Thermal structure of flame spread in partially premixed atmospheres and effects of fuel Lewis number

by

Kazuhiro Yamamoto
Department of Mechanical Science and Engineering
Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8603, JAPAN

Satoshi Seo, Koichi Mori
Department of Mechanical Engineering, Toyohashi University of Technology
1-1 Hibarigaoka, Tempaku, Toyohashi-shi, Aichi 441-8580, JAPAN

ABSTRACT

The experimental study on the flame spread in partially premixed atmospheres was presented. Two samples of different filter thickness and density were used. Gaseous fuels of hydrogen, methane, and propane were added in the opposed air, focusing on the fuel Lewis number (Le). In the partially premixed atmospheres, the pyrolysis zone and the region of high temperature are expanded. Since the flame temperature is increased, the heat transfer rate to the preheat zone of the filter is promoted, which is confirmed by the de Ris's formula of the thermally thin model. The heat transfer due to the heat conduction from the flame is 60 to 80 % of total heat transfer. By comparing the results of the preheated air, the corresponding temperature rise caused by fuel addition is evaluated. For all fuels, the linear increase of temperature rise with the fuel concentration (Cf) is confirmed. However, at the fixed fuel concentration, the temperature rise depends on the fuel type. Generally, there are two factors directly related with thermal structure of combustion field such as the flame temperature. One is the heat of combustion (H), and the other is the fuel Lewis number, because the opposed flow is the lean mixture. Since Le is proportional to the inverse of the fuel diffusivity, the temperature rise could be corrected by 1/Le. Resultantly, for all fuels, the temperature rise collapses to a single curve with the correlation of (Cf*H/Le). Thus, the Lewis number is a very important and useful parameter to discuss the thermal structure and the flame spread rate in partially premixed atmospheres.

1. Introduction

Generally, combustion-induced disasters can be divided into two types: fire and accidental explosions [1]. Needless to say, a fire becomes more serious as the burning area spreads widely. Therefore, in order to mitigate losses in fire, it is essential to elucidate the flame spread mechanism [2-9]. For simplicity, many studies have been performed using solid fuel such as filter papers [3,9-11] and polymethyl methacrylate (PMMA) [12-14]. More recently, a detailed 3D numerical simulation has been conducted [15]. New approach using a flame holder with moving filter paper has been tested to achieve a rigid stationary flame spread [16].

In our previous study, we have examined the flame spread in partially premixed atmospheres [17]. This situation may be realized under poorly ventilated conditions, where the combustible mixtures of oxygen and fuel vapors are formed [18]. It should be noted that, a de Ris's formula [1] is the most well-known for predicting the flame spread over thin and thick solid fuels, which have been modified in subsequent studies [4,16,19]. Thus, it could be meaningful to discuss the flame spread in partially premixed atmospheres based on de Ris's model.

In the present study, we investigate the flame spread over a thin filter paper. Hydrogen, methane, and propane are added in the ambient air to set partially premixed atmospheres. For this purpose, these gaseous fuel concentrations are kept below the lean flammability limit. Two approaches are adopted. One is a direct measurement of temperature field in partially premixed atmospheres using thermocouples, named by experiment of A (Ex. A). The other is an indirect investigation on the flame spread in preheated air, named by experiment B (Ex. B). Since the added fuel can be interpreted as the heat input to the combustion field [17], it must be fruitful to compare these experiments for discussing the thermal structure in terms of the fuel Lewis number [20].

2. Experimental setup

To control conditions of ambient atmospheres, we used a wind tunnel system used in our previous study [17]. Opposed flow of fuel and air was supplied, and the filter paper was placed at the wind tunnel exit. In this experiment, the velocity of opposed flow, U_{in}, was kept at 25 cm/s. The cross section of the wind tunnel exit is 80 mm × 80 mm. Hydrogen, methane, or propane was added in the opposed flow in Ex. A. The fuel concentration was below the lean flammability limit.

Two types of filter were used (produced by Toyo filter company). The properties of thickness, δ, and density, ρ, are 0.12 mm and 800 mg/cm^3 for sample No.1 and 0.25 mm and 560 mg/cm^3 for sample No.2, corresponding to "thermally thin" model [2]. To set the constant moisture of filter papers, all samples were kept in a moisture-controlled storage. The filter width is 40 mm. The filter was ignited linearly by a Nichrome wire for the two-dimensional flame spread. To void the effect of ignition, the flame spread rate was measured 20 mm below the ignition line. For the temperature measurement, we used a Pt/Pt-13%Rh thermocouple (wire diameter is 50 μm). Experimental procedure and position of thermocouples were referred to previous measurements [10,21]. A correction was made for radiative heat loss [22,23].

In order to reveal the thermal structure of the flame spread in partially premixed atmospheres, the opposed air was preheated in Ex. B. The commercially available coil-shaped electric heater was used. In experiments, the preheated temperature was up to 150 ℃, surely below the pyrolysis temperature of the filter.

3. Results

3.1. Experiment of partially premixed atmospheres (Ex. A)

Figure 1 shows an analytical model of downward flame spread over a filter paper [17]. For supporting the flame spread, the heat transfer to the preheat region is important. Indeed, in the thermally thin model [2], the downward flame spread rate, (V_f), is proportional to 1/(ρδ). Consequently, the heat transfer rate of Q described by Eq. 1 is constant.

$$Q = \frac{1}{2}\rho\delta w C_{ps} V_f (T_{pyr} - T_0) \qquad (1)$$

where V_f is the flame spread rate, w is the filter width, C_{ps} (=1.2 J/(g・K) [3]) is the heat capacity of the filter paper, T_{pyr} (= 345 °C [3]) is the pyrolysis temperature, and T_0 is the initial filter temperature or the ambient temperature. Here, the heat transfer rate of Eq. 1 is calculated in the partially premixed atmospheres, shown in **Fig. 2**. For all conditions, the flame spread was steady. In this figure, C_f is the fuel concentration (volume fraction). It is found that, for two samples, the heat transfer rate of Q has almost the same value. As more fuel is added, Q becomes larger. Resultantly, more heat input of added fuel supports the higher flame spread rate [17]. Next, we examine the temperature field.

Fig.1

Fig.2

In temperature measurements, only one thermocouple was used for minimizing the disturbance. Recognizing the flame spread was steady even in partially premixed conditions, the temperature profile in space was estimated in terms of temperature-time diagram. This implies is that, by multiplying the flame spread rate, the time is converted to the coordinate along the opposed flow direction, x. We set the origin at the upstream boundary of the pyrolysis region on the filter surface.

Figure 3 shows direct photographs of the pyrolysis region. These were taken nearly at the same position, not at the same period. The pencil line drawn on the filter is observed, by which the flame spread rate was evaluated. It was the downward flame spread. The added fuel is 1.5% H_2, 3% CH_4, and 0.75% C_3H_8 in volume. The photograph of no fuel condition is shown in **Fig. 3a**. The color of virgin (unburned) region is white, and that of the pyrolysis region is brown. It is seen that the thickness of the pyrolysis region becomes larger in partially premixed atmospheres, which is well in accordance with numerical simulations [17]. Fig.3

Figure 4 shows one example of temperature measurements by the thermocouple. Results of sample No.2 are shown. The thermocouple was set at 15 positions of $y = 0$ to 7 mm, where y is the distance from the filter surface. It is seen that the temperature increases quickly when the thermocouple crosses the flame zone. At the region of $y = 0$ to 3 mm, the plateau temperature profile due to the latent heat of vaporization is observed, where the pyrolysis reaction occurs [10,21,24]. Based on these temperature variations, a two-dimensional temperature distribution is obtained. Results of sample No.2 are shown in **Fig. 5**. The fuel is methane, and its volume fraction ($= C_f$) is 0, 1, and 4%. It is observed that the high temperature region is largely expanded [20]. The maximum temperatures are 1495, 1504, and 1568 °C, respectively. Therefore, as the fuel concentration in the opposed flow is higher, the maximum temperature of the flame is increased. It is easily expected that the heat transfer to the preheat region could be increased, because there is an additional heat input of added fuel.

Fig.4

Fig.5

For further discussion, the effect of fuel addition on the temperature distribution is examined. **Figure 6** shows the temperature gradient of $\partial T/\partial y$ at $y = 0$ mm, estimated by the temperature profiles at $y = 0, 0.5, 1.0$ mm. The quadratic curve fit was applied. Results of two samples are shown. The fuel is methane, and its volume fraction is 0 to 4 %. Interestingly, as the fuel concentration is higher, its profile is shifted more upstream, although the maximum temperature gradient is not increased. By using the thermal conductivity of the gas phase, the heat transfer rate to the preheat zone due to heat conduction is calculated by integrating the temperature gradient for $-\infty < x < 0$ [25], which is expressed by

$$Q_{HC} = w\int_{-\infty}^{0} \left[\lambda \left(\partial T/\partial y\right)_{y=0}\right] dx \qquad (2)$$

The thermal conductivity of the gas phase, λ, is obtained from the CHEMKIN database [26]. Results are shown in **Fig. 7**. Fuel is methane. For comparison, the total heat transfer rate estimated by de Ris's formula of Eq. 1 is also plotted. It is found that, as more fuel is added in the opposed flow, both heat transfer rates are increased, but the difference is almost the same. It should be noted that there is no convective heat transfer from the flame, because the ambient flow opposes the flame spread [2]. However, only one thermocouple was used in temperature measurement. The error of temperature gradient was within 10 %. Then, it is confirmed that the heat transfer due to the heat conduction accounts for approximately 60 to 80 % of the total heat transfer. The rest could be due to the radiation. More work may be needed to estimate the contribution of radiation [27].

Fig.6

Fig.7

3.2. Experiment of preheated atmospheres (Ex. B)

Next, experiments of preheated atmospheres were conducted. In this case, the opposed air was preheated. This situation is slightly different from the previous experiments [28], where only the temperature of the filter paper was raised by two heaters positioned on both sides of the filter paper. In order for preheat effect to be more effective, temperatures of both the filter and the opposed flow were increased in our experiments, so as to avoid the temperature reduction due to the opposed flow of low temperature. **Figure 8** shows the flame spread rate. Results of two samples are shown, separately. The opposed flow temperature was from 20 to 150 °C (= T_0), corresponding to the initial filter temperature. For both samples, the linear increase of the flame spread rate with T_0 is observed.

In accordance with Eq. 1, the heat transfer rate from the flame to the preheat region of the filter, Q, was estimated. Results are shown in **Fig. 9**. The values of both samples sufficiently show a good agreement. Thus, in the case of the preheated atmosphere, the thermally thin model [2] can be applied as well.

Fig.8

Fig.9

4. Discussion

We are now ready to discuss the mechanism of the flame spread over the filter paper in partially premixed atmospheres. In our previous simulation, the flame temperature is increased by the added fuel [17]. The similar temperature increase is observed in **Fig. 5**. Thus, it is derived that the higher flame spread in partially premixed atmospheres is caused by the larger heat input of added fuel. Indeed, the higher flame spread rate is observed in the preheated atmosphere. Supposing that most of added fuel is reacted in the flame region, the resultant heat input can be transported to the unburned solid fuel as well as the gas phase. So far, we only know the flame temperature increase recognized in **Fig. 5**. The overall effect of added fuel on the whole combustion field in partially premixed atmospheres is not fully understood. If the overall contribution due to the added fuel could be equivalent to the temperature rise, it is more straightforward to discuss the thermal structure in the partially premixed atmospheres.

Let us consider the overall effect of added fuel based on the similarity of preheating experiments. It is therefore useful to speak of the temperature rise (*ΔT*) in partially premixed atmospheres. We take following three steps. In step 1, the increment heat transfer rate caused by the added fuel, *dQ*, is calculated.

$$dQ = Q - Q_0 = \frac{1}{2}\rho\delta C_{ps}(V_f - V_{f,0})(T_{pyr} - T_0) \qquad (3)$$

where Q_0 is the original heat transfer rate in the air (no fuel or not preheating), and $V_{f,0}$ is also the original flame spread rate. For Q in **Fig. 2**, the above increment heat transfer rate is obtained. In step 2, the flame spread rate of experiments A and B is plotted with *dQ*, which is shown in **Fig. 10**. It is not surprising that the flame spread rates of both experiments are plotted on the same line, because these situations belong to the thermally thin model. More important is that, based on **Fig. 10**, we could estimate the temperature rise of *ΔT*, by considering that the effect of added fuel is regarded as the corresponding temperature rise in the preheated atmosphere, which is step 3. Basically, the increment heat transfer rate by added fuel is presumed to be equivalent to that of preheated temperature of ΔT. Fig.10

Figure 11 shows the estimated temperature rise, ΔT, for three different fuels. The temperature rise is plotted with the fuel concentration of C_f. In case of methane, the temperature rise at $C_f = 4\%$ is 60 ℃, which is the maximum in the present experiments. For all fuels, the almost linear increase of ΔT with the fuel concentration is confirmed. It rather seems reasonable, because the heat input of added fuel is proportional to the fuel concentration. In case of propane, the temperature rise is higher. This may be simply because the heat of combustion per unit mole is higher than that of methane. However, in case of hydrogen, the same temperature rise of methane is observed, although its heat of combustion per unit mole is much lower than that of methane.

For three fuels, the Lewis number (Le) is different. It is well-known that, if the deficient reactant is fuel, the flame temperature becomes higher when more fuel diffuses due to preference diffusion [23]. For lean mixture of hydrogen, methane, and propane, the fuel Lewis number is 0.30, 0.97, 1.8, respectively [26]. Indeed, in the numerical simulation [20], the higher flame spread rate is predicted for Le < 1. Since the value of Le is proportional to the inverse of the fuel diffusivity, the temperature rise could be corrected by 1/Le.

Additionally, the temperature is expectedly increased by adding the fuel of higher heat of combustion (molar heat of combustion, H). Then, ΔT is plotted with the fuel concentration multiplied by H and 1/Le. Results are shown in **Fig. 12**. When only the heat of combustion is considered in **Fig. 12a**, the temperature rise of propane is the smallest at the same value of (C_f*H), and that of hydrogen is the largest. Surprisingly, in **Fig. 12b**, the same dependence of the temperature rise on (C_f *H/Le) is observed. In other words, the corresponding temperature rise of added fuel is well correlated with the value of (C_f*H/Le). Thus, the Lewis number is a very important and useful parameter to discuss the thermal structure and the flame spread rate in partially premixed atmospheres.

Fig.11

Fig.12

5. Conclusions

The experimental study on the flame spread in partially premixed atmospheres was presented. Different fuels of hydrogen, methane, and propane were added in the opposed air, focusing on the fuel Lewis number (Le). Two filter samples were used. To discuss the overall contribution of the added fuel to the thermal structure of the flame spread, experiments of preheated atmosphere were also conducted. The following conclusions were derived.

(1) In the partially premixed atmospheres, the pyrolysis zone as well as the region of high temperature is expanded. Since the flame temperature is increased, the heat transfer rate to the preheat zone of the filter is promoted, which is confirmed by the de Ris's formula of the thermally thin model. The heat transfer due to the heat conduction from the flame is 60 to 80 % of total heat transfer.

(2) In the preheated experiments, the linear dependence of the flame spread rate on the ambient temperature (initial filter temperature) is observed. The estimated heat transfer rate of both filter samples has the same value. By comparing results of partially premixed and preheating experiments, the corresponding temperature rise (ΔT) caused by the fuel addition is evaluated. For all fuels, the linear increase of ΔT with the fuel concentration (C_f) is confirmed, because the heat input of added fuel is proportional to the fuel concentration. However, at the fixed fuel concentration, ΔT depends on the fuel type.

(3) There are two factors related with the above temperature rise; the molar heat of combustion (H) and the fuel Lewis number (Le). Even though the correction with heat of combustion is conducted, the dependence of the fuel still remains. In contrast, the temperature rise collapses to a single curve with the correlation of (Cf*H/Le). Thus, the Lewis number is a very useful parameter for discussing the thermal structure and the flame spread rate in partially premixed atmospheres.

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Figure captions

Fig. 1 Analytical model of downward flame spread over filter paper.

Fig. 2 Heat transfer rate into preheat zone estimated by Eq. (1).

Fig. 3 Direct photograph of pyrolysis region of sample No. 1; (a) no fuel, (b) 1.5% H_2, (c) 3% CH_4, (d) 0.75% C_3H_8.

Fig. 4 Temperatures of sample No. 2 measured by thermocouples.

Fig. 5 Temperature distributions of sample No.2; (a) 0% CH_4, (b) 1% CH_4, (c) 4% CH_4.

Fig. 6 Profiles of temperature gradient of $\partial T/\partial y$ at filter surface.

Fig. 7 Heat transfer rate into preheat zone estimated by Eq. (1), compared with measured value by heat conduction. Fuel is methane.

Fig. 8 Flame spread rate in preheated air.

Fig. 9 Heat transfer rate into preheat zone in preheated air.

Fig. 10 Variation of flame spread rate with heat input in fuel addition and preheating conditions.

Fig. 11 Estimated temperature rise caused by fuel addition.

Fig. 12 Estimated temperature rise caused by fuel addition, corrected by heat of combustion (H) and the fuel Lewis number (Le).

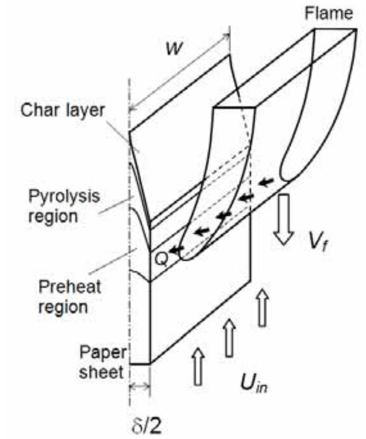

Fig. 1 Analytical model of downward flame spread over filter paper.

[Word Count] = (58+10)*2.2*1 + 11 (caption) = 161 words

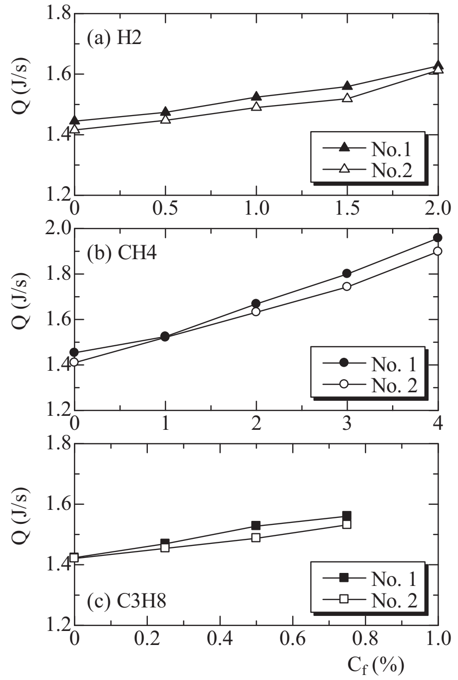

Fig. 2 Heat transfer rate into preheat zone estimated by Eq. (1).

[Word Count] = (89+10)*2.2*1 + 13 (caption) = 224 words

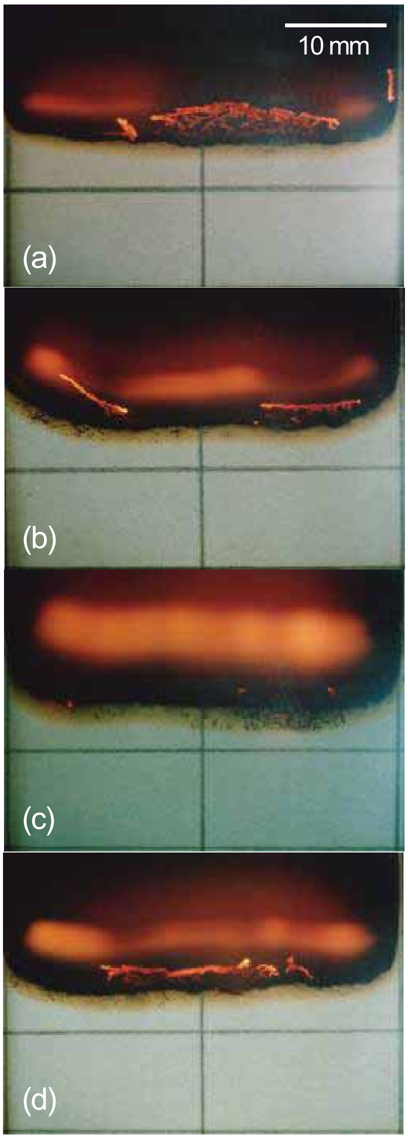

Fig. 3 Direct photograph of pyrolysis region of sample No. 1; (a) no fuel, (b) 1.5% H_2, (c) 3% CH_4, (d) 0.75% C_3H_8.

[Word Count] = (149+10)*2.2*1 + 23 (caption) = 373 words

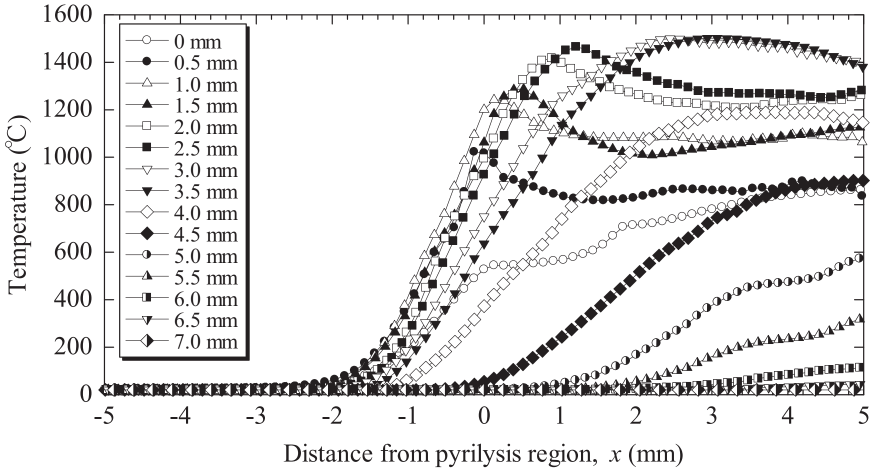

Fig. 4 Temperatures of sample No. 2 measured by thermocouples.

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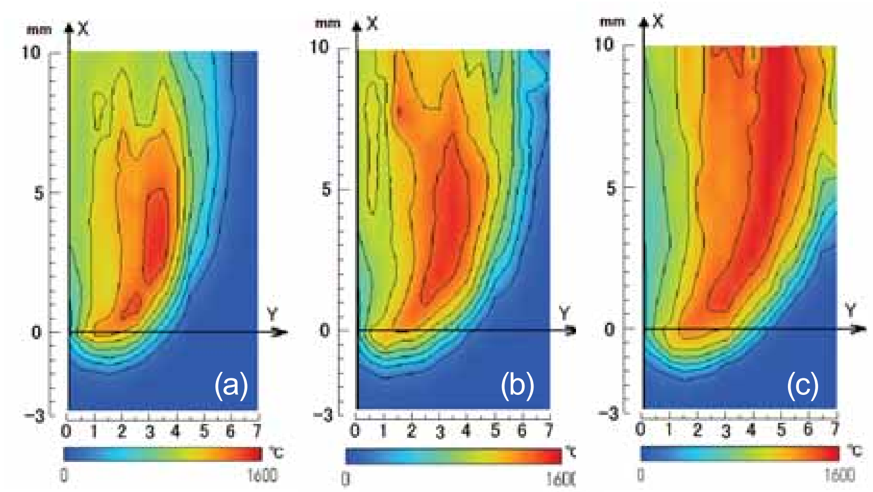

Fig. 5 Temperature distributions of sample No.2; (a) 0% CH_4, (b) 1% CH_4, (c) 4% CH_4.

[Word Count] = (63+10)*2.2*2 + 16 (caption) = 338 words

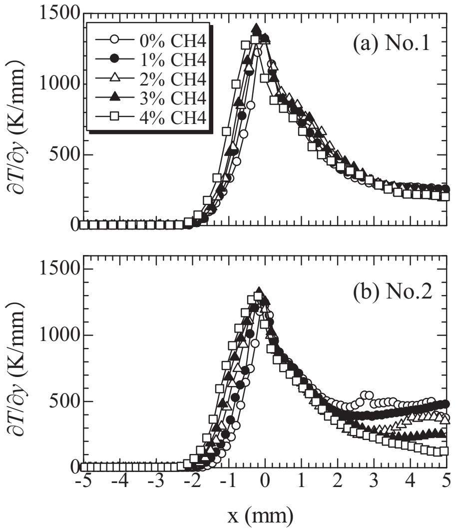

Fig. 6 Profiles of temperature gradient of $\partial T/\partial y$ at filter surface.

[Word Count] = (69+10)*2.2*1 + 11 (caption) = 185 words

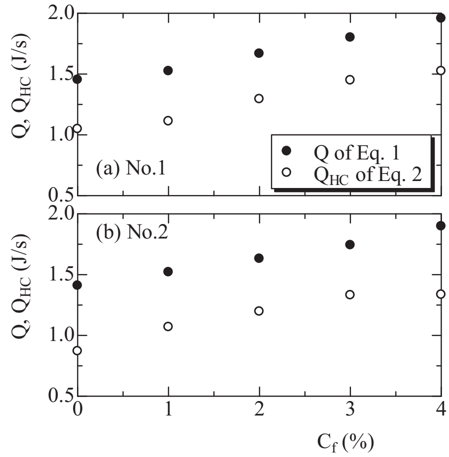

Fig. 7 Heat transfer rate into preheat zone estimated by Eq. (1), compared with measured value by heat conduction. Fuel is methane.

[Word Count] = (59+10)*2.2*1 + 22 (caption) =174 words

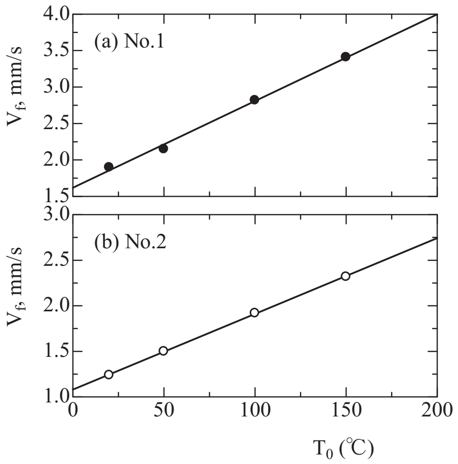

Fig. 8 Flame spread rate in preheated air.

[Word Count] = (60+10)*2.2*1 + 8 (caption) =162 words

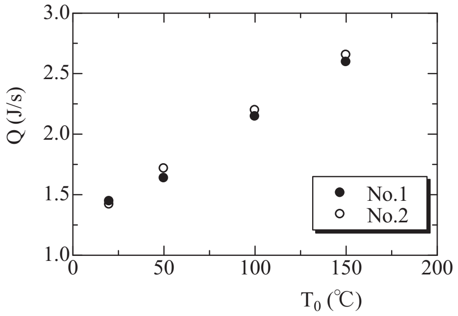

Fig. 9 Heat transfer rate into preheat zone in preheated air.

[Word Count] = (41+10)*2.2*1 + 11 (caption) = 124 words

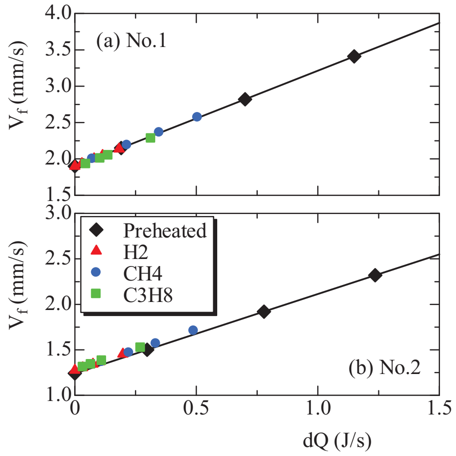

Fig. 10 Variation of flame spread rate with heat input in fuel addition and preheating conditions.

[Word Count] = (59+10)*2.2*1 + 17 (caption) = 169 words

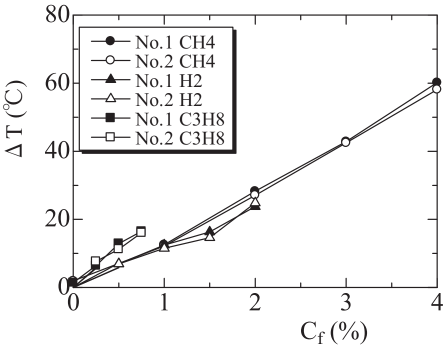

Fig. 11 Estimated temperature rise caused by fuel addition.

[Word Count] = (45+10)*2.2*1 + 9 (caption) = 130 words

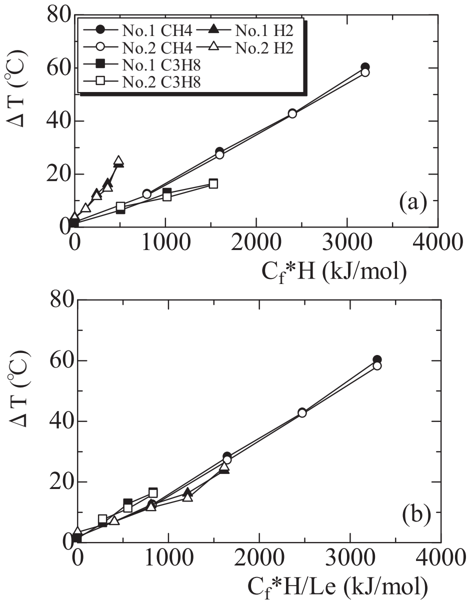

Fig. 12 Estimated temperature rise caused by fuel addition, corrected by heat of combustion (*H*) and the fuel Lewis number (Le).

[Word Count] = (79+10)*2.2*1 + 21 (caption) = 217 words