Effect of Ambient Gas on Flammability Limit of Flat Materials in Microgravity

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The flammability map of a thin PMMA sheet with an opposed flow in microgravity environment was investigated with varying the thermal properties of the ambient gas. We also developed a new model to predict the limiting oxygen concentration (LOC) in 1g, minimum limiting oxygen concentration (MLOC) and critical opposed flow velocity, V_{cr} , at which MLOC was observed. We compared the predicted results with the experiment results by changing the gas-phase properties to validate the model. As the balance gas, nitrogen, carbon dioxide, and argon were used. It was found by experiment that LOC, MLOC, and V_{cr} significantly changed for each balance gas. These differences were reasonably predicted by the scale analysis which included the effects of radiation and kinetics on the suppression of the flame spread.

Key Words: Flame Spread, Flammability Map, Ambient Gas, Microgravity

Nomenclature

A	: Pre-exponential factor
a_{abs}	: Absorption coefficient of gas
c_g	: Specific heat of gas
c_s	: Specific heat of solid
Da	: Damkohler number
E	: Activation energy
Δhr	: Combustion heat
L_g	: Gas-phase diffusion length scale
L_{sx}	: Length of the preheated solid phase
L_{sy}	: Thickness of the preheated layer
R	: Gas constant
R_{rad}	: Radiation loss number
T_f	: Characteristic (adiabatic) flame temperature
T_v	: Constant pyrolysis temperature
T_∞	: Ambient temperature
t_{res}	: Residence time
t_{chem}	: Characteristic chemical time
V_g	: Ambient flow velocity
V_f	: Flame spread rate
$V_{f,th}$	: Flame spread rate in thermal regime
V_r	: Velocity relative to the flame, $V_r = V_g + V_f$
W	: Width of the fuel in z-direction
Y_o	: Oxygen mass fraction of the surrounding
α_g	: Thermal diffusivity of gas, evaluated at T_v
ε	: Surface emissivity
λ_g	: Gas-phase conductivity evaluated at T_v
η	: Non-dimensional spread rate, $\eta = V_{fl} V_{f,th}$
ρ_g	: Gas density evaluated at T_v
ρ_s	: Solid density
σ	: Stefan-Boltzmann constant
τ	: Fuel half-thickness

ω : Chemical reaction rate

1. Introduction

For space development, recently, human activity in space such as the International Space Station (ISS) has increased. Because fire is very dangerous, knowing the characteristics of the flame in space is very important. One of the most characteristic features of microgravity environment is the absence of buoyant flow that exists as natural convection (30~40cm/s) in normal gravity.

Until now, many flammability tests such as NASA STD-6001¹⁾ and ISO-4589-2 have been conducted in normal gravity. On the other hand, in the previous researches,²⁻⁶⁾ it was found that flame can exist in lower oxygen concentration with lower opposed flow velocity than natural convection. Therefore, there may remain fire hazard in some conditions to use NASA STD-6001 as flammability standard in microgravity environments.

Hence, we developed a simplified model⁷⁾ that can predict the difference between the flammability limit of a thin material in normal gravity and microgravity environment. The schematic of typical flammability map of a solid material with an opposed flow is shown in Fig. 1. The horizontal axis shows the forced opposed flow velocity relative to the flame on the solid material. In this paper, we define limiting oxygen concentration (LOC) and the minimum limiting oxygen concentration (MLOC) as important indexes of the material. The LOC is an index which can be obtained by ground-based flammability test. In order to find the LOC, we set up a solid thin sample vertically, ignite it at the top end and observe the flame spread with varying the ambient oxygen concentration. The LOC is defined as the minimum oxygen concentration in which steady downward spread achieved. The MLOC is an

index which indicates the measure of flammability of the material in microgravity environments. In order to find the MLOC, we observe the flame spread in parabolic flights with varying the opposed flow velocity and the oxygen concentration. The MLOC is defined as the minimum oxygen concentration among the all experimental conditions in which steady flame spread is achieved. We also defined the critical opposed velocity, V_{cr} , at which the MLOC is

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

Fig. 2. Schematic of experimental apparatus for parabolic flight.

observed. It is easy to find the LOC of a certain material by ground-based tests, but it takes large cost and time to obtain the MLOC of the material. Hence, it is advantageous if the MLOC can be predicted from the LOC and other properties which can be obtained in normal gravity condition. Thus, our final objective is to predict the flammability limit in microgravity environments from ground-based data, such as the LOC or Limiting Oxygen Index (LOI) in ISO 4589-2 using the developed simplified model. Because there are many data of flammability of materials in normal gravity tests, the model will be a useful tool to confirm the flammability of materials in space.

In this article, to validate the developed model, we investigated the flammability of a PMMA film with changing the thermal properties of the ambient gas. Then, we compared the results predicted by the model with the experimental results, and discussed the effect of the difference in the properties of ambient gas.

2. Experimental Setup

Figure 2 shows the experimental apparatus. The sample used in this experiment was a thermally thin PMMA sheet (Acrylen: Mitsubishi Rayon Co., Ltd.) with a thickness of 0.125 mm. The PMMA sample, which was 8 cm in length and 2 cm in width, was set vertically in a closed chamber of volume 35 L. The sample was ignited at the end of the downstream side with an electrically heated Ni-Cr wire, and then the flame propagated upstream. The chamber had a suction fan for creating a flow ranging from 0 to 20 cm/s in the test section. The dimensions of the test section were 14cm×14cm×13cm, and honeycomb plates were installed on both the upstream side and the downstream side of the test section. Molecular sieves and zeolites were packed inside the test chamber to absorb the water and carbon dioxide generated during the combustion process. For the CO₂ balance condition, we replaced the molecular sieves with glass beads. A pressure transducer, a thermocouple, and an oxygen sensor were also installed to monitor the pressure, temperature, and oxygen concentration, respectively.

The flame spread behavior was recorded with a visible CCD camera and an IR camera to obtain the spread rate and the length of the preheat zone on the PMMA sheet, respectively. The spread rate V_f was defined as the average spread rate in 5 seconds. The oxygen level and the balance of the ambient gas were varied as parameters. We choose nitrogen (N₂), argon (Ar) and carbon dioxide (CO₂) for the balances to change thermal properties of the ambient gas (see Table 1).

In the normal gravity test to obtain the LOC, we set the apparatus vertically so that flame spread downward direction. In order to obtain the MLOC in a microgravity environment, we then conducted 20-s parabolic flight experiments by Diamond Air Service (DAS). The downstream end of the sample was ignited by the Ni-Cr wire 10 s before the onset of microgravity. When the initial oxygen concentration was lower than the LOC, we could not ignite the sample before the

Table 1. Properties of balance gases at 300K and 1atm.

	C_p [J/mol K]	λ_g [W/m K]	α_g [mm ² /s]	a_{abs}
N ₂	29.06	0.0249	21.1	0.0
CO ₂	37.20	0.0164	10.9	0.6
Ar	20.78	0.0178	21.1	0.0

Fig. 3. Schematic of the 2D flame for scale analysis.

onset of microgravity. Hence, under such conditions, we ignited the sample at the onset of microgravity.

3. Scale Analysis

In order to discuss the impact of the parameters concerning with the flame spread, scale analysis^{8, 9)} was developed for two-dimensional flame spread over a solid material. The schematic of the flame front is shown in Fig. 3.

The heat balance in the preheat zone with low opposed flow is expressed by the following equation.

$$V_f \rho_s c_s L_{sy} W (T_v - T_\infty) + Q_{rad} = \lambda_g \frac{(T_f - T_v)}{L_{gy}} L_{gx} W \quad (1)$$

where $Q_{rad} = \varepsilon(1 - a_{abs})\sigma(T_v^4 - T_\infty^4)L_{sx}W$.

This equation means that the heat conduction due to the temperature gradient in the preheat zone balances the sum of the heat to preheat the solid material and the heat emitted from the heated surface to the surroundings by radiation.

In the thermal regime, the radiation term is negligible and the spread rate is derived as Eq. (2).¹⁰⁾

$$V_{f,th} \sim \frac{\lambda_g}{\rho_s c_s \tau} \frac{T_f - T_v}{T_v - T_\infty} \quad (2)$$

Introducing the non-dimensional spread rate, $\eta = V_f/V_{f,th}$, which is shown in Fig. 1, Eq. (1) can be reduced to the following non-dimensional equation.

$$\eta + R_{rad} = 1 \quad \text{where} \quad R_{rad} \sim \frac{\varepsilon(1 - a_{abs})\sigma(T_v^4 - T_\infty^4)}{\rho_g c_g V_r (T_f - T_v)} \quad (3)$$

Eq. (3) means that if R_{rad} approaches unity, η approaches zero; thus, radiative extinction occurs. It is found that R_{rad} becomes larger as the relative opposed-flow V_g becomes smaller. Therefore, if the opposed-flow velocity V_g is small enough that R_{rad} is close to 1, the regime changes to the microgravity regime.

On the other hand, if the opposed-flow velocity V_g is much higher, the regime changes to the kinetic regime. The ratio of

the residence time to the characteristic chemical time is defined as Damkohler number, expressed in Eq. (4).

$$t_{res} \equiv L_g / V_r, \quad t_{chem} \equiv \rho_g / \dot{\omega} = [\rho_g Y_O A \exp(-E / RT_f)]^{-1}$$

$$Da \equiv \frac{t_{res}}{t_{chem}} \sim \frac{\alpha_g}{V_r^2} \rho_g Y_O A \exp(-E / RT_f) \quad (4)$$

The Da also represents the ratio of heat needed to sustain gas-phase reaction to the total heat in the preheat zone.

$$Da \equiv \frac{t_{res}}{t_{chem}} \sim \frac{L_g / V_r}{\rho_g / \dot{\omega}} = \frac{L_g^2 W \dot{\omega} \Delta h_r}{\rho_g c_g L_g W V_r (T_f - T_v)}$$

Therefore, we assumed that the conduction heat from the flame to the solid is reduced by the factor of $(1 - 1/Da)$. Thus, we obtained Eq. (5) to express the effect of Da on flame spread rate with high opposed flow.

$$V_f \rho_s c_s L_{sy} W (T_v - T_\infty) = \left(1 - \frac{1}{Da}\right) \lambda_g \frac{(T_f - T_v)}{L_{gy}} L_{gx} W \quad (5)$$

Using the two non-dimensional factors R_{rad} and Da, we could draw the flammability map in Fig. 3 that the vertical line shows oxygen level and the horizontal one opposed flow velocity. However, the effects of both R_{rad} and Da suppress the flame spread near the flammability limit. Therefore, we combined two non dimensional factors and obtained Eq. (6).

$$\eta + R_{rad} + \frac{1}{Da} = 1 \quad (6)$$

Using this equation, U-shape curve of the flammability limit like as shown in Fig. 1 can be obtained. The model predicts that the limiting oxygen concentration shows its minimum value at a certain opposed flow velocity. We found the minimum oxygen concentration (MLOC) and the critical flow velocity, V_{cr} , where MLOC is achieved from the predicted map. Then we compared these values with the experimental results by parabolic flight.

4. Results and Discussion

Figure 4 shows the flammability map with N₂ balance obtained by the parabolic flight experiments. The solid circle means that the flame survived until the end of the microgravity environment. The cross means that ignition failed or extinction occurred until the end of the microgravity environment. Further, the results of downward spread tests conducted in normal gravity are plotted on the flammability map as open circles assuming that the buoyant flow velocity is 35 cm/s. The number beside the symbol expresses the flame spread rate calculated by observing the flame spread distance for 5 seconds during microgravity environment.

In N₂ balance, we could observe the flame spread below the LOC. The extinction limit oxygen concentration in the normal gravity was 17%, whereas that in the microgravity was 14.7%, which was 2.3% lower. However, the MLOC predicted by the model was 13%, which was 1.7% lower than experiment results. Therefore, the simplified model underestimated the flammability limit. The developed model can predict the critical flow velocity, V_{cr} , at which the flame spread becomes

most robust. In nitrogen balance, the V_{cr} was expected near 8cm/s as shown in Fig. 4. Then, we draw curve of the spread rate versus opposed flow at several oxygen levels near MLOC in Fig. 5. In order to plot the spread rate at a certain oxygen concentration, we calculate the spread rate by an interpolation method as follows. If there are spread rate data at $y1\%$ oxygen concentration and $y2\%$ oxygen concentration, we calculate the flame spread rate at $x\%$ which is between $y1\%$ and $y2\%$ ($y1 < x < y2$) as

$$V_{f,x} = \frac{(y2-x)V_{f,y1} + (x-y1)V_{f,y2}}{y2-y1} \quad (7)$$

In N_2 balance, the maximum spread rate was observed at V_g of 10cm/s, which was close to the predicted value.

In CO_2 balance, the LOC was higher than that in N_2 balance, because flame temperature became lower than that in N_2 balance and Damkohler number decreased. The obtained results are shown in Figs. 6 and 7. This is due to the difference of C_p (shown in Table 1). Additionally, the MLOC, V_{cr} was different from that in N_2 balance because there is significant effect of re-absorption of radiative energy¹¹⁾ in CO_2 balance and the radiation limit curve shifted to lower opposed velocity side. From the above reasons, ΔO_2 value was larger than that

in N_2 balance. We could observe the flame spread below the LOC. The extinction limit oxygen concentration in the normal gravity was 24.3%, whereas that in the microgravity was 19.2%, which was 5.1% lower. However, the MLOC predicted by the model was 15.4%, which was 3.8% lower than experiment results. Therefore, the simplified model underestimated the flammability limit. However, the trend of the ΔO_2 value in CO_2 balance being much larger than that in N_2 balance agreed with the prediction. In CO_2 balance, the maximum spread rate was observed at V_g of 10cm/s at relatively high oxygen level. However, it shifted lower velocity region as it approaches the MLOC. This result agreed with the prediction that the critical V_{cr} of CO_2 balance is smaller than other balance gas.

In Ar balance, the LOC was lower than that in N_2 balance, because flame temperature became higher than N_2 balance and Damkohler number increased. The obtained results are shown in Figs. 8 and 9. This is the same reason as that mentioned earlier in CO_2 balance. Therefore ΔO_2 value was smaller than that in N_2 balance. We could observe the flame spread below the LOC. The extinction limit oxygen concentration in the normal gravity was 12.9%, whereas that in the microgravity was 11.6%, which was 1.3% lower. However, the MLOC

Fig. 4. Flammability map in N_2 diluent.

Fig. 5. Flame spread rate vs. opposed flow velocity in N_2 diluent.

Fig. 6. Flammability map in CO_2 diluent.

Fig. 7. Flame spread rate vs. opposed flow velocity in CO_2 diluent.

predicted by the model was 9.2%, which was 2.4% lower than experiment results. Therefore, the simplified model underestimated the flammability limit. However, the trend of the ΔO_2 value in Ar balance being much smaller than that in the N_2 balance agreed with the prediction. The observed V_{cr} was near 9cm/s, which agreed with the predicted value by the model.

Figure 10 shows the preheat zone taken by IR camera. It was found that the preheat zone length increases with the decrease

of opposed flow velocity. This is because the preheat zone length is inversely proportional to the opposed flow velocity ($L_g = \alpha/V_g$). In CO_2 balance, the preheat zone length is much smaller than those in N_2 balance. This is because the thermal diffusivity of CO_2 is smaller than N_2 . These were consistent with the prediction by scale analysis.

The obtained results are summarized in Table 2. From these results, it was found that the simplified model underestimated the MLOC in all balance gas conditions. It is thought that the

Fig. 8. Flammability map in Ar diluent.

Fig. 9. Flame spread rate vs. opposed flow velocity in Ar diluent.

Fig. 10. Comparison between the preheat zone length of the solid phase in each balance gas condition.

reason of the discrepancy is as follows. In the model, we assume that the extinction occurs at $\eta=0$, that is, the breakdown of the heat balance is only the cause of extinction. However, this criteria is very strong, and there are several results^{5, 12)} that the extinction occurs at $\eta \sim 0.2-0.5$ not $\eta=0$. Therefore, for more accurate prediction, the model needs some modification for the treatment of η . However, the model gives safe side predictions and it would be a useful expression to give fire criteria of materials in space.

Table 2. Comparison between LOC and MLOC, and critical opposed flow velocity, V_{cr} for each balance gas.

Balance gas		N ₂	CO ₂	Ar
LOC	Predicted	17.0%	24.0%	12.0%
	Measured	17.0%	24.3%	12.9%
MLOC	Predicted	13.0%	15.4%	9.2%
	Measured	14.7%	19.2%	11.6%
ΔO_2	Predicted	-4%	-8.6%	-2.8%
	Measured	-2.3%	-5.1%	-1.3%
V_{cr}	Predicted	8 cm/s	3 cm/s	9cm/s
	Measured	10 cm/s	2-6cm/s	9cm/s

5. Conclusions

We conducted parabolic flight experiments using three balance gases to investigate the accuracy of the developed model. In all balance gases, it was found that limiting oxygen concentration in microgravity was lower than that in normal gravity. The ΔO_2 in CO₂ balance was the largest value. On the other hand, the ΔO_2 in Ar balance was the smallest value. These were consistent with results expected from the developed model. It was also found that the developed model can predict the critical flow velocity at which the flame spread

becomes most intensive. On the other hand, the developed model underestimated the MLOC with using the strong extinction criteria, $\eta=0$, but it is safe side discrepancy and the predicted values can work as the fire safety limits in space.

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