Limiting Oxygen Concentration Trend of ETFE-Insulated Wires under Microgravity

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Abstract

This study investigated the flammability of the fire-resistant material ethylene-tetrafluoroethylene (ETFE) as insulation for copper wires under different flow velocity and gravity conditions. The limiting oxygen concentration (LOC) of flame spreading horizontally over the sample was investigated at external opposed flow velocities ranging from 0 to 200 mm/s under normal gravity (1g0) and microgravity (μg0). The LOC under μg0 showed a U-shape, which has been reported in previous studies. A minimum LOC of approximately 26% was found at external flow velocities ranging 50–100 mm/s. An expanded heat balance model and radiation for wire combustion (R_rad,wire) were proposed considering the heat conduction through the copper core, which is a notable feature of wire combustion. The U-shaped LOC curve was qualitatively explained in the low flow velocity region by this model and in the high flow velocity region by the Damköhler number. We also compared the LOC trend of ETFE with that of polyethylene (PE)-insulated wires reported in a previous study and demonstrated that the drop of LOC in ETFE was much larger than that of PE when the gravitational condition was changed from 1g0 to μg0 (ALOC). This large difference was explained by two factors. First, the rate of change of flame temperature with an increasing oxygen concentration is small at high oxygen concentrations. Second, the increase in heat input through the copper core owing to gravity change was larger for ETFE than for PE because of the difference in the rate of change in flame length along the copper core.

Keyword(s): Flame spread, Extinction, Ethylene-tetrafluoroethylene (ETFE), Limiting oxygen concentration (LOC)

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1. Introduction

As space exploration is being pursued by both national space agencies and private companies, the safety of astronauts has become more and more important. Fire is a key hazard during space missions. A large number of electrical devices and cables are installed in spacecraft, and these are a potential source of fire when short-circuiting or overloading. In fact, incidents involving electrical cables have already been reported in manned space missions 1 although none have led to fatalities. To prevent such incidents, materials used in spacecraft are regulated by NASA’s fire safety standard STD-6001B 2. In the case of electrical wiring, Test 4 in this standard applies. However, this test only denotes whether it is a pass or fail and provides no quantitative values. Fujita 3,4 noted that the test does not address actual flammability in microgravity (μg0) and suggested the necessity for a quantitative evaluation, for example, by applying the limiting oxygen index method, as defined in ISO 4589-2 5 or ASTM D2863 6.

Fire in a spacecraft may be different from one on the ground because of the lack of gravity and particularly the lack of natural convection. In the early days, spacecraft materials were assumed to have lower flammability in μg0 because less oxygen is supplied owing to a reduced buoyant flow. However, recent researches 7,8 have revealed that materials can become more flammable under certain conditions. Takahashi et al. 8,9 investigated flame propagation over a thermally thin flat PMMA plate and constructed a flammability map that showed the limiting oxygen concentration (LOC) as a function of opposed flow velocity. The minimum oxygen concentration to sustain flame spread was identified for a thin flat PMMA sheet. The flammability map clearly showed a flammable region at a lower flow velocity and lower oxygen concentration than that at ground-level conditions in normal gravity (1g0). Other research has examined flame propagation over electrical wiring insulation. Work conducted by Takahashi 10 revealed that wire insulation under μg0 could be more flammable than under 1g0. They measured the LOC at a range of external opposed flow velocities (60–200 mm/s) using polyethylene (PE) insulation on copper (Cu) and nickel–chromium (NiCr) wire. In this test, they observed that the LOC dropped by approximately 2–3% when shifting to the μg0 condition with both the Cu and NiCr cores. More recently, Osorio et al. conducted flame spread experiments with ethylene-tetrafluoroethylene (ETFE)-insulated Cu wire 11. This is known as a fire resistant (FR) material and has a high limiting oxygen index (LOI: LOC under the condition specified by ISO 4589-2 12) defined for downward flame spread.) value of 31% 12, compared with 18% for PE 13. In this research, they measured LOC variations with different external radiative heat fluxes (0–25 kW/m²) at a fixed external flow velocity (120 mm/s). They also...
observed a drop in LOC with the shift to μg. Interestingly, the drop in LOC (ΔLOC) was approximately 6%, which was clearly greater than that of PE-insulated wire. This result suggested that the LOC flammability gap of FR materials under 1g0 and μg0 is larger than that of PE despite the difference in insulation thickness: 0.15 mm for PE and 0.3 mm for ETFE. This suggests that we need to consider how the choice of insulation material affects the change in LOC under different gravity conditions.

When we consider the extinction of flame propagation across solid fuels, two types of mechanism should be considered: blow-off in high flow velocity regions and quenching in low flow velocity regions. In the blow-off region, LOC decreases as flow velocity decreases. This is explained by the Damköhler number (Da) which is the ratio of residence time to characteristic chemical time as shown in Eq. (1)\(^8,14,15\).

\[
Da = \frac{t_{\text{res}}}{t_{\text{chem}}} = \frac{\alpha_g}{V_r} \rho_g Y_0 A \exp \left( - \frac{E}{RT_f} \right)
\]  

(1)

where \(t_{\text{res}}\) and \(t_{\text{chem}}\) indicate the residence time of fuel and oxidizer in reaction zone and the chemical reaction time and \(A, E, R, T_f, V_r, Y_0, \alpha_g,\) and \(\rho_g\) are pre-exponential factor, activation energy, constant, flame velocity, temperature relative to the flame \((V_r = V_y + V_f),\) where \(V_f\) and \(V_y\) are flame spread rate and opposed-flow velocity), mass fraction of oxygen, thermal diffusivity of gas, and density of gas, respectively. Once Da drops to some critical value (Da < Da_crit), flame is extinguished because the residence time is too short. Conversely, in a quenching region, the LOC increases as flow velocity decreases.

The flame extinction here is explained by the Radiation number (\(R_{rad}\)), which is the ratio of heat loss to heat input in a pre-hear region, as shown in Eq. (2)\(^8,16,17\).

\[
R_{rad} = \frac{\epsilon(1 - a_{\text{abs}})g(\frac{R}{v} - \frac{T_\infty}{T_0})}{\rho_g c_g V_f(T_f - T_0)}
\]  

(2)

where \(a_{\text{abs}}, c_g, T_v, T_\infty, \epsilon,\) and \(\sigma\) indicate absorption coefficient of gas, specific heat of gas, vaporization temperature of solid, ambient temperature, surface emissivity, and Stefan–Boltzmann coefficient, respectively. The flame extinguishes when \(R_{rad}\) reaches the critical value (\(R_{rad} > R_{rad, \text{crit}}\)) as the radiative heat loss exceeds the heat input. In theory, these characteristics make the flammability boundary V-shaped. As the external flow velocity changes, the condition that defines the bottom of the V-shape should be a fundamental limit (the minimum limiting oxygen concentration (MLOC)). However, the MLOC estimated by the V-shaped model shows the smaller value than that obtained by the μg experiment. Because in reality, the boundary forms a U-shape because the region around the MLOC is affected by both extinction mechanisms\(^7,10\). Takahashi et al. estimated the effect of the Da on the heat transfer from flame to solid phase\(^9,10\) on the spreading of flame over a thin PMMA plate. They successfully constructed a theoretical model that gave a more accurate flammability limit than the ordinal V-shaped model.

In the case of wire insulation combustion, a significant feature is heat transfer through the metal core, which can act either as a heat sink or heat source depending on the surrounding flow and temperature profile. Takahashi et al.\(^10\) discussed the quenching and blow-off of wire combustion by qualitatively treating the wire as a flat plate and considering the core effect, thereby using the PE-insulated samples as laboratory material. Nonetheless, flammability limit estimation for electrical wiring is still remained as difficult problem because the heat transfer between insulation and metal core is unclear. To understand the mechanism, it is indispensable to grasp metal core temperature profile which is briefly mentioned but not discussed enough in the work conducted by Takahashi et al.\(^10\).

The present study focuses on the LOC of ETFE-insulated wires with opposed flow velocity variation. First, we carried out LOC measurements at different flow velocities to obtain the flow velocity dependencies of the LOC under 1g0 and μg0 conditions, and these results are presented in Section 3.1. In Section 3.2, we discuss the heat balance model for a wire and propose the \(R_{rad}\) for wire combustion considering the core effect in more detail. In section 3.3, we compare the trend of LOC of ETFE with that of PE\(^10\) and discuss the ΔLOC differences between the materials.

2. Experimental Configuration

Figure 1 shows a schematic of the combustion chamber that had a volume of approximately 46 L. The test section in this chamber has a 60 mm diameter and 250-mm-long flow duct made of glass tube and is located in the top section of the chamber. A manifold with a sample supply system on both sides of the duct connected the duct and bottom sections of the chamber. An air suction fan (Sanyo Denki 9GV0612P1H031) was attached at the bottom end of the manifold and produced left-to-right airflow of 0–200 mm/s inside the duct (Fig. 1). Airflow was made uniform by honeycomb flow straighteners at both manifolds. The sample wire (Sugita Densen Co., Ltd.) had a 0.5-mm-diameter copper
core and 0.15-mm-thick ETFE coating. The sample geometry was the same as that in a previous study\(^9\) to make comparison convenient. The sample wire was placed along the center line of the flow duct and ignited by a 0.5-mm-thick and 8-mm-diameter Kanthal coil downstream of the duct using 92 W (14.7 V, 6.3 A) of power and 12 s of energizing time. A programmable logic controller (Mitsubishi MELSEC FX2N-16MR) and power supply (Takasago EX-375L2) controlled ignition to realize opposed-flow flame spreading over the wire insulation. The combustion products (carbon dioxide, water, and hydrogen fluoride) were absorbed by a zeolite filter and hydrogen fluoride filter placed upstream of the suction fan. Chamber pressure, oxygen concentration, and temperature were monitored by a pressure sensor (Nagano Keiki KP15-17G), an oxygen sensor (Jikco JKO-25LII), and a T-type thermocouple placed in the bottom section of the chamber, respectively. All data were recorded by a data logger (Graphtec GL220 midi LOGGER dual). Before the start of each test run, the total pressure inside the chamber was set to 100 kPa for all conditions, and the oxygen concentration was set to the desired value using partial pressure. Once the ambient gas composition was at the target value, the chamber was completely sealed until the end of the test. The change in oxygen concentration by the combustion reaction during each test was less than 1%. For the \(\mu\)g experiments, the combustion chamber, control systems, power supply systems, and gas supply/evacuation systems were installed in a \(\mu\)g environment provided by parabolic flights of an airplane (Gulfstream-II) operated by Diamond Air Service Co. Ltd. in Nagoya, Japan. The duration of \(\mu\)g was approximately 20 s and acceleration was approximately \(10^{-2}\) g. The suction fan was turned on and the mixing fan was turned off 30 s before \(\mu\)g was induced. The igniter was energized 10 s before \(\mu\)g because of the ignition delay time, thus, allowing the flame spreading to begin immediately after \(\mu\)g conditions began.

We defined “propagation” as the condition under which flame propagated by more than 100 mm under 1g, and the condition under which the flame was sustained throughout the \(\mu\)g duration of 20 s. As the 20 s of \(\mu\)g duration was insufficient for 100 mm propagation, this distinction was necessary. These two different criteria were applied in a previous study and did not produce any significant differences\(^10, 19\). When the extinction limit was determined according to the above definitions, the propagation and no propagation results overlapped near the flammability limit.\(^20\) This was attributed to the stochastic nature of the extinction phenomenon, as reported by Olson et al.\(^21\). In the present study, we defined an intermediate value between the maximum oxygen concentration with no propagation \(\left( N_{P_{\text{max}}} \right) \) and the minimum oxygen concentration with propagation \(\left( P_{\text{min}} \right) \), as the LOC for each flow velocity. The gap between the \(N_{P_{\text{max}}} \) and the \(P_{\text{min}}\) was plotted as an error bar.

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**Fig. 2** LOC of ETFE-insulated copper wire (0.5 mm core diameter and 0.15 mm insulation thickness) under 1g and \(\mu\)g. The triangles and squares represent the 1g and \(\mu\)g LOCs, respectively.

**Fig. 3** Typical flame shape of PE- and ETFE-insulated wires under 1g. The oxygen concentration was 19% for PE and 38.5% for ETFE. The external flow velocity was 150 mm/s for both samples. Both conditions represented propagation.

**Fig. 4** Typical flame shapes of PE- and ETFE-insulated wires under \(\mu\)g. The oxygen concentrations were 18% and 29% for PE and ETFE, respectively. The external flow velocity was 150 mm/s for both samples. Both conditions represented propagation.
3. Results and Discussion

3.1 Experimental Results

Figure 2 shows the LOC of ETFE for each external opposed flow velocity under 1g0 and μg0. The horizontal axis represents the external opposed flow velocity, and the vertical axis represents the ambient oxygen concentration. No U-shaped curve or MLOC was observed in the 1g0 test. The LOC had a constant value of approximately 37%, except at a 0 mm/s flow velocity, where the value was approximately 42%. Figure 3 compares the typical flame shapes of PE and ETFE under 1g0. In both cases, the flame wrapped around the wire and stretched upwards owing to buoyancy-induced flow. In contrast to the previous study (11), no drop in molten insulation was observed because the insulation used in this study was thinner (0.15 mm) than that in the previous study (0.3 mm). The LOCs at each external flow velocity in the μg0 experiment are shown in Fig. 2; a clear U-shape and MLOCs were observed. The MLOC was present at external flow velocities range 50–100 mm/s, with a value of approximately 26%. Note that this value is much lower than the LOI of ETFE, i.e., 31% (22). Figure 4 compares the typical flame shape of PE with ETFE under μg0. In contrast to 1g0, the flame for both PE and ETFE elongated downstream along the copper core.

3.2 U-Shaped Trend in Wire Combustion

As discussed in Section 1, Takahashi et al. (10) have suggested a radiation number for wire combustion using the core effect. The radiation number \( R_{loss} \) is given by Eq. (3):

\[
R_{loss} = \frac{\dot{Q}_{rad} + \dot{Q}_{sc}}{\dot{Q}_{gs}} = \frac{r_{E} \sigma (T_{c}^{4} - T_{d}^{4}) + \lambda_{s} (T_{o} - T_{c}) / \ln(\tau_{c} / r_{c})}{\lambda_{g} (T_{f} - T_{o}) / \ln(1 + a_{g} / (\tau_{c} V_{f}))}
\]

where \( \dot{Q}, r, T_{c}, \), and \( \lambda \) are the amount of heat transport per unit time, radius, the core temperature, and the thermal conductivity, respectively. Subscripts rad, sc, gs, c and s represent radiative heat loss, heat conduction from insulation to metal core, and heat conduction from a gas phase to insulation, the metal core, and the insulation, respectively. However, in this model, \( T_{c} \) and heat transfer from insulation to core \( \dot{Q}_{sc} \) need to be specified to draw flammability map for electrical wire. This term is strongly affected by the overlap length of the flame and burned core wire (22).

At a longer overlap length \( \dot{Q}_{sc} \) may increase and vice versa. These characteristics suggest that the ordinal control volume in the gas phase pre-heat region is insufficient to explain the heat balance of wire combustion. Therefore, we reconsidered the expanded heat balance with two additional regions: a pyrolysis region and a flame-wire overlap region, as region, as shown in Fig. 5. Subscripts gc heat conduction from gas phase to metal core. The terms \( pr \) and \( py \) following these subscripts represent the pre-heat and pyrolysis regions, whereas \( cc1 \) and \( cc2 \) indicate heat conduction from the burned bare wire core to the pyrolysis region through the wire core and heat conduction from the pyrolysis region to the pre-heat region through the wire core, respectively. In this model, flame spreading at a constant velocity is assumed. When the right edge of the wire core is assumed to be the adiabatic boundary, based on the work done by Hu et al. (22), \( \dot{Q}_{gc} \) and \( \dot{Q}_{cc1} \) can be equated. We also substituted \( \dot{Q}_{sc,pr} = -\dot{Q}_{cc2} \) and \( \dot{Q}_{cc2} = \dot{Q}_{sc,py} + \dot{Q}_{cc2}. \) Finally, the overall heat balance can be expressed by Eq. (4):

\[
\dot{Q}_{gc} + \dot{Q}_{gs,py} + \dot{Q}_{gs,pr} - \dot{Q}_{rad,py} - \dot{Q}_{rad,pr} = \dot{Q}_{req,pr} + \dot{Q}_{req,py}
\]

where \( \dot{Q}_{req,pr} \) and \( \dot{Q}_{req,py} \) are the heat required to maintain pre-heat and pyrolysis length at a steady flame spread velocity of \( V_{f}. \)

We then normalized Eq. (4) by heat input to the pre-heat region, \( \dot{Q}_{gc} + \dot{Q}_{gs,py} + \dot{Q}_{gs,pr} - \dot{Q}_{req,py}, \) following Takahashi’s study for flat plates (31). We obtained the following expression:

\[
R_{rad,wire} = 1 - \eta_{wire}
\]

where

\[
R_{rad,wire} = \frac{\dot{Q}_{rad,py} + \dot{Q}_{rad,pr}}{\dot{Q}_{gc} + \dot{Q}_{gs,py} + \dot{Q}_{gs,pr} - \dot{Q}_{req,py}} \quad \text{and} \quad \eta_{wire} = \frac{\dot{Q}_{req,pr}}{\dot{Q}_{gc} + \dot{Q}_{gs,py} + \dot{Q}_{gs,pr} - \dot{Q}_{req,py}}
\]

are the radiation number for wire and a non-dimensional flame spread velocity, respectively. When \( R_{rad,wire} \) reached unity (or when \( \eta_{wire} \) became zero), the flame was assumed to be extinguished, same as that in the flat-plate case. The observed U-shaped trend can then be explained consistently by Eqs. (1) and (5) as follows.

In regions with a low flow velocity (less than ~100 mm/s in this study), radiative heat loss from the pre-heat region, \( \dot{Q}_{rad,pr}, \)
becomes relatively larger than the heat input from the increase in pre-heat length. Therefore, $R_{rad\_wire}$ becomes larger and then the LOC becomes higher as the flow velocity decreases. In wire combustion, it is expected that the heat input to the wire core, $Q_{gc}$, enhances flammability by decreasing $R_{rad\_wire}$. However, this term may not affect the shape of the LOC trend in the low flow velocity region because flame length does not significantly vary with flow velocity. Instead, $\dot{Q}_{gc}$ may just shift down the LOC curve when the gravity condition changes from $1g_0$ to $\mu g_0$. On the other hand, in the high flow velocity region (more than ~100 mm/s in this study), the effect of blow-off owing to the short residence time becomes dominant according to Eq. (1). Therefore, LOC increases with flow velocity. The LOC trend observed in the $\mu g_0$ experiment is consistently explained by the theory above.

3.3 Comparison of $\Delta$LOC for PE and ETFE

Figure 6 represents the LOC curves for PE (from Takahashi et al. 10) and ETFE under $1g_0$ and $\mu g_0$. The most notable feature of Fig. 6 is the large ALOC of the ETFE. For example, the ALOC at 100 mm/s of external flow velocity was 10% for ETFE compared with 3% for PE. A possible explanation for this difference is the oxygen concentration dependence of the flame temperature. As shown in Section 3.1, when flame spreads under $\mu g_0$, it wraps around and stretches along the burned bare copper core, which has high thermal conductivity. This results in an increase of flame wire overlap length so that $\dot{Q}_{gc}$ is increased under $\mu g_0$ and the net heat input to the pre-heat region becomes larger than that under $1g_0$. We suggest that this difference ($\Delta Q_{in}$) causes $\Delta$LOC. In particular, in the quenching (low flow velocity) region, a decrease in oxygen concentration is needed to cancel the $\Delta Q_{in}$ by a decrease in flame temperature to maintain the net heat input in the pre-heat region (extinction occurs at a certain heat input according to Eq. (5)). The rate of temperature increase with the increase of oxygen concentration is known to become smaller as the oxygen concentration becomes larger, as shown in Fig. 7. This reflects the relation between the adiabatic flame temperature and the oxygen concentration, which is in line with the chemical equilibrium calculation from the NASA equilibrium program (CEA2) 23. As a result, material that has a higher LOC under $1g_0$ (ETFE in this study) requires a larger oxygen concentration drop to achieve the same temperature decrease ($\Delta T_f$). From experimental observations, the downstream flame stretching was much larger for ETFE than for PE. Thus, both $\Delta Q_{in}$ and $\Delta T_f$ of ETFE may be larger than those of PE, which may result in a larger $\Delta$LOC for ETFE than for PE. In addition, if the external flow velocity is high enough to make buoyant flow negligible, the flame shape under $1g_0$ becomes similar to that under $\mu g_0$, and the LOCs should be close to one another (as the $\Delta$LOC becomes smaller). The decrease in $\Delta$LOC with the increase in the flow velocity, observed in Fig. 6, supports this hypothesis.

4. Conclusions

This study investigated the LOC variation, i.e., the flammability boundary, of ETFE at different external flow velocities (0–200 mm/s) under $1g_0$ and $\mu g_0$. Under $\mu g_0$, the LOC curve showed a U-shape, often found in other flammability maps. The MLOC of the ETFE, at approximately 25%, was also observed at external flow velocities ranging 50–100 mm/s. The 25% of MLOC is much lower than ETFE’s LOI value so that it supports its importance of flammability analysis on electrical wiring in $\mu g_0$.

The heat balance model for wire combustion has been developed to duplicate core effect by considering two additional control volumes: the pyrolysis and flame wire overlap regions.
The U-shaped LOC trend for wire samples has been explained by the radiation number in the new model ($R_{rad,wire}$) and the $Da$ from the extinction theory proposed by previous researchers. Core temperature estimation included to this model can be a key of quantitative flammability assessment. A significant large LOC difference between $I_{g0}$ and $\mu_{g0}$ (ΔLOC) was observed; at 100 mm/s of external flow velocity, ΔLOC was approximately 10% for ETFE and it was approximately 3% for PE. This difference has been explained by the relation between the flame temperature and the ambient oxygen concentration. It was predicted that high-LOC materials (which are usually fire-resistant) would have a higher ΔLOC than low-LOC materials such as PE.

The results suggest that flammability is enhanced by changes in gravity, particularly in the case of polymer–metal composites, such as electrical wiring, because of a change in flame shape. Although this research has only provided a qualitative assessment, follow-up studies will contribute to the development of novel fire-safety standards for use in space.

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**References**