Progress in Scale Modeling, an International Journal

Volume 2
Issue 2 *Special issue of Scale Modeling for Fire Research*
Article 1

2021

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Recommended Citation

Matsuoka, Tsuneyoshi; Nakashima, Kentaro; Kajimoto, Takuma; Yoshimasa, Akihiro; and Nakamura, Yuji (2021) "Fingering behavior of flame spread over solid combustibles," *Progress in Scale Modeling, an International Journal*: Vol. 2 : Iss. 2 , Article 1.
DOI: https://doi.org/10.13023/psmij.2021.02-02-01
Available at: https://uknowledge.uky.edu/psmij/vol2/iss2/1

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Category

Research Article

Abstract

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Keywords

Fire, Flame spread, Thermoplastic, Narrow channel, Fingering

Progress in Scale Modeling, an International Journal, Vol. 2, Issue 2 (2021) Article 02-02-01, pp. 1–6
https://doi.org/10.13023/psmij.2021.02-02-01

Fingering behavior of flame spread over solid combustibles

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Received April 2, 2020, Accepted April 9, 2020

Abstract

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Keywords: Fire; Flame spread; Thermoplastic; Narrow channel; Fingering

Nomenclature

a	empirical coefficient
A_f	area of flamelet
c	specific heat
d_f	diameter of flamelet
D	mass diffusivity of oxygen
h	channel height
I_b	background luminance of image
I_{max}	maximum luminance of image
l_f	flame diameter
Le	Lewis number
N	number of flamelets
T	temperature
U	flow velocity
V_f	spread rate
α	thermal diffusivity
β	collision frequency function
δ	thickness of sample specimen
ϵ	threshold value for binarization
λ	thermal conductivity
ρ	density

Subscripts

eff	effective
g	gas
i	i-th image
s	solid

Introduction

It is known that when thin combustible solids such as paper burn under oxygen-limited conditions the smoldering front separates into multiple fragments forming a fingering pattern [1–3]. To know the appearance condition and to predict their behaviors are of particular importance for fire safety because a sole finger can survive in such limiting conditions and may initiate fires. Previous studies manifested that the fingering pattern formation is considered to occur due to thermal-diffusive instability. Zhang et al observed

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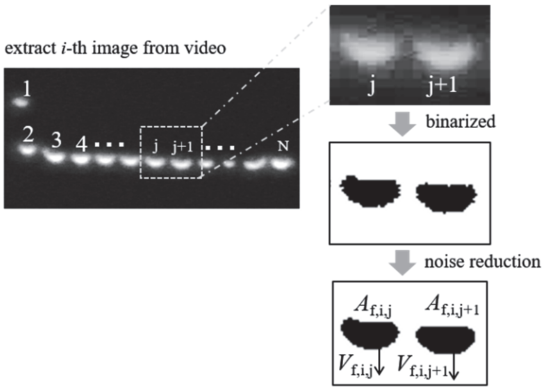

Fig. 1. Schematic diagram of image analysis.

similar phenomena, though they called it cellular flame spread, when the filter paper burns in O_2-CO_2 and O_2-SF_6 atmospheres where the Lewis number is relatively low [4]. Kagan and Sivasinky formulated the phenomenon [5]. Based on the quasi-two-dimensional conservation equations, they conducted stability analysis and examined the mechanism of the fingering pattern formation. Kuwana and co-workers simplified the Kagan and Sivasinsky model by eliminating the convection term and demonstrated that convection is not a crucial factor of the fingering instability [6, 7]. Recently, the model has been updated by including both effects, heat loss and convection [8]. A similar fingering behavior has also been confirmed for flame spread. Olson et al. conducted drop tower tests using 0.6 mm PMMA sheet and confirmed the uniformly spreading flame breaks into two flamelets [9]. More recently, we demonstrated that a similar kind of separation phenomenon appears even for thermally thick combustibles [10].

Narrow channel apparatuses are often used to cause the fingering behavior, because it appears near the quenching limit. In such situations, however, clear observation is not easy due to the characteristic scale of the system. Measurements of characteristic parameters such as flame temperatures, concentrations of reactants and products are even more difficult. Those difficulties prevent understanding of the whole physics of the phenomenon. To enable detailed observation and precise measurement, a scaling-up experiment is a great candidate. To do so, it is necessary to obtain a scaling law which reproduces the physics. The effective Lewis number (Le_{eff}) is proposed as a controlling parameter for smoldering combustion over thin fuel [6–8]. However, it is not obvious for the thick flaming case, although Le_{eff} correlation has been examined under limited conditions [10].

An objective of this study is to examine whether Le_{eff} is a dominant parameter for fingering behavior over thick fuel (hereafter it is called flamelet spreading). In our previous study [10], the flame spread rate was used as a characteristic parameter, leaving ambiguity for evaluation of the appearance condition. In this study, an image analysis method is developed to quantify the number of individual flamelets and their size. Experiments are conducted with three different kinds of solid materials. Two parameters are varied; the channel height and the oxidizer velocity. Based on the data obtained by the image analysis, the correlations between the number of flamelets or the flame size and Le_{eff} are investigated.

Experimental method

Experimental setup and conditions

This section briefly describes the experimental setup. A detailed description is found in Ref. [10]. Polymethyl methacrylate (PMMA), Poly carbonate (PC) and Poly ethylene (PE) are chosen as fuel. A test specimen of 150 mm long, 30 mm width and 10 mm depth was mounted on the sample holder made of stainless and installed into the channel. The whole length of the channel is 540 mm and its width is 50 mm. The uppermost upstream end of the sample is located 270 mm from the inlet. A non-combustible ceiling was installed into the opposite wall to the sample. Side walls are made of quartz glass to enable observation. Visual observation through the sample itself (top view) is also possible for PMMA and PC tests, while it is not for PE due to the opacity of the sample. Hence the quartz glass plate was alternatively used instead of the ceiling. The burning test was recorded by CCD camera. The motion video was divided into continuous still images at the corresponding frame rate.

Pure oxygen was used an oxidizer. The oxidizer flow was adjusted at the desired velocity and fed into the channel through a straightener. The velocity boundary layer is expected to be fully-developed [10]. In order to validate the scaling law under wide conditions, the channel height, h [mm], and oxidizer velocity, U [cm/s], were varied as experimental parameters. To avoid extinction, the sample was ignited at a velocity higher than the prescribed value. Once a uniform downward flame spread against the incoming flow was achieved, the velocity was then reduced to set U at the prescribed value.

Image analysis

A schematic diagram of image analysis is shown in Fig. 1. First, the obtained movie was divided into instantaneous still images. Each still image was binarized with a threshold value and a median filter was applied to reduce the noise in the picture. Since the luminosity of the flamelet widely varied depending on the conditions, it was difficult to determine a common specific threshold value which could be applied to all the data obtained. Alternatively, the threshold value was determined by the following equation,

$$\varepsilon_i \equiv a\left(I_{i,max} - I_{i,b}\right) + I_{i,b} \quad (1)$$

ε_i is the threshold of i-th image, defined as the ratio of maximum and minimum luminance appearing in the image. $I_{i,max}$ is the maximum luminance and $I_{i,b}$ is the background luminance, respectively. a is an empirical coefficient to correct the area change based on the flow velocity.

The image analysis successfully provides the following parameters; the number of individual flamelets, N_i, and its area, $A_{f,i,j}$. Here j is the flamelet number counted from left to right in each image. Assuming the flame shape is spherical, the mean flame diameter of i-th image, d_f [mm] was evaluated as,

$$d_f \equiv \overline{d_{f,\iota}} \sim \sqrt{\overline{A_{f,\iota}}} = \sqrt{\left(\frac{\sum_J A_{f,\iota,J}}{N}\right)} \quad (2)$$

The flamelets sometimes meandered around the fuel, resulting in the flame spread perpendicular to the mean direction of the downward spread and/or extinguishment. Hence, the flame spread rate was determined as follows. An instantaneous spread rate of each flamelet is calculated using the displacement between consecutive two images. The mode value of spread rate, V_f [mm/s] is then determined from the distribution of each burning test. It is noticed that much higher spread rates were sometimes found. Considering the experimental fact that even the flamelet on the edge spreads about twice faster than the others, such data that were three times higher than the apparent spread rate were treated as abnormal and excluded from the data analysis. The cause of this might be due to image noise and/or the algorithm of image analysis.

Results and discussion

Flamelets spreading over various kinds of fuel

Fig. 2 shows typical examples of flame separation process observed from the top view. Note that the brightness and the contrast of the pictures for PMMA (Fig. 2a) were appropriately adjusted to improve their appearance. The channel height and the oxidizer velocity were 2 mm and 7 cm/s, respectively. The flame uniformly spread against the opposed flow just after the ignition, then broke up into multiple flamelets as the flow velocity was reduced. The separation process and the following flamelet spreading were successfully captured in the pictures despite the kinds of fuel materials used. Accordingly, it suggests that the flamelet instability is considered as a common feature of solid combustion. Other features are also found. The flamelets spread with a slight meandering against the oxidizer gas. Local extinction and generation often occurred especially when the number of flamelets was small. Another feature is that the burnt sample of PC was covered with something like soot, while such adhesion was not confirmed for PMMA or PE.

Instantaneous values of the number of flamelets, N_i, and their averaged area, $A_{f,i}$, are shown in Fig. 3. Note

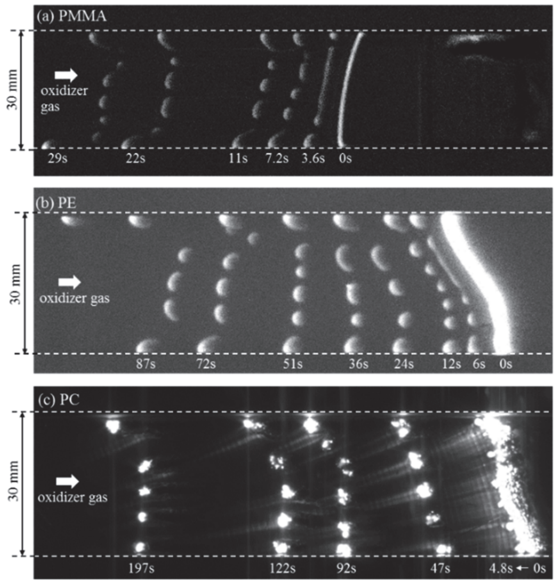

Fig. 2. Typical examples of flamelets spreading over (a) PMMA, (b) PE and (c) PC. Flame spread direction is from top to bottom, while the oxygen gas flows from bottom to top. Mean flow velocity and the channel height were respectively 7 cm/s and 2 mm.

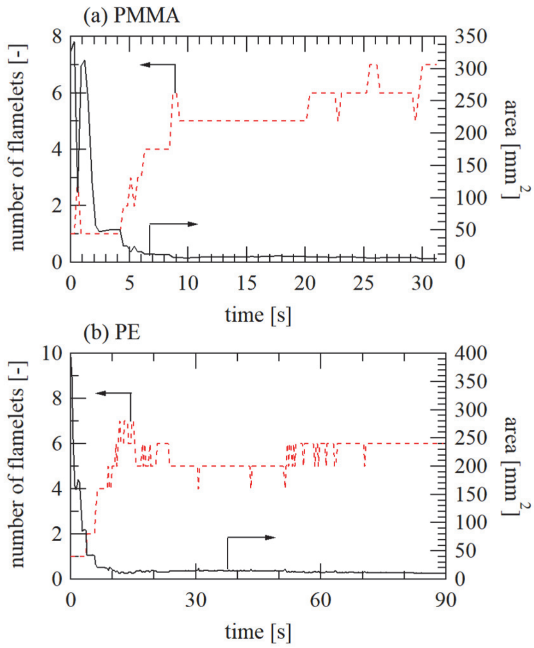

Fig. 3. Data obtained by image analysis for (a) PMMA and (b) PE at U = 7 cm/s and h = 2 mm. Red dashed line shows the actual number of flamelets counted and black solid line shows the averaged area of individual flamelets.

that the data were not obtained from that shown in Fig. 2, and hence the abscissa axis, time, is not exactly the same as those. As the flame broke up, the averaged area immediately decreased and eventually became nearly unchanged during the test. The number of flamelets

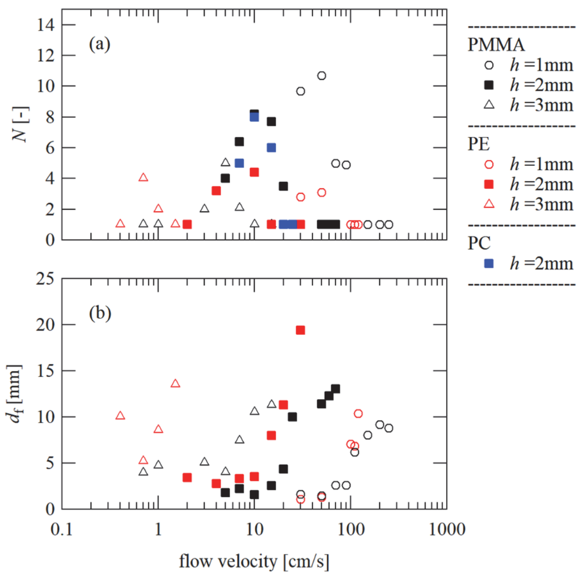

Fig. 4. (a) Time-mean of the number of flamelets, (b) time-mean of the averaged flame diameter.

fluctuated slightly due to local extinction or generation. It was difficult to distinguish individual flamelets for PC under most conditions performed in this study due to strong emission from the flame, resulting in an image analysis failure. Thus, the measurement was not done for PC. Fortunately, however, the strong emission enabled to specify the flame location and only the mean spread rate was acquired.

The time mean value of the number of flamelets, N, are calculated from the obtained data for various conditions as shown in Fig. 4a. Since N is defined as the time mean of N_i during the test, its value can be a decimal value, though it is physically incorrect. Note that $N = 1$ are seen in both low and high velocity regions, although they are obviously different from each other. When the flow velocity is sufficiently high, the flame spreads uniformly and the number of flame (flamelet) obviously becomes one. On the other hand, in a low flow velocity region, the flame does not break up into multiple flamelets but shrinks. Considering dependence of the flame size (i.e., the flame diameter d_f) and the distance between adjacent flamelets on the flow velocity, this trend is explained as follows. As shown in Fig. 4b, d_f decreased as the flow velocity was decreased. On the contrary, the distance between the flamelets is expected to show an opposite trend. Although this study did not measure actual values of flame width and distance, it was experimentally confirmed by previous studies by Zik et al. [1] and Kuwana et al. [8]. Therefore, if the fuel width is sufficiently large, N has a peak value at moderate flow velocity. However, the limited fuel width omits the flamelets out of range, resulting in a single flamelet.

As shown in Fig. 4a, the number of flamelets, N, increased as the oxidizer velocity was decreased. When the number is large, the flamelets spread almost straight toward and against the flow with splitting and local extinction. With a further decrease in the velocity, N decreased and eventually formed a single flamelet. In this region, a flamelet often spreads meandering, i.e., it moves perpendicular to the mean direction of the downward spread. While a similar trend was confirmed for all kinds of fuels, its value at the same h was varied depending on the fuels.

Validation of the effective Lewis number correlation

Appearance of flamelet instability was confirmed in spite of solid fuels. In this section, the scaling law to determine the appearance condition and to reproduce the phenomenon in large scale is discussed. Considering the flamelet instability is caused by the thermal-diffusive instability, the Lewis number is a strong candidate to be a key parameter to control the phenomenon. Although the Lewis number is usually defined as the thermal and mass diffusivity in the gas phase, the definition needs to be remedied to include the heat transfer through solid phase. Hence, the effective Lewis number for the fingering formation is proposed by Uchida et al. [6]:

$$Le_{\rm eff} = \frac{\alpha_{\rm eff}}{D} = \frac{\lambda_g(h-\delta)+\lambda_s\delta}{D\left[\rho_g c_g(h-\delta)+\rho_s c_s\delta\right]} \quad (3)$$

where, ρ [kg/m³] is the density, c [J/kg·K] is the specific heat, T [K] is the temperature, λ [W/m·K] is the thermal conductivity, D [m²/s] is the mass diffusivity of oxygen and δ [m] is the thickness of solid phase. The subscripts g and s respectively denote the gas and solid phases. $\alpha_{\rm eff}$ [kg/m³] is the effective thermal diffusivity, which comes from the ratio of thermal conduction to the thermal inertia in both gas and solid phases. Eq. (3) is applicable for thin fuel where the heat transfer perpendicular to the surface is negligible. Therefore, δ determined by the following equation should be used instead of the actual thickness [11]:

$$\delta \sim \sqrt{\frac{\alpha_g \alpha_s}{U V_f}} \quad (4)$$

Fig. 5 shows the time-mean number of flamelets plotted against $Le_{\rm eff}$. Although the data is slightly scattered, it shows that the flame uniformly spreads ($N = 1$) when $Le_{\rm eff}$ is larger than about 0.02, while the multiple flame spreading occurs when $Le_{\rm eff}$ becomes less than the value. The critical value approximately coincides with that found in Ref. [10]. The result demonstrates that the appearance condition of fingering instability is determined by the critical $Le_{\rm eff}$. Accordingly, it is concluded that the flame separation behavior is inherently similar to that of smoldering. In other words, it is caused by the thermal-diffusive instability. The oxygen mass transfer is enhanced at the convexity portion toward the upstream, while the heat

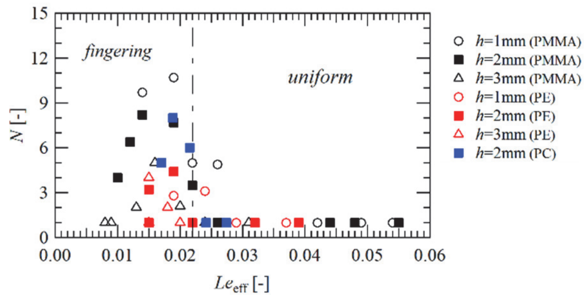

Fig. 5. The time-mean number of flamelets, N, are plotted against Le_{eff}. The dashed line shows an approximate critical Le_{eff} where the fingering instability appears.

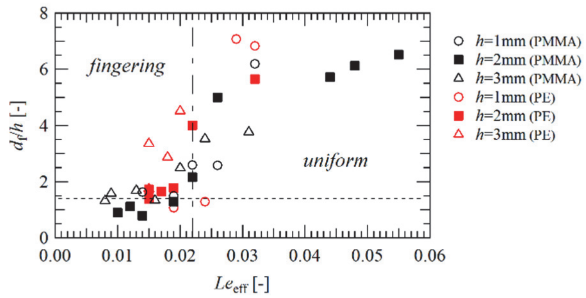

Fig. 6. Correlation between d_{f}/h and Le_{eff}.

transfer is weakened. As a result, the convexity becomes larger and eventually causes separation into multiple flamelets.

Eq. (3) indicates that the channel height appears as the characteristic length scale, which dominates mass and thermal diffusion in the gas phase in this system. Fig. 6 shows a correlation between the non-dimensional length, d_{f}/h and Le_{eff}. As mentioned, since the area could not be measured for PC, the data are not on the figure. All the data seem to be nearly constant, $d_{\mathrm{f}}/h \sim 1$ for $Le_{\mathrm{eff}} < 0.02$. Here, it is considered the wavenumber of the flamelet structure is a function of the flame diameter. Accordingly, the wave number becomes a function of the channel height through the flame diameter. Therefore, Fig. 6 implies a correlation between the wavenumber and Le_{eff} as well as for the smoldering combustion [8]. Furthermore, this correlation may provide a methodology to reproduce a similar phenomenon in a larger channel. It is expected that the buoyancy driven flow inhibits the development of the instability in a large-scale experiment. Hence, a specific method such as microgravity is required to reduce the buoyancy effect.

It is noticed that Fig. 6 implies another possible reason why the flame diameter becomes proportional to h; flamelets larger than h may not be able to exist, resulting in as if the flamelet scale is well-organized in the d_{f}/h–Le_{eff} correlation. In fact, a rough estimation of the diffusion length, $\sqrt{Dd_f/U}$, becomes comparative to the channel height when the given condition approaches the flamelet mode. Further study is needed to verify the mechanism how the flame scale is determined, i.e., by conventional instability or simply limited by the channel height.

Conclusions

Flame spreading over 10 mm thick PMMA, PE and PC was observed under various channel heights and oxidizer flow velocities. Flamelet instability was observed for all the solid fuels used. An effective Lewis number, Le_{eff}, was developed by considering the heat transfer for the solid phase. The time-mean number of flamelets was summarized with Le_{eff}. The result shows that the flame separation occurs at the critical Le_{eff} and thus this phenomenon is inherently similar to that of the fingering or flamelet instability of smoldering. The critical Le_{eff} in this study was about 0.02. Further, the non-dimensional flame diameter becomes nearly constant when the fingering instability occurs. Although a key factor which determines the flame scale is yet to be understood, this correlation provides a possibility to reproduce a similar phenomenon in larger scale.

Acknowledgment

This work was partially supported by JSPS KAKENHI Grant Number JP16K16365. The authors acknowledge Mr. Lindsay Prescott (Technical Advisor at TUT-RAC) for his language editing.

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