Behavior of Flame Spread on Thin PMMA near Extinction Limit at Low Oxygen Level

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1. Introduction

The downward flame spread rate and limiting oxygen index (LOI) were investigated with varying oxygen level in normal gravity. Four kinds of diluents, nitrogen, argon, helium and carbon dioxide were used to change the thermal properties of the ambient gas. In order to clarify the impact of the properties on spread rate, simple scale analysis was developed for two-dimensional flame spread. The scale analysis predicted strong dependence of LOI on the flame temperature and the predicted LOIs agreed with the measured LOIs; the Damkohler number is the important factor for LOI of the downward spread. In the microgravity experiment, the flame spread rate was measured with varying opposed flow velocity at 18% oxygen level. The faster flame spread than that in normal gravity condition was observed when the opposed flow was about 15 cm/s, which was consistent with the regime map predicted by the scale analysis.

Key Words: Flame Spread, Extinction, Limiting Oxygen Index, Microgravity

Nomenclature

\( A \) Pre-exponential factor
\( a_{abs} \) Absorption coefficient of gas
\( c_g \) Specific heat of gas
\( c_s \) Specific heat of solid
\( E \) Activation energy
\( L_{gx} \) Gas-phase diffusion length scale in x-direction
\( L_{gy} \) Gas-phase diffusion length scale in y-direction
\( L_{sx} \) Length of the preheated solid phase
\( L_{sy} \) Thickness of the preheated layer
\( R_{rad} \) Radiation loss number
\( R_{side} \) Side loss number
\( T_f \) Characteristic (adiabatic) flame temperature
\( T_v \) Constant vaporization temperature
\( T_w \) Ambient temperature
\( V_g \) 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
\( \alpha_g \) Thermal diffusivity of gas, evaluated at \( T_v \)
\( \varepsilon \) Surface emissivity
\( \lambda_g \) Gas-phase conductivity evaluated at \( T_v \)
\( \lambda_s \) Solid-phase conductivity
\( \eta \) Non-dimensional spread rate
\( \rho_g \) Gas density evaluated at \( T_v \)
\( \rho_s \) Solid density
\( \tau \) Fuel half-thickness

The flame spread over a thermally thin material in microgravity has been studied for the last several decades\(^1\) to \(^4\). The characteristics of the flame spread in microgravity are very low ambient flow velocity around the flame and very weak flame due to large radiative heat loss and insufficient oxygen diffusion. In our previous researches, it was found that the preheat zone in front of the flame became large with decrease of the opposed flow velocity. The large preheat zone increased the radiative heat transfer from the heated solid surface to the surroundings, which eventually caused extinction. Therefore, the flame spread at mild flow velocity has been considered safer than that in normal gravity where the buoyant flow exists. On the other hand, the extinction does not occur only in slow ambient flow conditions.

Figure 1 shows the normalized flame spread rate on a filter paper with varying opposed flow velocity in several oxygen levels calculated in our previous research\(^5\). The flame spread rate is normalized with the maximum spread rate in each condition. The spread rate decreases in either condition where the ambient flow is fast or slow. When the opposed flow velocity is large, the residence time of the combustible mixture in the preheat zone is comparable to the characteristic time of chemical reaction, that finally leads to blow-off. Therefore, the flame spread rate phenomena are categorized into three regimes\(^6\). One is “Thermal regime” where the flame spread does not suffer from any major suppressing factor. The rests are “Microgravity regime” and “Kinetic regime” in which the radiative heat loss and the finite chemical reaction rate suppress the flame spread, respectively.
regime. However, when the oxygen level decreases, the kinetic regime shifts to the lower ambient velocity due to lower flame temperature, and the microgravity regime and kinetic regime merge eventually.

In this study, we investigated the downward flame spread at low oxygen level in normal gravity with varying the thermal properties of the ambient gas, and measured the limiting oxygen index (LOI). Then, we carried out drop experiments to clarify the characteristics of the flame spread in slow ambient flow and low oxygen level conditions. We also developed the scale analysis to discuss the important factors that determined the extinction limit in low oxygen condition.

2. Experimental Setup

The downward flame spread was measure in the constant volume vessel of 7 liter. The sample is a poly-methyl-methacrylate (PMMA) film whose thickness is 125 micron. The length of the sample is 80mm, and the width was changes as 20mm, 10mm and 5mm, respectively. The sample was set vertically with the sample holder in the vessel, and ignited at the top end by an electrically heated Ni-Cr wire. The flame spread was recorded with the CCD camera and the spread rate was measured from the images.

In order to discuss the impact of the parameters concerning with the flame spread, scale analysis was developed for two-dimensional flame spread over a solid material. The schematic of the flame front is shown in Fig. 3. If the sample is thermally thin, the lengths of the preheat zone were varied as parameters. We choose nitrogen (N$_2$), helium (He), argon (Ar) and carbon dioxide (CO$_2$) for the diluents to change thermal properties of the ambient gas (see Table 1).

![Fig. 2. Schematic of the wind tunnel for drop experiments.](image)

![Fig. 3. Schematic of the 2D flame for scale analysis.](image)

3. Scale Analysis

In order to discuss the impact of the parameters concerning with the flame spread, scale analysis was developed for two-dimensional flame spread over a solid material. The schematic of the flame front is shown in Fig. 3. If the sample is thermally thin, the lengths of the preheat zone were estimated as follows;

\[ L_{sa} = L_{gs} = L_{gy} \sim \frac{a_g}{V_r} \quad \text{and} \quad L_{rg} = r. \]

The heat balance in the preheat zone is expressed by the following equation.

\[ V_f \rho_c L_{rg} W (T_e - T_s) + Q_{rad} = \lambda_s \left( \frac{T_s}{L_{gy}} - \frac{T_e}{L_{gy}} \right) L_{gy} W \]  

(1)

where \( Q_{rad} = \varepsilon (1 - a_d) \sigma (T_e^4 - T_s^4) L_{gy} W \).

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. The absorption coefficient, \( a_d \), affects the re-absorption phenomenon of the emitted radiation energy from the solid preheat zone. If the large part of the emitted energy is re-absorbed within the gas-phase preheat zone, the emitted energy is not counted as heat loss because it is used to sustain
the temperature of gas-phase preheat zone. For N₂, Ar and He balance conditions, the \( a_{\text{abs}} \) is assumed to be zero, whereas it is estimated to become 0.8 for CO₂ balance condition. In the thermal regime, the radiation term is negligible and the spread rate is derived as Eq. (2). This equation is identical with the formula of de Ris except the constant \( b \).

\[
V_{f,th} = \frac{\Delta g}{\rho_c c_f T_f - T_a} \]

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.

\[
\eta + R_{\text{rad}} = 1 \quad \text{where} \quad R_{\text{rad}} = \frac{\varepsilon(1-a_{\text{abs}})\sigma(T_t^4-T_a^4)}{\rho_g c_v V_f(T_t-T_a)} (3)
\]

It is found that the radiation term, \( R_{\text{rad}} \), can be eliminated if the opposed flow velocity is large. Equation 3 means that if the magnitude of \( R_{\text{rad}} \) is close to unity, the flame spread shifts to microgravity regime.

The condition to hold the thermal regime is that the chemical reaction is sufficient fast compared with the residence time of the combustible mixture in the preheat zone. The ratio of the residence time to the characteristic chemical time is defined as Damkohler number \( Da \).

\[
t_{\text{res}} = L_e/V_f, \quad t_{\text{chem}} = \frac{\rho_e}{\dot{\omega}} = \frac{\rho_e Y_\alpha A \exp(-E/RT_f)}{V_f} \]

\[
Da = \frac{t_{\text{res}}}{t_{\text{chem}}} = \frac{\alpha_e}{V_f} \frac{\rho_e Y_\alpha A \exp(-E/RT_f)}{V_f} (4)
\]

If the magnitude of the \( Da \) is close to unity, the flame spread shifts to the kinetic regime. The Damkohler number is strongly affected by the flame temperature, so that the kinetic regime can emerge in slow ambient flow condition at low oxygen level. The properties of PMMA used for evaluation of the non-dimensional numbers are listed in Table 2. The properties of the ambient gas were calculated by the theoretical equations.

<table>
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<th>Table 2. Properties of PMMA used for the scale analysis.</th>
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4. Results and Discussions

The downward spread rate in normal gravity was measured with varying the oxygen level. The results for each balance gas and sample width (\( W \)) are shown in Fig. 4. The spread rate decreased with the decrease of the oxygen level, and the extinction occurred eventually. The limiting oxygen index (LOI) was defined as the oxygen level where the extinction was observed. The LOI was the lowest in Ar balance (12%), that in N₂ balance followed (17.5%) and that in CO₂ balance was the highest (24%). The LOI increased with the decrease
of the specific heat of the ambient gas, and this trend was independent of the sample width. The extinction is expected to be caused by the buoyant flow, so that the $Da$ is the important factor of the LOIs in normal gravity. The observed trend can be explained by the change of the $Da$ in Eq. (4). The $Da$ calculated with varying the oxygen level at $V_g=40\text{ cm/s}$ is calculated in Fig. 5. The oxygen level at which the $Da$ becomes unity agrees with the obtained LOI qualitatively. In He balance, however, the LOI depended on sample width, which was not consistent with the prediction. When the sample width was narrow, the LOI became larger. Additionally, the observed LOI was larger than the prediction shown in Fig. 5. This result is caused by three-dimensional effect due to large thermal diffusivity of helium \cite{11}. In our previous research, the non-dimensional heat transfer toward side direction, $R_{side}$, was expressed as Eq. (5).

$$R_{side} \sim \left( \frac{\alpha}{V/W} \right)^2 \frac{T_f - T_w}{T_f - T_w}$$  \hspace{1cm} (5)$$

If the sample width ($W$) is wide enough, the $R_{side}$ is negligible. The result that LOI is independent of the sample width in Ar, N$_2$ and CO$_2$ balances means that the sample width for those conditions are sufficient large to assume two-dimensional flame. On the other hand, in He balance, the thermal diffusivity of the ambient gas was about 3.4 times larger than that in N$_2$ balance at the oxygen level of 21%, for example. Therefore, the $R_{side}$ becomes more than 10 times and the sample width used in this experiment is not regarded as sufficient large.

In microgravity condition, the flame spread rates at the oxygen level of 30% and 18% were measured with varying the opposed flow velocity. The diluent was nitrogen in all drop experiments. The obtained spread rates are shown in Fig. 6. When the oxygen level is 30%, the flame temperature is high enough to guarantee fast chemical reaction. Therefore, the flame spread is in the thermal regime if the opposed flow velocity is near the buoyant flow velocity, which is about 40 cm/s. The spread rate decreases monotonically with the decrease of opposed flow velocity, which means that the flame spread is suppressed due to the radiation heat loss. On the other hand, at 18% oxygen level, the spread rate does not decrease monotonically. With decreasing the opposed flow velocity, the spread rate slightly increases and then decreases, that is, it has a peak around $V_g=15\text{ cm/s}$. As expected by the result shown in Fig. 5, when
the oxygen level is low, the kinetic regime expands to the slower velocity area than the buoyant flow. The oxygen level of 18% is very close to the LOI, which is 17.5%, therefore, it is expected that the flame spread is in the kinetic regime around \( V_g = 30 \text{ cm/s} \). In such a condition, the suppression effect due to the radiation heat loss and the enhancing effect due to increase of the Damkohler number compete. Consequently, the robust flame can exist in slow ambient flow conditions.

Figure 7 shows the regime map predicted by the \( R_{rad} \) and the \( Da \) calculated with Eq. (3) and Eq. (4). This figure predicts the presence of flame spread at quite low oxygen level, which is lower than the LOI of the normal gravity condition. Moreover, it predicts the extinction at very high oxygen level near a quiescent condition. The similar phenomena have been calculated and observed in the other researches [12, 13]. The conditions of the drop experiment are also shown in Fig. 7. At 30% \( O_2 \) level, the experimental condition moved from the thermal regime to the microgravity regime with decreasing the opposed flow velocity. At 18% \( O_2 \) level, the condition moved from the kinetic regime to the thermal regime, and then to the microgravity regime with decreasing the opposed flow velocity. The trend of the flame spread rate by drop experiments agrees with the map obtained from simple scale analysis, and it is found that the scale analysis can be the useful tool to explore the regime mapping.

5. Concluding Remarks

The downward flame spread over a thin PMMA film in normal gravity at low oxygen level was investigated and the limiting oxygen index (LOI) was measured in \( N_2, Ar, He \) and \( CO_2 \) balance conditions, respectively. In order to clarify the effect of the thermal properties of the ambient gas on the LOI, simple scale analysis for the two-dimensional flame spread was developed. The measured LOI for each diluent condition agreed with the prediction by the scale analysis. The LOI was strongly affected by the flame temperature in principle; the LOIs for \( Ar, N_2 \) and \( CO_2 \) balance were 12%, 17.5% and 24%, respectively. The LOIs are well agreed with the prediction by using the Damkohler number \( (Da) \) of the scale analysis.

In He balance condition, however, the flame was influenced by the three-dimensional effect, which led to extinction at higher oxygen level than predicted. In microgravity, the flame spread rates with varying the opposed flow at 30% and 18% oxygen levels were investigated and compared. When the oxygen level was 30%, the spread rate decreased monotonically with the decrease of the opposed flow velocity; the flame spread was suppressed by the radiation loss. At 18% oxygen level, the spread rate had the maximum with decreasing the opposed flow velocity and robust flame was observed at low opposed flow velocity. The regime mapping by using the non-dimensional numbers, \( R_{rad} \) and \( Da \), of the scale analysis predicted the presence of this robust flame in slow opposed flow.

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References