Flame Propagation and Fractal Dimension in a Concentric Double Cylinders Apparatus

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Abstract
The aim of this study is to estimate the flame fractal dimensions of methane/air mixtures by experimentally measuring the apparent flame-propagation velocities. In this study, we used an apparatus consisting of two concentric cylinders. It was found that the larger the cylinder size, i.e. the flame scale, is, (i) the more the number of wrinkles of flame is, (ii) the faster the apparent flame-propagation velocity is, and (iii) the values of flame fractal dimension are varied from 1.3 to 2.0. It was also found that the fractal dimension increases with a decrease in equivalence ratio, which is likely because of the effect of preferential diffusion and/or the change in the Lewis number.

Key words
Fractal Structure, Fractal Dimension, Flame Propagation, Concentric Double Cylinders Apparatus, Preferential Diffusion, Lewis Number

1. Introduction
An accidental gas explosion is a phenomenon with a propagating flame; the faster the flame-propagation velocity is, the greater the damage is. Therefore, in order to predict the damage of a gas explosion accident, it is important to predict the flame-propagation velocity [1]. A typical flame scale of a gas explosion accident exceeds 10 meters. Such a large-scale flame has a fractal structure caused by hydrodynamic instability, even though the atmosphere does not have turbulence. In general, a flame propagation velocity is proportional to the flame area. The area of a flame with a fractal structure is increased by the hydrodynamics instability [2]. Therefore a flame-propagation velocity can be expressed in term of the flame fractal dimension [1].

Gostintsev et al. proposed a method to calculate the fractal dimension from the time history of the radius of a spherically propagating flame [3]. However, for using this method, a large-scale flame needs to be established. When the flame scale is large and the flame-propagation velocity is fast, it is difficult to conduct experiment for safety reasons. On the other hand, a previous study [2] proposed to predict the fractal dimension by computationally simulating a planar flame propagating in one direction. The value of the fractal dimension of the planar flame propagating in one direction is reported to be 1.19 [4]. The aim of this study is to estimate the fractal dimension by experimentally measuring the propagation velocity of planar flame propagating in one direction. In this study, we used an apparatus consisting of two concentric cylinders. An annular planar flame propagates in the narrow gap of two cylinders. The scale of annular planar flame in this study is large in terms of its diameter and circumference, but the experiment is safe to conduct because the amount of the combustible gas used is limited.

2. Experimental
Figure 1 shows a schematic of the concentric double cylinders apparatus, which consists of two concentric cylinders with the top open to the atmosphere and the bottom closed. The inner cylinder is made of stainless steel and the outer cylinder is made of Pyrex glass. Methane-air mixture enters through approximately 1000 small holes at the bottom of the inner cylinder and exits via the open top of the apparatus. The axial flow velocity of the mixture is maintained at the constant velocity of 5 cm/s.
The mixture is ignited by torch at a point near the top of the cylinders, and then an annular flame is immediately formed and starts propagating downward, consuming the reactant. It might be better to ignite more uniformly rather than ignition at a single point. However, visible observation shows that an annular flame is formed immediately after the ignition, and the ignition method does not significantly alter the resultant apparent flame-propagation velocity. Four sets of cylinders are used in this study. The inner diameter (ID) of outer cylinders (the outer diameter (OD) of inner cylinders) are varied as 70 (50), 130 (110), 180 (160) and 250 (230) mm. The gap between the outer and the inner cylinders under each condition is fixed at 10 mm. The flame scales \( l \) are defined by the circumference of the centerline between ID of the outer cylinder and OD of the inner one and are 188, 377, 534, 754 mm, respectively. The height of apparatus is 676 mm.

The existence of the cylinders causes heat loss from flame to them. Because the gap distance between the outer and the inner cylinders is fixed at 10 mm in this study, the relative influence of heat loss to heat generation does not significantly vary among different cylinder diameters. Therefore, the heat loss effect is not considered in this study. The heat loss effect can be studied, for example, by changing the gap distance. Such a study will be reported in future work.

The equivalence ratio \( \phi \) of methane and air mixture is varied from 0.8 to 1.4 at every 0.1. A Photron FASTCAM APX RS high-speed video camera is used to record the direct image of the downward flame progression at 1000 frames per second. The camera is placed at the front of the apparatus and records the front image of propagating flame. From this camera record, the apparent flame-propagation velocity \( V_f \) is determined from the time that the lowest point of flame front takes to propagate a fixed distance. Note that the average apparent flame-propagation velocity within the fixed distance does not significantly fluctuate. In a previous computational study [2], the apparent flame-propagation velocity was determined from the evolution of burned volume. The present method is expected to yield a similar propagation velocity to the previous method provided that the thickness of flame brush remains unchanged. Since visual observations confirmed that the flame brush thickness does not significantly change over time, we do not consider the difference in the definition of apparent flame-propagation velocity. The apparent flame-propagation velocity \( V_f \) reported in this paper is the average of 15-time measurements under each condition and the standard deviation is not greater than 5%. The turbulent burning velocity \( S_t \) is calculated by adding the mean upward velocity of the reactants, maintained at 5 cm/s, to the apparent flame-propagation velocity \( V_f \).

3. Result and Discussion

Figure 2 shows the relation between apparent flame-propagation velocity and flame scale, where equivalence ratio is \( \phi = 1.0 \). The apparent flame-propagation velocity tends to increase with the increase in the flame scale \( l \). The solid line in Fig. 2 indicates the propagation velocity that is equal to the laminar burning velocity of minus the mixture flow velocity, 0.32 m/s under the conditions of \( \phi = 1.0 \). The apparent flame-propagation velocity of \( l = 754 \) mm reaches about 0.96 m/s, which is about three times as fast as the apparent flame-propagation velocity of the laminar flame. In order to understand the increase in the apparent flame-propagation velocity with flame scale, the images of the instantaneous shapes of propagating flame for various flame scales \( l \) are shown in Fig. 3, where equivalence ratio is \( \phi = 1.0 \). Panels (a), (b), (c), and (d) show flame shapes for \( l = 188 \) mm, 377 mm, 534 mm, and 754 mm, respectively. Each image is the front view from the high-speed camera. Since the inner cylinder is not transparent, the back side is not shown in the figure. The location of the flames shown is about 400 mm from the top of the apparatus. In all cases, the flames have wrinkles. The larger the flame scale is, the more the number of wrinkles of flame. The flame structure consists of both small scale (less than ~50 mm) wrinkles and as large scale as \( l \), which can be characterized by different flame curvatures. These experimental observations are in qualitative agreement with previous studies [2, 4], and the flame area is increased with flame scale. In general, an apparent flame-propagation velocity is proportional to the flame area. The increase in the flame wrinkle with flame scale observed in Fig. 3 is responsible for the increase in apparent flame-propagation velocity with flame scale. The area of a flame with a fractal structure is increased by hydrodynamic instability. Therefore, the apparent flame-propagation velocity can be expressed in term of the flame fractal dimension.

The previous study [2] proposed to predict the fractal dimension by simulating a planar flame propagating in one direction using the following equation (Eq. (1)):

\[
V_f \sim l^{D-1}
\]

where \( D \) is the flame fractal dimension. In this study, the upward velocity of reactant is maintained at 5cm/s, while in the previous study [2] \( V_f \) represents the value relative to the reactant. For the present setup, the turbulent burning velocity \( S_t \) relative to the reactant is therefore calculated by adding the mean upward velocity of the reactants to the apparent flame-propagation velocity \( V_f \). Then, in the case of the
present setup, the apparent propagation-velocity $V_f$ in Eq. (1) should be replaced with the turbulent burning velocity $S_t$. The flame fractal dimension $D$ could be calculated by the power-law relationship between the turbulent burning velocity $S_t$ and the flame scale $l$ and expressed by the following equation (Eq. (2)):

$$D = d \frac{\log(S_t)}{\log(l)} + 1$$  \hspace{1cm} (2)

Figure 4 and Figure 5 show the logarithm relation between the turbulent burning velocity ($\log(S_t)$) and flame scale ($\log(l)$), where Fig. 4 shows the result for the equivalence ratio of 0.8, and Fig. 5 for 1.4. The flame fractal dimensions could be calculated from the slope of the plot in

Fig. 3 Instantaneous flame shape recorded by the high-speed camera for different cylinder sizes

Fig. 4 Logarithm relation between turbulent burning velocity and flame scale of equivalence ratio 0.8

Fig. 5 Logarithm relation between turbulent burning velocity and flame scale of equivalence ratio 1.4
Fig. 4 and Fig. 5. The values of slope in Fig. 4 ($\phi = 0.8$) and Fig. 5 ($\phi = 1.4$) are 0.93 and 0.31, respectively. Hence, the values of flame fractal dimensions for $\phi = 0.8$ and 1.4 are 1.93 and 1.31, respectively.

Figure 6 shows the relation between fractal dimension $D$ and equivalence ratio $\phi$. For the annular planar flame-propagation in this study, the values of flame fractal dimension are varied from 1.3 to 2.0 depending on the values of $\log(S_t)/\log(l)$ such as those shown in Figs. 4 and 5. The flame fractal dimension (1.3~2.0) by the present experiment is slightly larger than the value reported in the previous computational study (1.19) [4]. Furthermore, the fractal dimension of lean mixture of methane-air is larger than that of rich mixture. These might indicate that the fractal structure of flame is induced not only by hydrodynamic instability but also by the effect of preferential diffusion and/or the change in the Lewis number. These effects will be analyzed in more detail in future work.

As shown in Fig. 6, the fractal dimension tends to decrease with an increase in equivalence ratio. The observed tendency qualitatively agrees with the previous study by Wu et al. [5]. The major advantage of the present experimental method over the previous one is that the fractal dimension can be easily and safely measured by the present method. Also, the present setup can be extended to a larger size for better accuracy to determine the fractal dimension. For example, when the diameter of annulus flame is 1000 mm, the volume in which the combustible gas is filled is about 30L, whereas a typical experiment of spherically expanding flame requires the volume of about 500L. Such a large-scale experiment must be conducted in a special outdoor facility [6]. Alternatively, an experiment of spherically expanding flame can be conducted in a high pressure environment to strengthen the effect of hydrodynamic instability, thereby enabling to reduce the size of experiment. For example, Ref. [5] reports experiments with initial pressures as high as 60 atm. The present method, not requiring a large volume of combustible gas or a high initial pressure, is expected to serve as a simple method to obtain the fractal dimension of a combustible gas mixture.

4. Conclusions
The aim of this study is to estimate the fractal dimension by experimentally measuring the apparent flame-propagation velocity. In this study, we used an apparatus consisting of two concentric cylinders. The following conclusions are obtained:
(i) The larger the flame scale is, the more the number of wrinkles of flame is.
(ii) The larger the flame scale is, the faster the apparent flame-propagation velocity is.
(iii) The values of flame fractal dimension are varied from 1.3 to 2.0 and are slightly larger than the value reported in a previous computational study (1.19).
(iv) The fractal dimension of lean mixture of methane-air is larger than that of rich mixture, which is likely because of the effect of preferential diffusion and/or the change in the Lewis number.

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References