. The wire insulation at the top end of the glass tube was ignited with a gas torch. The top bar of the holder used to fix the wire sample was placed 55 mm above the top end of the glass tube to prevent flow disturbance in the test column.

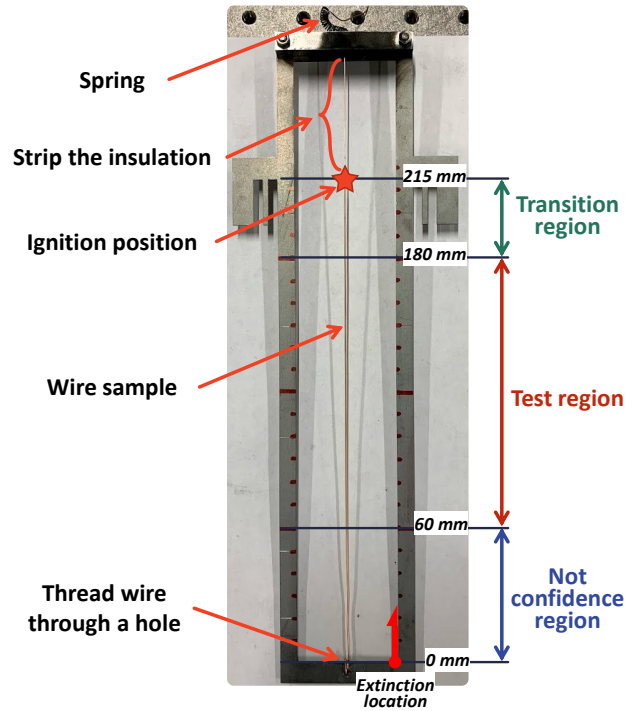


Figure 3: Wire sample holder.

LOCs of wire samples were obtained under various gas flow velocity conditions via a prescribed process followed by ISO 4589-2 [4] or ISO 4589-4 [20] (the up-and-down method [25], in which the oxygen concentration is increased or decreased a certain number of times according to the results of flame spread tests and the LOC is obtained in a small number of tests). Here, we briefly describe the experimental procedure. As shown in Figure 2, the sample holder was set in the test column and the shutoff valve (V1) connected to the oxygen analyzer was opened. Then, while checking the oxygen concentration indicated by the oxygen analyzer, the volume flow rates of oxygen and nitrogen were adjusted by mass flow controllers to achieve the desired values of oxygen concentration and gas flow velocity. The shutoff valve (V1) was then closed again to supply the oxidizer to the main line. The bypass valve (V2) was then opened for the ignition procedure. At this time, most of the oxidizer gas was discharged to the bypass line rather than the test column to facilitate the ignition of the sample. Note that ISO 4589-4 [20] recommends that the gas flow velocity in the test section during ignition should be less than 10 cm/s. Therefore, the control valve (V3) installed in the bypass line was adjusted so that the flow velocity in the test section was less than 10 cm/s when the bypass valve was opened. The sample was ignited by a gas torch flame. The wire insulation at the top end of the glass tube was exposed to the diffusion

flame to initiate the flame spread test. As shown in Figure 3, a 35 mm long region was provided for the transition to self-sustained flame spread after ignition. When the flame spreading over the wire sample passed through the reference line at 35 mm from the top end of the glass tube, the bypass valve (V2) was closed so that the prescribed flow velocity condition was achieved in the test column. Another reference line was set at 60 mm from the bottom plate edge of the sample holder as shown in Figure 3. Then, the experimental condition in which the flame spreads beyond this reference line was judged as “flammable” condition, while the flame quenched before reaching this reference line was judged as “not flammable” condition. The reason for giving the reference line is to eliminate the effects of heat losses through the high conductive wire core to the sample holder on the extinction limits. Previous results [26] measuring the wire temperature distribution showed that during downward flame spread under near extinction conditions, the high temperature region of a 0.5 mm diameter Cu core extends up to 40 mm upstream from the flame front due to heat conduction. Therefore, the reference line is set at 60 mm from the bottom of the sample holder including safety margin of 20 mm.

2.2. *Microgravity experiments*

To identify the gas flow velocity condition under which the MLOC exists, a flame spread test was conducted in a microgravity environment. Microgravity experiments were conducted in parabolic flights onboard Gulfstream-II airplane operated by Diamond Air Service in Japan. Microgravity environment of 10^{-2} g was provided for about 20 seconds in each parabolic flight. The details of the experimental setup used in microgravity experiments are available in other literature [22,27], so only brief description is given here.

A wind tunnel placed in a closed chamber was used to observe the opposed flame spread over wire samples. The test section consists of a cylindrical glass tube with an inner diameter of 60 mm and a length of 250 mm. The forced flow velocity in the test section was controlled by a DC fan. The relationship between the applied voltage to the fan and the wind velocity measured by a hot-wire anemometer was recorded in advance, and the applied voltage was adjusted to obtain the desired flow velocity condition in the test section. A wire sample was placed along the center line of the glass tube and ignited by an electrically heated wire coil. The initial ignition

conditions, such as the shape of the igniter (a Kanthal wire, an 8mm diameter coil with 8 turns), the heating method, the heating power (94 W), and heating time (8s) were determined by referring to the previous study by Nagachi et al. [8], which provide sufficient ignition intensity to obtain the extinction limits of flame spread over the wire samples. In microgravity experiments, ignition was performed under a constant flow velocity condition and flow velocity was not varied as in the HOI test. Additionally, in parabolic flight experiments, previous work [17] has been reported that natural convection of about 3 cm/s can be generated by residual gravity during flame spread tests even for small flat sheet specimens with a width of a few centimeters and a thickness of less than 1 mm. Therefore, parabolic flight experiments were conducted with forced flow velocities in the range of 5 – 20 cm/s to ensure that flame spread process is not dominated by residual gravity.

2.3. Laboratory wire samples

The wire sample used in the present study are summarized in Table 1. LDPE and ETFE (copolymer of C₂H₄ and C₂F₄), which have lower and higher OI than the oxygen concentration in air, were selected as insulation materials. Cu and NiCr were used as metallic cores. For convenience, each wire sample is assigned an ID as shown in Table 1 and will be referred to as the ID in this paper. LDPE and ETFE are thermoplastics, and both melted before gasification during flame spread process, and a portion of the molten matter dripped down. However, the melting and dripping of ETFE is not as pronounced as that of LDPE. Furthermore, ETFE exhibits flame retardancy due to a radical trapping mechanism in which halides recombine the chain carrier H radicals into H₂ during the gas phase combustion ($H + HF \rightarrow H_2 + F$). As the concentration of H radicals decreases, the reaction rate of one of the chain branching reactions, $H + O_2 \rightarrow O + OH$, decreases, and the concentration of chain carriers O and OH radicals also decreases [28,29]. Due to this mechanism, halogenated polymers exhibits flame retardant properties and ETFE has a high LOI value of 30% [23] compared to that of 18% for LDPE [24]. In addition, H radicals play a role in increasing the rate of soot pyrolysis [28]. Therefore, it is known that the sooting tendency of hydrocarbon fuels under diffusion flame conditions increases when the concentration of H radicals decrease due to the addition of halogens [30].

Table 1: Configurations of tested wire sample.

ID	Wire dimension		Material	
	Core diameter [mm]	Outer diameter [mm]	Wire core	Insulation
LDPE–Cu#2	0.5	0.8	Cu	LDPE
LDPE–NiCr#2	0.5	0.8	NiCr	LDPE
ETFE–Cu#2	0.5	0.8	Cu	ETFE
ETFE–NiCr#2	0.5	0.8	NiCr	ETFE

3. Results and discussion

3.1. Visible flame shapes in microgravity and normal gravity

Figure 4 shows the instantaneous flame shapes observed during the flame spread process in microgravity and normal gravity conditions. The flame shape features observed in LDPE–Cu#2 are similar to those of typical laminar jet diffusion flames for hydrocarbon fuels observed in microgravity and normal gravity environments [31–34]. As can be seen from Figure 4 (a) and (b), the downstream edge of the spreading flame was closed under normal gravity (Figure 4 (b)), whereas it was opened under microgravity because oxygen transport is suppressed (Figure 4 (a)). It can also be seen that the overall flame radius increased in microgravity (Figure 4

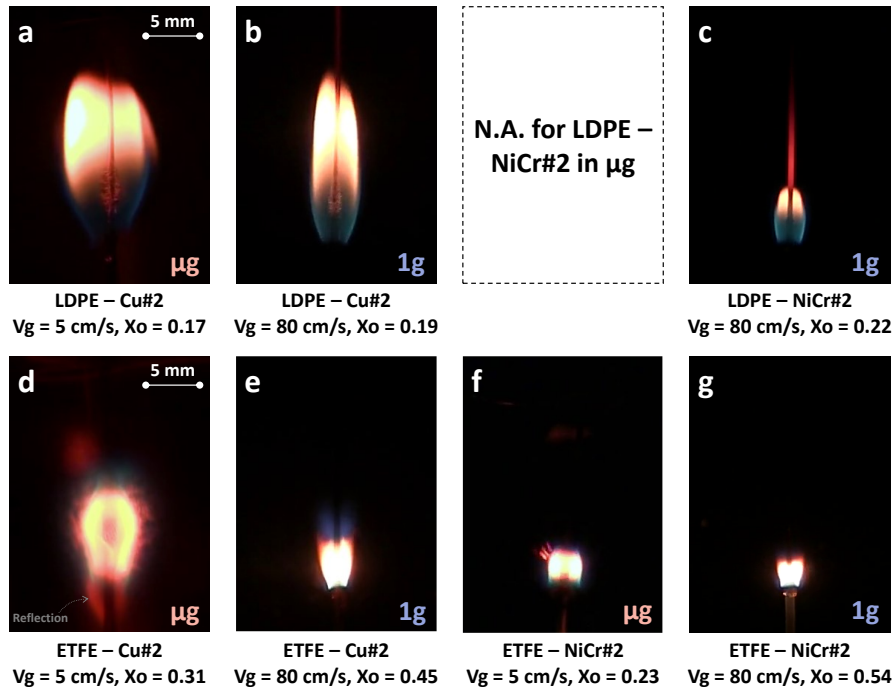


Figure 4: Typical flame shapes during steady flame spread in various flow velocities and oxygen concentrations. a) LDPE–Cu#2 in μg , b) LDPE–Cu#2 in 1g, c) LDPE–NiCr#2 in 1g, d) ETFE–Cu#2 in μg , e) ETFE–Cu#2 in 1g, f) ETFE–NiCr#2 in μg , g) ETFE–NiCr#2 in 1g. The blurred image in d) is due to corrosion of the inner wall of the glass tube by hydrogen fluoride generated during repeated experiments to burn ETFE insulated wire.

(b)). Comparison of LDPE and ETFE flames shows that a major part of the ETFE flame is composed of a luminous flame and the light intensity of the luminous flame is very strong. In other words, ETFE, a flame-retardant polymer, cannot sustain flame spread without forming such a robust flame under high oxygen concentration conditions. Focusing on the flame along ETFE–Cu#2, a bluish luminescence can be seen at the downstream of the luminous flame. This is due to the flame color reaction of Cu when Cu is corroded by fluorine compounds.

3.2. Flame spread rate in both micro- and normal-gravity

The flame spread rates (V_f) under both normal and microgravity conditions were measured by tracing the leading edge of the visible flame during the flame spread process. Representative data for the motion history of the flame leading edge are shown in Figure 5 for both LDPE and ETFE insulated wire samples. As can be seen in the figures, regardless of the experimental conditions and the wire samples, flame spread process showed nearly steady state. Thus, the slope of the linear fitting of the flame motion history was defined as V_f in the analysis.

The measured V_f as a function of oxygen concentration are shown in Figure 6. V_f for microgravity test are also presented in Figure 6 except for LDPE–NiCr#2. Note that wind tunnels with an inner diameter of 75 mm and 60 mm were used in normal gravity and microgravity experiments, respectively. Therefore, to verify the validity of comparing the data acquired in different wind

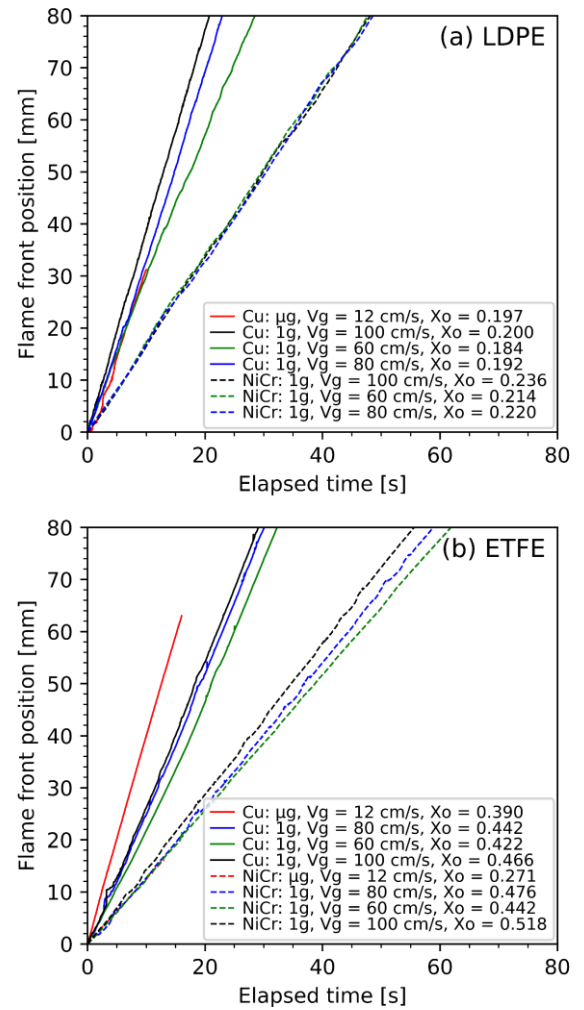


Figure 5: Position of the flame front with time for LDPE and ETFE insulated wires.

tunnels, data from the previous study [26] using a wind tunnel with an inner diameter of 60 mm are also plotted in Figure 6. Although a comparison can only be made with the V_f for LDPE insulated wires subjected to a forced flow velocity of 4 cm/s on the ground, Figure 6 shows that there is little difference in V_f and extinction limits obtained in different wind tunnel, indicating that the different geometries of the wind tunnels used in this study are not significantly dependent on the experimental results.

As can be seen in the figures, V_f increased with increasing oxygen concentrations for all flow velocity conditions. The Cu wire samples, which has a higher thermal conductivity, exhibited a higher V_f than the NiCr wire samples under the same experimental conditions regardless of the insulation materials. These trends are consistent with the results of previous studies [26,35–39] which investigated the effect of core materials on the flame spread over electric wires. Therefore, when the thermal conductivity of the core material is large, the flame spread phenomena is enhanced under steady spreading condition.

It is interesting to note that the minimum V_f for Cu wire samples in Figure 6 showed larger value than those for NiCr wire samples regardless of insulation materials (note that the microgravity data for LDPE insulated

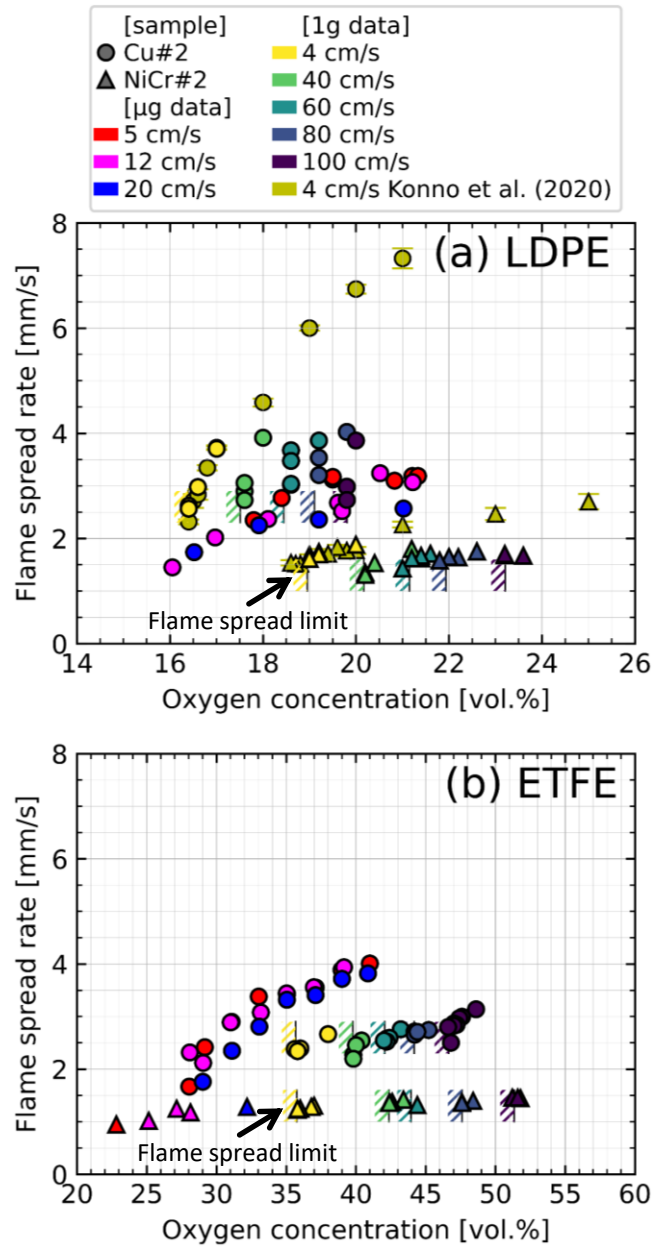


Figure 6: Flame spread rate as a function of oxygen concentration under different flow velocity conditions for LDPE and ETFE insulated wires.

wires are not subject to discussion since there are no results for the V_f of LDPE-NiCr#2). These experimental results are supported by the theoretical analysis performed by Konno et al. [26]. They revealed that flames spreading over high conductive wires are extinguished with a larger V_f than those over low conductive wires because of the heat losses from the unburned zone during the flame spread process. When the forward heat conduction in the solid phase plays an important role in the flame spread process, the heat losses from the unburned zone causes a negative feedback loop in the flame spread system because high temperature region in the solid phase is expanded as V_f decreases. This negative feedback mechanism is pronounced with a high conductive wire because it can increase the heat losses from the unburned zone.

Additionally, we can notice that the rate of V_f increase with increasing oxygen concentrations showed different trends depending on the wire core materials. As seen in Figure 6, V_f of Cu samples are more sensitive to the oxygen concentrations than those of NiCr sample regardless of insulation materials. This is also one of the unique features of the flame spreading over electric wire. In composite materials such as electric wires, the metallic core remains after the insulation burning out and the metallic core is heated by the downstream flame. As a result, high conductive wire promotes heat recirculation from the downstream to the upstream unburned zone, making the flame spread more sensitive to the flame temperature and flame length [39].

Comparing V_f in normal and microgravity, V_f in microgravity is smaller than that in normal gravity for LDPE-Cu#2, while the opposite trend was observed for ETFE-Cu#2. The different trend may be attributed to the difference in flame spread regimes in terms of flow velocity, that is microgravity or kinetic regimes. For instance, V_f of ETFE-Cu#2 increases with decrease in external flow velocity such in microgravity because the flame of ETFE wire is in the kinetic regime. Further discussion on the effect of external flow velocity on the insulation flammability will be made in the next section, together with the flammability diagram as a function of the opposed flow velocity.

3.3. *Flammability boundary*

The relationship between opposed flow velocity and LOC are shown in Figure 7. As mentioned in section

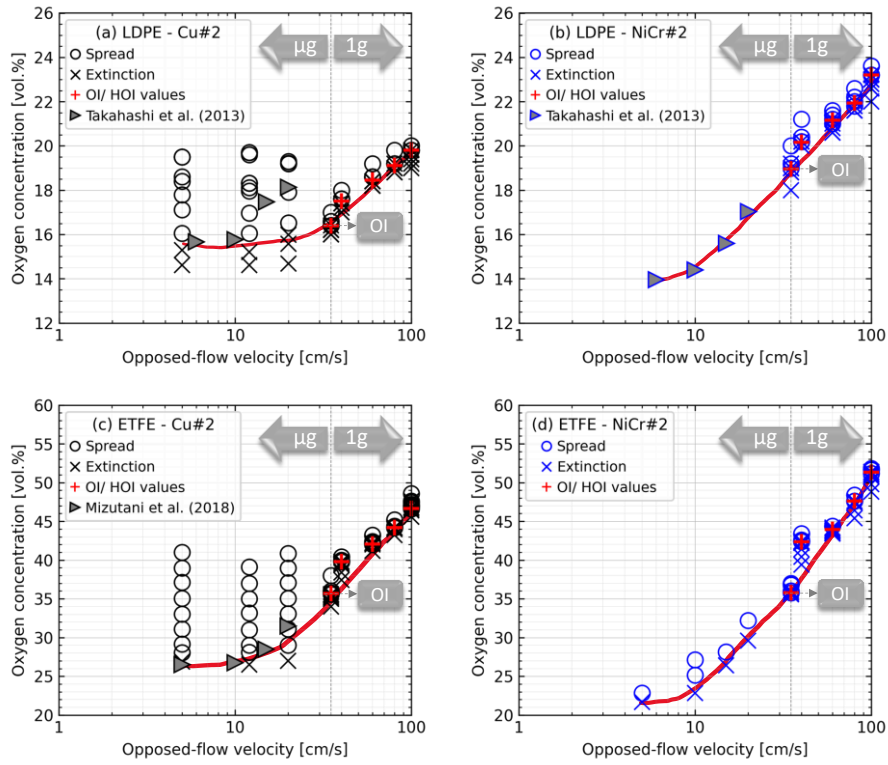


Figure 7: Flammability diagrams as a function of opposed flow velocity. Note that the flow field in the OI test is assumed to be controlled by natural convection, and the buoyant flow is assumed to be 35 cm/s with reference to previous studies [18].

1, a forced flow velocity of 4 cm/s was supplied for the OI method in accordance with ISO 4589-2 [4]. In this case, the flow field around the spreading flame is considered to be dominated by the buoyancy-induced flow around the flame, and the results of LOCs obtained by the OI method are plotted assuming a buoyant flow of 35 cm/s, referring to the previous studies by Takahashi et al. [17–19]. The other experimental results are not corrected for buoyant flow, but they are plotted based on forced flow velocity. The results of microgravity experiments are represented by open circles and crosses corresponding to sustained combustion and extinction, respectively. The results of the microgravity experiments of the previous study [21,22] are also shown together except for ETFE-NiCr#2. In the microgravity data for LDPE-Cu#2 (Figure 7 (a)), there is a discrepancy between the past results [21] and the present ones, which were obtained under conditions of forced flow velocities greater than 10 cm/s. This is because in the previous study [21] the ignition energy to ignite the wire sample was weaker than in the present study, resulting in a higher LOC. The data obtained in this study were more consistent with LOCs acquired under high flow velocity conditions in normal gravity test.

As can be seen in Figure 7, the relationship between LOC and flow velocity obtained in normal and microgravity were consistently connected well for all tested wires, which shows validity of application of the OI/HOI test methods to the electric wires. Namely, it is possible to tell whether LOC decreases or increases further in a microgravity condition referring to the OI and HOI values taken in normal gravity. Further, Figure 7 implies that the development of a theoretical model, as was done for flat sample [17–19], leads to quantitative prediction of MLOC by utilizing the data shown in the figure, which is a subject for future research.

It has been well established that flammability boundary of the flame spreading over solid surface consists of two branches [9]; the low gas flow velocity side is the quenching extinction branch, where heat losses play important role in the flame spread process; and the high gas flow velocity side is blow-off branch, where the finite rate chemistry are dominant. However, for the range of gas flow velocity conditions in the present study, quenching extinction branches could not be observed clearly in low flow velocity side, considering a monotonic decrease in LOC with decreasing gas flow velocity. Therefore, to confirm the quenching extinction branch of the wire sample used in the present study, experimental conditions that can achieve a forced flow velocity smaller than 5 cm/s is required. As mentioned earlier, in the parabolic flight experiment, residual gravity and g-jitter have an influence on the combustion phenomena, so it is better to apply a certain degree of forced flow velocity to obtain reproducible results. Therefore, the results of the present study are considered as the best data that can be obtained in a ground-based experiments, which suggests the necessity of microgravity experiments on orbit such as utilization of ISS [2,12–14].

A comparison of the LOC trends for Cu and NiCr wires showed that the change in the wire core material changes the tendency of insulation flammability with respect to the flow velocity. Looking at the LOC trend for the NiCr wires, the blow-off branch shift to lower flow velocity conditions than the Cu wires regardless of insulation materials. This would be the result of the increased heat losses caused by the greater axial heat conduction through the Cu wire, which shifts the quenching extinction branch to higher gas flow velocity conditions. More interestingly, comparing the absolute value of LOC for the Cu and NiCr wires, the NiCr wires

have a lower LOC than the Cu ones under low flow velocity conditions, while the Cu ones has a lower LOC than the NiCr ones under high flow velocity conditions regardless of insulation materials. This suggests that the greater axial heat conduction through the wire core can suppress the flammability of the insulation under low velocity conditions and can enhance it under high velocity conditions [26][40].

A comparison of the LOC trends for LDPE and ETFE showed that LOCs of ETFE were significantly reduced under microgravity low flow velocity conditions. Osorio et al. [27] and Mizutani et al. [22] have also measured LOC for ETFE insulated Cu wire in both normal and microgravity, and they also reported a significant decrease in LOC in microgravity. Thus, multiple studies have confirmed the fact that materials with sufficient flame retardancy on the ground become extremely flammable in microgravity, which is a very dangerous problem that threaten the safety of space mission. Therefore, the effect of gravity on the flame retardancy of materials must be carefully considered in the safety design of spacecraft. As a further step, it is necessary to make the MLOC of various materials predictable and to clarify which materials can exhibit sufficient flame retardancy in a microgravity environment.

4. Conclusions

The HOI test specified in ISO 4589-4, which was developed to measure LOC of thermally thin sheet specimens in high flow velocity, was modified so that it can be used to measure LOC of wire samples. The modified HOI test method properly worked to determine LOCs of wire samples, and the acquired data are effective for prediction of the MLOC. The validity of the HOI test was also demonstrated by the fact that the data obtained in the microgravity experiment, which is close to the MLOC, were well consistent with the data obtained in the HOI test. The major findings obtained through this study are summarized as follows.

- The LOC of all tested wire in the present study tended to decrease monotonically with decreasing flow velocity in the range of tested flow velocity conditions. Namely, both LDPE and ETFE insulated wire should be more flammable without buoyancy-induced flow in microgravity rather than in normal gravity conditions.

- Regardless of the insulation materials, the NiCr wire showed smaller LOCs than the Cu wire under low flow velocity conditions in microgravity while this flammability order was reversed under high velocity conditions in normal gravity. Since the combustion characteristics of the same insulation material change depending on core materials, the flammability of composite material (e.g., electric wire) should be determined as its unique characteristics rather than that of insulation material alone.
- LOC of ETFE, which has flame resistant nature on the ground, exhibits very low values (high flammability) in the low flow velocity conditions in microgravity.

Acknowledgements

This research was supported by JAXA as a candidate experiment for the third stage use of JEM/ISS titled “Evaluation of gravity impact on combustion phenomenon of solid material toward higher fire safety” (called “FLARE”). This research was also supported by JSPS KAKENHI grant numbers JP19J10187 and JP21K20389.

References

- [1] NASA-STD-6001B, Flammability, Offgassing, and Compatibility Requirements and Test Procedures, Washington, DC, 2011. <https://standards.nasa.gov/standard/NASA/NASA-STD-6001>.
- [2] O. Fujita, Solid combustion research in microgravity as a basis of fire safety in space, *Proc. Combust. Inst.* 35 (2015) 2487–2502. <https://doi.org/10.1016/j.proci.2014.08.010>.
- [3] A. Guibaud, G. Legros, J.L. Consalvi, J. Torero, Fire safety in spacecraft: Past incidents and Deep Space challenges, *Acta Astronaut.* 195 (2022) 344–354. <https://doi.org/10.1016/J.ACTAASTRO.2022.01.021>.
- [4] ISO 4589-2, Plastics — Determination of burning behaviour by oxygen index — Part 2: Ambient-temperature test, 2017. <https://www.iso.org/standard/60786.html>.
- [5] UL94, Tests for Flammability of Plastic Materials for Parts in Devices and Appliances, 2023. https://www.shopulstandards.com/ProductDetail.aspx?productId=UL94_7_S_20230228.
- [6] X. Huang, Y. Nakamura, D. Urban, Introduction to Special Issue on Spacecraft Fire Safety, *Fire Technol.* 56 (2020) 1–4. <https://doi.org/10.1007/s10694-019-00941-6>.
- [7] X. Huang, J. Gao, A review of near-limit opposed fire spread, *Fire Saf. J.* 120 (2021) 103141. <https://doi.org/10.1016/j.firesaf.2020.103141>.
- [8] S.L. Olson, P. V. Ferkul, J.S. T’ien, Near-limit flame spread over a thin solid fuel in microgravity, *Symp. Combust.* 22 (1989) 1213–1222. [https://doi.org/10.1016/S0082-0784\(89\)80132-8](https://doi.org/10.1016/S0082-0784(89)80132-8).
- [9] S.L. Olson, Mechanisms of Microgravity Flame Spread Over a Thin Solid Fuel: Oxygen and Opposed

- Flow Effects, *Combust. Sci. Technol.* 76 (1991) 233–249. <https://doi.org/10.1080/00102209108951711>.
- [10] Y. Ju, Understanding cool flames and warm flames, *Proc. Combust. Inst.* 38 (2021) 83–119. <https://doi.org/10.1016/j.proci.2020.09.019>.
- [11] Y. Konno, N. Hashimoto, O. Fujita, On the radiation extinction of opposed flame spread over curved solid surface in low flow velocity conditions, *Combust. Flame.* 254 (2023) 112836. <https://doi.org/10.1016/j.combustflame.2023.112836>.
- [12] O. Fujita, Solid Combustion Research in ISS/JEM, *Int. J. Microgravity Sci. Appl.* 28 (2011) 90–95. <https://doi.org/10.15011/jasma.28.3.90>.
- [13] O. Fujita, Introduction of JAXA Priority Project FLARE utilizing ISS/“KIBO,” *Int. J. Microgravity Sci. Appl.* 32 (2015) 320402. <https://doi.org/10.15011/jasma.32.320402>.
- [14] M. Kikuchi, Overview of the “Solid Combustion” Experiment and the Solid Combustion Experiment Module, *Int. J. Microgravity Sci. Appl.* 32 (2015) 320407. <https://doi.org/10.15011/ijmsa.32.320407>.
- [15] S. Takahashi, K. Tsuboi, T. Ihara, S. Bhattacharjee, Modeling of Flammability Limits of Thin Materials in Microgravity Environment, *Int. J. Microgravity Sci. Appl.* 31 (2014) 179–185.
- [16] S. Takahashi, Prediction of Flammability Limit of Flat Materials in Microgravity Environments, *Int. J. Microgravity Sci. Appl.* 32 (2015) 320403. <https://doi.org/10.15011/ijmsa.32.320403>.
- [17] S. Takahashi, T. Ebisawa, S. Bhattacharjee, T. Ihara, Simplified model for predicting difference between flammability limits of a thin material in normal gravity and microgravity environments, *Proc. Combust. Inst.* 35 (2015) 2535–2543. <https://doi.org/10.1016/j.proci.2014.07.017>.
- [18] S. Takahashi, M.A.F. Bin Borhan, K. Terashima, A. Hosogai, Y. Kobayashi, Flammability limit of thin flame retardant materials in microgravity environments, *Proc. Combust. Inst.* 37 (2019) 4257–4265. <https://doi.org/10.1016/j.proci.2018.06.102>.
- [19] S. Takahashi, K. Terashima, M.A.F. bin Borhan, Y. Kobayashi, Relationship Between Blow-Off Behavior and Limiting Oxygen Concentration in Microgravity Environments of Flame Retardant Materials, *Fire Technol.* 56 (2020) 169–183. <https://doi.org/10.1007/s10694-019-00880-2>.
- [20] ISO 4589-4, *Plastics — Determination of burning behaviour by oxygen index — Part 4: High gas velocity test*, 2021. <https://www.iso.org/standard/75215.html>.
- [21] S. Takahashi, H. Ito, Y. Nakamura, O. Fujita, Extinction limits of spreading flames over wires in microgravity, *Combust. Flame.* 160 (2013) 1900–1902. <https://doi.org/10.1016/j.combustflame.2013.03.029>.
- [22] K. Mizutani, K. Miyamoto, N. Hashimoto, Y. Konno, O. Fujita, Limiting Oxygen Concentration Trend of ETFE-Insulated Wires under Microgravity, *Int. J. Microgravity Sci. Appl.* 35 (2018) 350104. <https://doi.org/10.15011/jasma.35.1.350104>.
- [23] DuPont Tefzel, *ETFE FLUOROPLASTICS - Safety Data Sheet*, 2015.
- [24] J.G. Quintiere, *Fundamentals of Fire Phenomena*, John Wiley & Sons, Ltd, Chichester, UK, 2006. <https://doi.org/10.1002/0470091150>.
- [25] W.J. Dixon, The Up-and-Down Method for Small Samples, *J. Am. Stat. Assoc.* 60 (1965) 967–978. <https://doi.org/10.1080/01621459.1965.10480843>.

- [26] Y. Konno, N. Hashimoto, O. Fujita, Role of wire core in extinction of opposed flame spread over thin electric wires, *Combust. Flame*. 220 (2020) 7–15. <https://doi.org/10.1016/j.combustflame.2020.06.026>.
- [27] A.F. Osorio, K. Mizutani, C. Fernandez-Pello, O. Fujita, Microgravity flammability limits of ETFE insulated wires exposed to external radiation, *Proc. Combust. Inst.* 35 (2015) 2683–2689. <https://doi.org/10.1016/j.proci.2014.09.003>.
- [28] I. Glassman, R.A. Yetter, N.G. Glumac, *Combustion*, 5th ed., Academic Press, 2014. <https://www.elsevier.com/books/combustion/glassman/978-0-12-407913-7>.
- [29] A.R. Horrocks, D. Price, *Fire retardant materials*, 1st ed., Woodhead Publishing, 2001. <https://www.elsevier.com/books/fire-retardant-materials/horrocks/978-1-85573-419-7>.
- [30] K.P. Schug, Y. Manheimer-Timnat, P. Yaccarino, I. Glassman, Sooting Behavior of Gaseous Hydrocarbon Diffusion Flames and the Influence of Additives, *Combust. Sci. Technol.* 22 (1980) 235–250. <https://doi.org/10.1080/00102208008952387>.
- [31] D.L. Urban, Z.-G. Yuan, P.B. Sunderland, K.-C. Lin, Z. Dai, G.M. Faeth, Smoke-point properties of non-buoyant round laminar jet diffusion flames, *Proc. Combust. Inst.* 28 (2000) 1965–1972. [https://doi.org/10.1016/S0082-0784\(00\)80602-5](https://doi.org/10.1016/S0082-0784(00)80602-5).
- [32] D.L. Urban, Z.-G. Yuan, P.B. Sunderland, G.T. Linteris, J.E. Voss, K.-C. Lin, Z. Dai, K. Sun, G.M. Faeth, Structure and Soot Properties of Nonbuoyant Ethylene/Air Laminar Jet Diffusion Flames, *AIAA J.* 36 (1998) 1346–1360. <https://doi.org/10.2514/2.542>.
- [33] K. Lin, G. Faeth, P. Sunderland, D. Urban, Z. Yuan, Shapes of nonbuoyant round luminous hydrocarbon/air laminar jet diffusion flames, *Combust. Flame*. 116 (1999) 415–431. [https://doi.org/10.1016/S0010-2180\(98\)00100-X](https://doi.org/10.1016/S0010-2180(98)00100-X).
- [34] S.S. Krishnan, J.M. Abshire, P.B. Sunderland, Z.G. Yuan, J.P. Gore, Analytical predictions of shapes of laminar diffusion flames in microgravity and earth gravity, *Combust. Theory Model.* 12 (2008) 605–620. <https://doi.org/10.1080/13647830801966146>.
- [35] N.N. Bakhman, L.I. Aldabaev, B.N. Kondrikov, V.A. Filippov, Burning of polymeric coatings on copper wires and glass threads: I. Flame propagation velocity, *Combust. Flame*. 41 (1981) 17–34. [https://doi.org/10.1016/0010-2180\(81\)90036-5](https://doi.org/10.1016/0010-2180(81)90036-5).
- [36] Y. Nakamura, N. Yoshimura, H. Ito, K. Azumaya, O. Fujita, Flame spread over electric wire in sub-atmospheric pressure, *Proc. Combust. Inst.* 32 (2009) 2559–2566. <https://doi.org/10.1016/j.proci.2008.06.146>.
- [37] Y. Nakamura, N. Yoshimura, T. Matsumura, H. Ito, O. Fujita, Opposed-wind Effect on Flame Spread of Electric Wire in Sub-atmospheric Pressure, *J. Therm. Sci. Technol.* 3 (2008) 430–441. <https://doi.org/10.1299/jtst.3.430>.
- [38] L. Hu, Y. Zhang, K. Yoshioka, H. Izumo, O. Fujita, Flame spread over electric wire with high thermal conductivity metal core at different inclinations, *Proc. Combust. Inst.* 35 (2015) 2607–2614. <https://doi.org/10.1016/j.proci.2014.05.059>.
- [39] Y. Konno, N. Hashimoto, O. Fujita, Downward flame spreading over electric wire under various oxygen concentrations, *Proc. Combust. Inst.* 37 (2019) 3817–3824. <https://doi.org/10.1016/j.proci.2018.05.074>.

- [40] Y. Konno, Y. Li, J.-M. Citerne, G. Legros, A. Guibaud, N. Hashimoto, O. Fujita, Experimental study on downward/opposed flame spread and extinction over electric wires in partial gravity environments, *Proc. Combust. Inst.* (2022). <https://doi.org/10.1016/j.proci.2022.07.002>.