Effect of Sample Width on Flame Spread Rate over a Thin Material in Microgravity

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The effect of the sample width on the flame spread rate over a thin PMMA film in microgravity has been investigated by experiments and scale analysis. The oxygen level of the ambient gas is kept fixed at 30% while different diluents - N₂, Ar, He, and CO₂ - are used. The sample width is also used as a parameter, varying through 5mm, 10mm, and 20mm. When helium is used as the diluent, the conductive heat loss to the sides becomes large, and therefore, the flame is suppressed with a significant drop in the flame spread rate and flame size, especially at low oxygen level and for narrow sample widths. For other diluents, the radiative loss is the dominant factor for the suppression, and the sample width has small impact. These experimental findings can be explained with the scale analysis.

Key Words: Flame spread, Extinction, PMMA, Microgravity

Nomenclature

a_{abs}	Absorption coefficient of gas
c_g	Specific heat of gas
c_s	Specific heat of solid
F	Flame constant, Eq. (1)
L_g	Gas-phase diffusion length scale
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_{loss}	Total heat loss number, $R_{loss}=R_{rad}+R_{side}$
R_{rad}	Radiation loss number, Eq. (2)
R_{side}	Side loss number, Eq. (3)
T_f	Characteristic (adiabatic) flame temperature
T_v	Constant vaporization temperature
T_∞	Ambient temperature
V_g	Ambient flow velocity
$V_{g,cr}$	Critical ambient flow velocity
V_f	Absolute spread rate
V_r	Velocity relative to the flame, $V_r=V_g+V_f$
W	Width of the fuel in z-direction
α_g	Thermal diffusivity of gas, evaluated at T_v
α_s	Thermal diffusivity of solid
ε	Surface emissivity
λ_g	Gas-phase conductivity evaluated at T_v
λ_s	Solid-phase conductivity
η	Non-dimensional spread rate, Eq. (4)
ρ_g	Gas density evaluated at T_v
ρ_s	Solid density
τ	Fuel half-thickness

1. Introduction

Many studies that have been carried out on flame spread

phenomenon over a solid material in microgravity reveal that the flame spread is quite different from those in normal gravity especially with very slow ambient flow¹⁻⁶⁾. In such a situation, the flame becomes very weak, and it is thought that this weakness is due to radiative heat loss⁷⁻⁹⁾ and insufficient supply of oxygen¹⁰⁾. The lower the ambient flow velocity is, the larger the flame characteristic length, namely the preheat zone length, becomes. The enlarged preheat zone increases the ratio of the radiative loss to the heat conduction to the solid phase, which leads to a reduction in flame spread rate and, eventually, extinction when the conduction to the solid is insufficient to raise the fuel temperature to its vaporization temperature.

In previous publications, we have discussed the heat balance in the microgravity regime using a scale analysis, which can give insight for estimating the impact of factors that affect the spread rate, such as the ambient flow velocity, the thermal properties of the gas and the solid, the fuel geometry, and so on^{11,12)}. In this article, we present the impact of the sample width¹³⁻¹⁵⁾ on the spread rate by measuring the spread rate over a thin PMMA film in microgravity while varying the ambient velocity, the diluent gas, and the width of the fuel sample.

2. Experimental Setup

Figure 1 shows the experimental apparatus and the set up of the interferometer to measure the spread rate and the flame scales. The volume of the closed-type wind tunnel is 7000 cc, and the cross-section of test area is 10 cm in height and 9.5 cm in width. The oxygen level is 30.0% and the pressure is 100 kPa for all conditions. For these conditions, it can be shown that the oxygen concentration in the chamber can decrease from 30.0% to 29.3% under the most severe condition of complete combustion. The sample is a thin PMMA film whose thickness is 0.125mm

and length is 6cm. It is set in the test area and ignited with the electrically heated Ni-Cr wire. The ambient flow velocity is adjusted with a fan, driven by the brush-less motor from 0cm/s to 28cm/s.

To change the thermal properties of the oxidizer, we use N_2 , CO_2 , Ar, and He as diluents (see Table 1). We also selected different sample widths - 5 mm, 10 mm and 20 mm - to investigate three-dimensional effects. The flame is recorded with a CCD camera and the spread rate is measured from the video analysis afterwards. The interferometer is used to measure the pre-heat zone length in the gas phase ahead the flame. The microgravity environment is obtained with the 4.5sec drop tower of MGLAB in Toki City in Japan.

Fig. 1 Schematic of the closed-type wind tunnel for spread rate measurement and the interferometer system for flame size measurement

Table 1 Properties of diluent gases at 300K and 1atm

	Cp [J/mol K]	λ_g [W/m K]	α_g [mm ² /s]	Absorption band [μ m]
N_2	29.06	0.0249	21.1	-
CO_2	37.2	0.0164	10.9	4.4
He	20.78	0.158	186.6	-
Ar	20.78	0.0178	21.1	-

3. Scale analysis

When the dominant deriving factor is the thermal conduction from the gas-phase preheat zone to the solid-phase preheat zone, the flame spread rate can be estimated with the simple equation,

$$V_{f,th} \rho_s c_s L_{sy} W (T_v - T_\infty) \sim \lambda_g \frac{(T_f - T_v)}{L_{gy}} L_{gx} W,$$

which yields

Fig. 2 Schematic of flame structure for scale analysis

$$V_{f,th} \sim \frac{\lambda_g}{\rho_s c_s \tau} F \quad \text{where} \quad F \equiv \frac{T_f - T_v}{T_v - T_\infty}. \quad (1)^{16}$$

The above expression is identical to the de Ris's equation¹⁷. This equation states that large thermal conductivity and high flame temperature result in large spread rate. The situation where the thermal conduction from the flame to the solid is the dominant driving force of the flame spread is so-called "thermal regime."

We now consider the heat losses due to the radiation to the surroundings from the solid preheat zone and due to the conduction to surroundings from the gas-phase preheat zone sideward through the edges (see Fig. 2).

$$V_f \rho_s c_s L_{sy} W (T_v - T_\infty) + q_{loss} \sim \lambda_g \frac{(T_f - T_v)}{L_{gy}} L_{gx} W$$

where

$$q_{loss} = q_{rad} + q_{side}$$

$$= \varepsilon(1 - \alpha_{abs}) \sigma (T_v^4 - T_\infty^4) L_{sx} W + 2 \lambda_g \frac{(T_f - T_\infty)}{W/2} L_{gx} L_{gy}$$

The ratios of these losses to the heat conduction from the gas phase to the solid phase to drive the flame are expressed as below; R_{rad} and R_{side} .

$$R_{rad} = \frac{\varepsilon(1 - \alpha_{abs}) \sigma (T_v^4 - T_\infty^4)}{\rho_g c_g V_r (T_f - T_v)} \propto (1 - \alpha_{abs}) \frac{1}{V_r} \quad (2)$$

$$R_{side} = 4 \left(\frac{\alpha_g}{V_r W} \right)^2 \frac{T_f - T_\infty}{T_f - T_v} \propto \alpha_g^2 \cdot \frac{1}{W^2} \frac{1}{V_r^2} \left(= \frac{L_g^2}{W^2} \right) \quad (3)$$

Using these non-dimensional factors and the non-dimensional flame spread rate, η , the heat balance equation is reduced to the following simple equation;

$$\eta + R_{rad} + R_{side} = 1 \quad \text{where} \quad \eta \equiv V_f / V_{f,th}. \quad (4)$$

This equation expresses the spread rate in "microgravity regime," and it states that the extinction occurs if the sum of R_{rad} and R_{side} exceeds unity. The

heat losses, R_{rad} and R_{side} , increase with the decrease of the relative ambient flow velocity, V_r , however, the each impact on the spread rate is different. The radiative loss is proportional to the V_r^{-1} and independent on the width, W , whereas side loss is to the V_r^{-2} and depend on W . It is expected that side loss would overwhelm the radiative loss when the sample width is narrow and/or the thermal diffusivity of the ambient gas, α_g , is large. This implies that the flame becomes weak when helium is used as the diluent gas and it becomes robust if the sample width is wide.

4. Results and Discussion

4.1 Flames in the thermal regime

In order to confirm the tendency of the flame in the thermal regime, we first measure the downward spread rate in normal gravity, where the typical flame in the thermal regime was achieved. Figure 3 shows the calculated spread rate with Eq. (1) over the sample with infinite width, and the measured downward spread rate over the sample of 20mm width. The oxygen level is varied as a parameter. In downward spread conditions, the buoyant flow, which can be estimated to be about 30-40 cm/s, acts as the opposing flow. Therefore, the heat loss factors, R_{rad} and R_{side} , can be assumed to be small. Moreover, the sample width is 20mm large, making R_{side} relatively small. Hence, these flames are considered within the thermal regime.

In the thermal regime, therefore, we expect spread rates to be ordered for different diluents in the manner $\text{He} > \text{N}_2 \sim \text{Ar} > \text{CO}_2$, which is consistent to Eq. (1) and the thermal properties in Table 1. In the He balance condition, the thermal conductivity is large and the flame temperature is also large due to small heat capacity, which leads to large spread rate. On the other hand, in the CO_2 balance condition, the thermal conductivity and the flame temperature are both relatively low; therefore, the spread rate became small. The experimental results show good

agreement with these predictions, confirming that flame spread in the thermal regime is achieved in downward spread at 30% oxygen level.

4.2 Flames in the microgravity regime

In microgravity, the ambient flow velocity around the flame can be very small. In such a condition, the flame

a) Calculated spread rate

b) Experimental spread rate

Fig. 3 a) Calculated spread rate over infinite width sample with Eq. (1), and b) experimental spread rate over 20mm width sample.

Fig. 4 Flame spread rate in each balance gas condition. The oxygen level is fixed at 30%. The sample width is changed as a) 5mm, b) 10mm, and c) 20mm. When the 5mm width sample is used, the flame spread is not observed in all He balance conditions.

spread becomes smaller due to radiative heat loss and the conductive heat loss to the sides (three dimensional effect) as shown in Eqs. (2)-(4). Figure 4 plots the spread rate against the flow velocity for different diluents and sample width. In all conditions, the spread rate decreases when the ambient flow velocity approaches zero. This result implied that the heat loss increased near a quiescent condition. However, the degree of suppression is dependent on the diluents and the sample width.

In the case of N_2 or Ar, the flame spread rate decreases rapidly when the ambient flow velocity becomes less than 5 cm/s. On the other hand, for CO_2 , the spread rate is not

suppressed so much in spite of low ambient flow, that is, a robust flame can be observed in a quiescent condition. With He as the diluent, flame spread cannot be observed when the ambient flow is less than 10 cm/s. This is quite a contrast from the thermal regime, where He produces the fastest spread rate under similar conditions. It was worthy to notice that the suppression in the He balance condition was very sensitive to the sample width, whereas those in the other conditions were not.

The difference of the suppression tendency among these four conditions can be explained with the scale analysis. The heat loss factors, R_{rad} and R_{side} , are both sensitive to

Fig. 5 Non-dimensional heat loss factors with varying ambient flow velocity.

Fig. 6 Interferometer images in a quiescent condition and with a mild ambient flow.

the relative ambient flow velocity, V_r , whereas only R_{side} is affected by sample width, W . The high sensitivity of the experimental data (spread rate and flame size) on the width in the case of He dilution implies that the dominant heat loss path is primarily driven by sidewise heat loss. In the case of other diluents, however, it is the radiative loss which is dominant and sample width has relatively smaller effect.

Figure 5 shows the calculated heat loss factors, R_{rad} and R_{side} , for the condition shown in Fig. 4b. When the sum of R_{rad} and R_{side} reaches unity at the critical ambient velocity, $V_{g,cr}$, the flame is considered to be extinct. The result shows the robust flame for CO_2 in contrast to the weak flame in the case of He. The result shows not only the robustness of the flame near the quiescent condition, but also the ratio of R_{rad} and R_{side} , that reveals the dominant factor for the suppression. For He, the large R_{side} due to large thermal diffusivity results in large $V_{g,cr}$, which means weak flame in microgravity. At the critical velocity, the R_{side} is about 2 times R_{rad} ; therefore, the flame in the presence of He in a microgravity environment is affected by the sample width strongly. When the sample width is 5mm, the R_{side} becomes 4 times larger than that at 10 mm width. This is the reason why the flame spread is not observed in 5 mm wide with the He diluent.

According to the scale analysis, the difference in the suppression tendency discussed above resulted from the difference in the flame size in the microgravity regime. Hence, we measured the preheat zone length, L_g , in the four diluent conditions. Figure 6 shows the images obtained with the interferometer in the each balance condition¹⁸⁾. It can be seen from these images that the preheat zone length for He is much larger than those at other conditions, even in relatively fast ambient flow. This result is consistent with the fact that very weak flame is observed with He as the diluent. On the other hand, in the CO_2 balance condition, the preheat zone length is smallest of the four conditions. Additionally, the length in 16 cm/s flow and that in a quiescent condition are almost the same, which is consistent with the fact that the robust flame is observed with CO_2 as the diluent.

4. Conclusions

The flame spread rate in microgravity has been investigated with changing the diluent gas and the sample width in order to separate the radiative effects from the three dimensional side losses. Experimental results from drop tower experiments along are supported by a scale analysis to explore the relative significance of the two types of heat losses. It is found that the mechanism of the flame spread suppression in microgravity is quite different when diluents are switched. With He as the diluent, the conductive heat loss to the side direction is the dominant

factor, and the flame spread is suppressed strongly when the sample width is narrow. In all other situations, the radiative loss is the dominant factor for the suppression. This difference is linked to the difference in the preheat zone length in microgravity regime. For He, the flame becomes very weak and sensitive to the sample width and the ambient flow velocity, whereas in the thermal regime (downward spread in normal gravity), the results is just the opposite with He providing the fastest environment for flame spread. In the other extreme, when the diluents is CO_2 , the flame exhibits low sensitivity to both the ambient flow velocity and the sample width, even showing robustness in a quiescent condition. These experimental results are consistent with the prediction of the scale analysis.

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