JASMAC
Conference of the Japan Society of Microgravity Appllication

OR-0601

熱的に薄い固体材料の可燃限界に及ぼす厚みの影響

Effect of Thickness on Flammability Limit of Thermally –Thin Materials

高橋 周平 1，大岩 力哉 1，所 美鈴 1，小林 芳成 1

Shuhei TAKAHASHI[1], Rikiya OIWA[1], Misuzu TOKORO[1] and Yoshinari KOBAYASHI[1]

1 岐阜大学，Gifu University

1. Introduction

Recently, manned space activities have become more extensive, and it is one of the most important issues to guarantee fire safety in microgravity and planetary habitation environments. The flammability limit of a solid material in opposed flow is one of the major topics concerning fire safety. To discuss the flammability of a material, its limiting oxygen concentration (LOC) is an important measure. In past extensive microgravity study, it has been reported that flammability limit in opposed flow shows U-shaped curve [1, 2] (see Fig. 1) and the thin materials in microgravity environments can burn at lower oxygen concentration than the LOC in normal gravity. Kumar et al. conducted numerical simulations and concluded that the flammability limit of thin materials can extend in slow/mild flow velocity conditions [3]. Takahashi et al. reported that the LOC in microgravity environments can be lower than the LOC for downward spreading flame in normal gravity [4]. Olson et al. investigated the LOC of flame retardant materials in micro/reduced gravity environments and reported that the LOC changed according to the gravity level [5]. Hence, it is important to understanding the trend of LOC change with opposed flow velocity for fire safety in space.

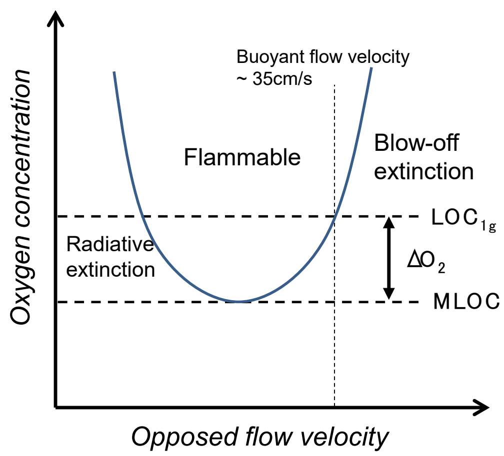


Fig. 1 Flammability map of a solid material in an opposed flow.

Currently, Japan Aerospace Exploration Agency (JAXA) is conducting the FLARE (Flammability Limits At Reduced-g Experiment) project, the orbital flight experiment in the International Space Station, with National Aeronautics and Space Administration (NASA), European Space Agency (ESA) and universities. One of the objectives of the FLARE project is to develop a simplified model for evaluating the limiting oxygen concentration of a thin solid material in microgravity environments to give it as an index for fire safety in space environments. In the FLARE project, we have developed a simplified model and a novel method to predict the flammability limit for thermally-thin material [6-8]. Using the developed method, we predicted the limiting curve for several materials, and had good agreement with experimental results especially for thin materials. Generally, in modeling the energy balance for thermally-thin materials, it is often assumed that the temperature distribution is uniform in depth in the preheat zone of the sample. In such assumption, the LOC is independent of sample thickness. However, in our recent parabolic flight experiments, obvious effect of the sample thickness was observed even in a thermally-thin material. In the present article, we investigated the flammability map of thin Polymethyl methacrylate (PMMA) and polycarbonate (PC) sheets for different sample thickness, respectively, and discuss the effect of the thickness on LOC.

2. Scale analysis of limiting curve

In our developed model, we assumed uniform temperature profile in the solid and derived the following non-dimensional expression of non-dimensional flame spread rate, η [4].

$$\eta + R_{rad} + \frac{1}{Da} = 1 \quad \text{where} \quad \eta = \frac{V_f}{V_{f,th}}. \tag{1}$$

$$R_{rad} = B_2 \frac{\varepsilon(1-a_{abs})\sigma(T_v^4 - T_\infty^4)}{\rho_g c_g V_g (T_f - T_v)} \quad \text{where } B_2 = 4.2. \tag{2}$$

$$Da = \Pr \frac{x_d}{V_g} \rho_g Y_O A^* \exp(-E^*/RT_f) \tag{3}$$

This simplified model could predict the flammability limit of thermally-thin materials quite quantitatively. Both non-dimensional parameters above do not include the valuable describing the sample thickness, τ; this implies that the limiting curve of thermally-thin is independent of sample thickness. However, the result of parabolic flight experiments shows that even though the thickness is considered as thermally-thin, the limiting oxygen concentration increases as the sample thickness increases especially in slow opposed flow condition, as shown in Fig. 2. [9] This trend is similar to that observed when the pyrolysis temperature increases.

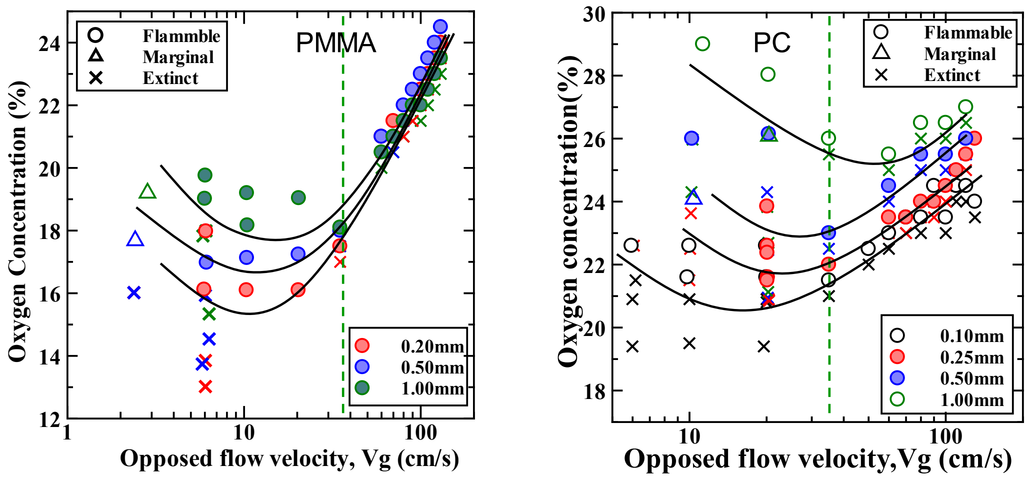


Fig. 2 Flammability map of PMMA and PC wi different sample thickness, respectively.

Hence, we modified our model to express the effect of thickness as follows. Figure 3 shows the details of the solid-phase preheat zone which are heated via conduction driven by the temperature gradient in gas-phase in front of flame. We assumed that the shape of the solid preheat zone as a parallelogram, and focused on the trapezoid zone which is surrounded red dashed line to build heat balance equation. The critical sample thickness that divide thermally-thin regime and thermally-thick regime is expressed as follows [10].

$$\tau_{crit} \sim \frac{\tau V_{f,thin}}{V_{f,thick}} = c_{crit} \frac{\tau V_{f,thin}}{V_{f,thick}} = c_{crit} \frac{\lambda_s}{\lambda_g} \frac{L_g}{F} \tag{4}$$

Assuming linear temperature profile in the solid, the ratio of incomplete heated length to the total preheat zone length, β, is estimated as

$$\beta = \frac{x}{L_g} = \frac{\tau}{\tau_{crit}} = \frac{\rho_g c_g \tau}{c_{crit} \lambda_s} F V_g = f(\tau, \lambda_s, V_g) \qquad (5)$$

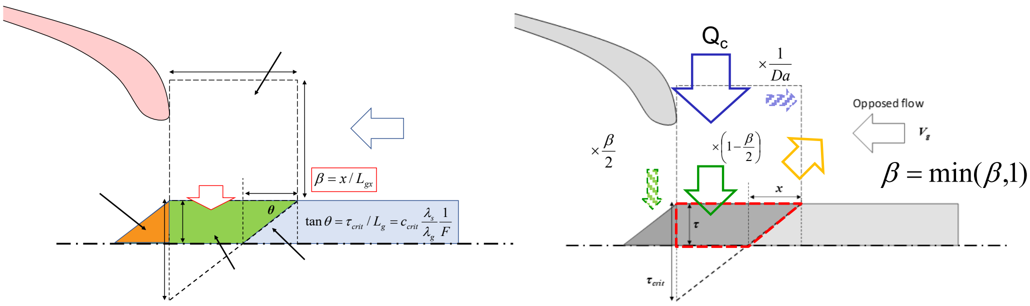


Fig. 3 Heat balance around the inclined solid-preheat zone with taking the incomplete heat penetration into account.

In Eq. 7, the β is a function of solid conductivity, sample half-thickness and ambient gas velocity. We now rewrite the β on the quenching limiting curve, on which the R_{rad} can be regarded as a constant; $R_{rad} = 1$.

$$\beta = \frac{B_2 \varepsilon (1-\alpha) \sigma (T_v^4 - T_\infty^4) F}{c_{crit} \lambda_s (T_v - T_\infty)} \tau = f(\tau, T_v, \lambda_s) \qquad (6)$$

It is found that the β is now the function of sample thickness, pyrolysis temperature and sold conductivity; of solid properties only. With these assumptions, we can modify the heat balance equation with incomplete heat penetration as follows.

$$(1-\beta/2) V_f \rho_s c_s \tau W (T_v - T_\infty) + \varepsilon (1-\alpha_{abs}) \sigma \left(T_v^{\,4} - T_\infty^{\,4}\right) L_g W \sim \left(1 - \frac{1}{Da}\right) \lambda_g \frac{(T_f - T_v)}{L_{gy}} (1-\beta/2) L_{gx} W \qquad (7)$$

The β should be less than unity for thermally-thin material, thus β=min(β, 1), Eq. 7 can be written in non-dimensional form as

$$\eta + \frac{R_{rad}}{1-\beta/2} + \frac{1}{Da} = 1 \quad \text{where} \quad \beta = \min\left(\frac{B_2 \varepsilon (1-\alpha) \sigma (T_v^4 - T_\infty^4) F}{c_{crit} \lambda_s (T_v - T_\infty)} \tau, 1 \right). \qquad (8)$$

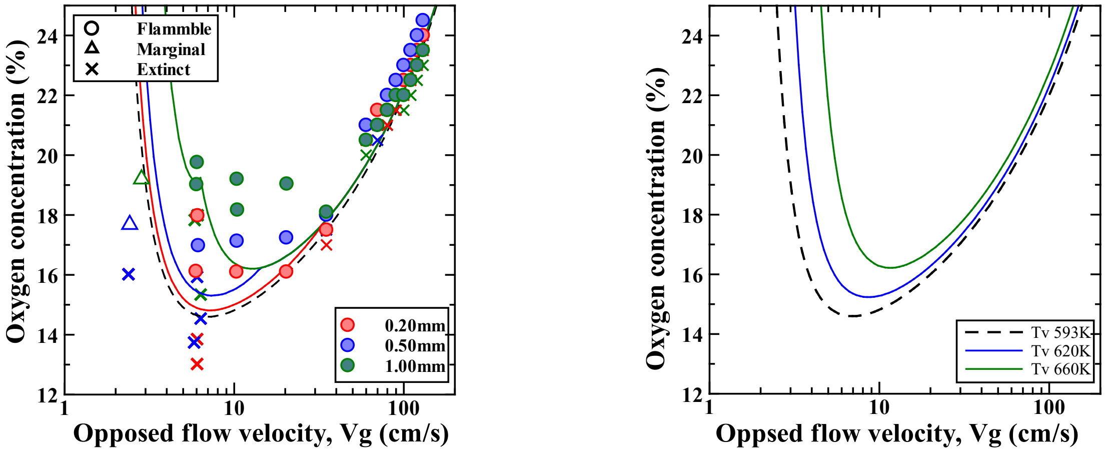
This non-dimensional heat balance equation means that as the sample thickness increases, the radiative heat loss increases relatively, which is consistent the result shown in Fig. 2. We applied the model to PMMA (CLAREX: Nitto Jushi Kogyo) and PC (CARBOGLASS C110C: Asahi Glass) and compared the predicted results with the experimental results. The properties of the materials used are listed in Table 1.

Table 1 Properties of PMMA and PC sheets used in this study.

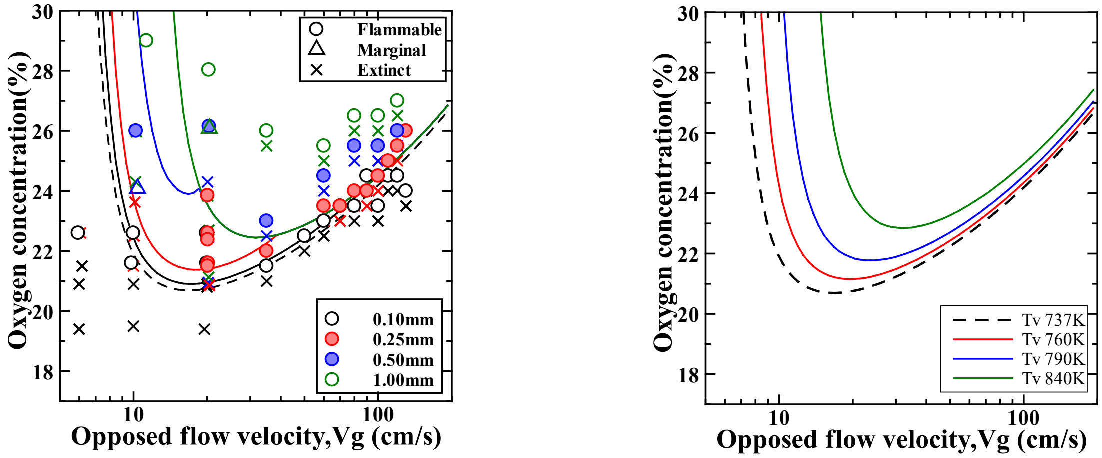
Thermoplastic resin	Thickness (mm)	Tv (K)	Δhc (kJ/g)	Thermal conductivity (W/mK)	LOC1g (%)
PMMA (CLAREX: Nitto Jushi Kogyo)	0.2	593	24.99	0.21	17.5
	0.5				18.0
	1.0				18.0
Polycarbonate (CARBOGLASS C110C: Asahi Glass)	0.1	737	30.32	0.19	21.5
	0.25				22.0
	0.5				23.0
	1.0				25.5

3. Comparison between prediction by β model and experimental results

The predicted limiting curves with the β model are shown in Fig. 4. The predicted curved well represent the increase of limiting oxygen concentration in slow opposed flow condition. The limiting curves with increased pyrolysis temperature, T_v, and original model (Eq. 1) are also shown, and it is found that the effect of sample thickness has similar effect of increased pyrolysis temperature. This means that if the thermal conductivity of the solid under consideration is unknown, reasonable prediction can be obtained as the primary estimation by simply giving increased T_v.

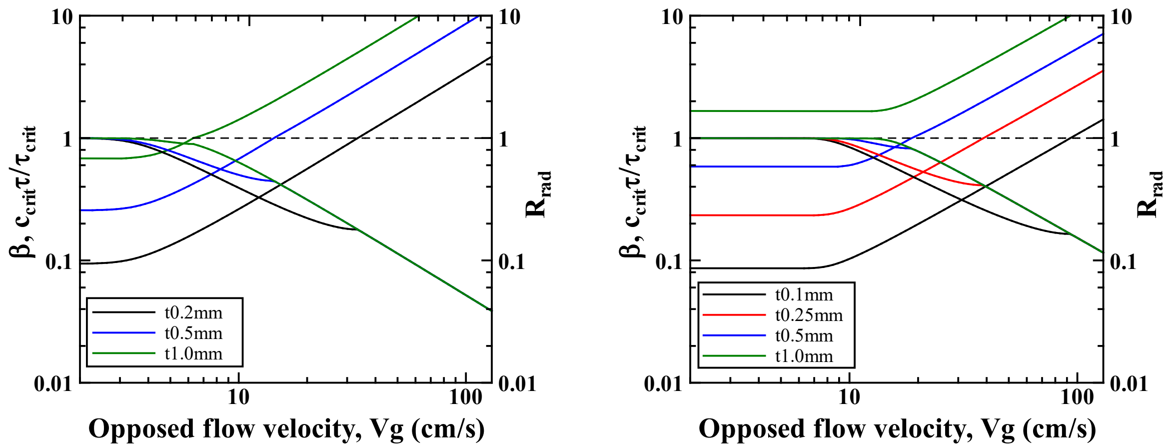


a) Predicted curves with the β model. Predicted curves with increased T_v.



b) Predicted curves with the β model. Predicted curves with increased T_v.

Fig. 4 Predicted limiting curve for a) PMMA and b) PC, respectively.



a) PMMA b) PC

Fig. 5 The values of β and R_{rad} along the limiting curve.

Figure 5 shows the value of β and R_{rad} along the limiting curve. It is found that when the opposed flow velocity is extremely low, the R_{rad} is close to unity and the β is almost constant. As opposed velocity increases, the β also increases, but the value of R_{rad} decreases exponentially, which means the effect of radiative heat loss becomes negligible. For PC of 1.0 mm thickness, the value of β is more than unity even in the slow opposed flow condition. In such case, the sample cannot be regarded as thermally-thin, and this would be the reason why the predicted limiting curve deviated from the experimental result.

4. Conclusions

The flammability limits of thermally-thin materials (PMMA and PC) in opposed flow were investigated with varying sample thickness. Generally, for thermally-thin material, the temperature profile inside the solid is considered to be uniform, and it is expected that the difference in sample thickness does not affect the flammability limit. Nevertheless, the experimental results show that significant difference in limiting oxygen concentration (LOC) exists according to the sample thickness. The thicker the sample is, the larger its minimum limiting oxygen concentration (MLOC) become large. To express this behavior, we modified our simplified model by taking the effect of incomplete heat penetration zone into account. The dimensionless parameter β, which expresses the ratio of incomplete heat penetration zone length to total preheat zone length, was introduced to the heat balance equation. The modified expression implied that the increase in thickness is equivalent to increase in radiative heat loss; thus increase in pyrolysis temperature. This idea could reproduce the trend of LOC in slow flow condition where MLOC is often achieved in microgravity environments.

Acknowledgment

This study was conducted as a part of the FLARE project supported by JAXA. We are also thankful to the staff of Diamond Air Service for their excellent technical support to parabolic flight experiments.

References

1) O. Fujita, Solid combustion research in microgravity as a basis of fire safety in space Proc. Combust. Inst. 35 (2015) 2487-2502.

2) S.L. Olson, P.V. Ferkul, J.S. T'ien, Near-limit flame spread over a thin solid fuel in microgravity, Proc. Combust., 22 (1988) 1213-1222

3) A. Kumar, H. Y. Shih, J. S. T'ien, A comparison of extinction limits and spreading rates in opposed and concurrent spreading flames over thin solids, Combust, Flame 132 (2003) 667-677.

4) 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.

5) S. L. Olson and P. V. Ferkul, Evaluating Material Flammability in Microgravity and Martian Gravity Compared to the NASA Standard Normal Gravity Test, 42nd International Conference on Environmental Systems (ICES), (2012) San Diego, CA, AIAA-2012-3492.

6) S. Takahashi, K. Tsuboi, K. Maruta, Prediction of flammability limit of a thin solid material in microgravity environments, Proc. Interflam 2016, Vol. 1 (2016) 733-738.

7) S. Takahashi, K. Maruta, Limiting oxygen concentration of thin materials in opposed flow under microgravity conditions, Proc. Fire and Materials 2017 Conference (2017) San Francisco, CA,181-194.

8). S. Takahashi, K. Terashima, M.A.F. bin Borhan, Y. Kobayashi. Fire Technology (2019). https://doi.org/10.1007/s10694-019-00880-2.

9) K. Terashima, R. Oiwa, M, Tokoro, Y. Kobayashi, S. Takahashi, Limiting oxygen concentrations of plastic materials with different thickness in opposed flow, JASMAC31 (2019) Sendai, Japan.

10) S. Bhattacharjee, M. D. King, S. Takahashi, T. Nagumo, K. Wakai, Downward Flame Spread over PMMA, Proc. Combust. Inst. 28 (2000) 2891-2897.