Study on Ignition-like Behavior Caused by Interaction of Curved Diffusion Flames

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1 Introduction

In the practical combustor, combustion field is fully filled by various eddies due to the combination of turbulent flow field. When such eddies interact with flames, flames are changed its shape and its inner structure, for example flames are folded and thus frequent flame-flame interaction (thermally as well as chemically) occurs. In this sense, one can say that the one of fundamental processes found in the combustor is the interaction of curved and stretched flamelets. This is a motivation in our study.

In the past, Petrov et al. studied on an interaction of parallel diffusion flames numerically [1]. In their model, two flat flames come close together with time and eventually interact with each other before the flame extinction experiences. They revealed that when adjacent parallel diffusion flames interacted with each other, the burning rate decreased. Interestingly, they observed an abrupt increase in temperature just before the interaction, and were convinced that such time-dependent behavior depended on the imposed strain rate. They concluded that interaction of parallel diffusion flames induced the merging of the two reaction zones, and such interaction behavior should be categorized as "chemical interaction", not "thermal interaction". Although they did not specify the reason of abrupt temperature rise, merging chemical structure brought by two adjacent flames could be the responsible, something like fuel meets oxidizer due to the "merge" to show unsteady temperature increase behavior there. Thus, we consider such "time-dependent flame-interaction behavior" as simply an "ignition-like behavior" hereafter. Petrov et al. interested in only the interaction of flat flames, because impact of curvature dominates the dynamics at the lending edge of the spiral and things are quite complicated once such effect is concerned simultaneously. Although they emphasized the importance of interaction of "curved" diffusion flames, this was out of concern in their paper.

Later, Yang et al. proposed a special counterflow burner to form two steady adjacent "curved" diffusion flames [2][3]. They utilized this burner to examine the extinction limit based on the flame interaction accomplished by diluted fuel and oxidizer flows. In this work, they confirmed the increase of OH radical at the interaction point, where was sandwiched by curved diffusion flames. Nonetheless, they could not observe any abrupt increase in temperature, such as "ignition-like behavior".

Obviously, these two studies have contradiction in terms of the response of the combustion field due to the interaction. The main reason for this inconsistency is thought to be the difference in the distance between two adjacent reaction zones. In fact, the moderate strain rate ($< 35\ s^{-1}$) was adopted in Yang's work [3] and this was much smaller than the work done by Petrov et al. [1].

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Previously, authors firstly made the numerical simulation for interaction of two curved-stretched flames with large strain rate (80 s^{-1}) and found the abrupt change in temperature successfully [4]. In the study, a pair of curved-stretched diffusion flames was formed with the burner which was similar to what was used in Yang's work [3]. According to the numerical analysis, interaction of reaction zones, which was predicted by Petrov et al., was confirmed. Due to the decrease of local reaction rate at the flame tip (the point showing the maximum curvature), a small leakage of oxygen into hot vitiated fuel gas occurs, and abrupt increase in temperature "ignition-like behavior" was confirmed in the center of the combustion domain where curved-stretched diffusion flames interacted with each other. Interestingly, frequency of this ignition-like behavior was proportional to the strain rate, which is the same meaning with characteristic flow time τ_f [5]. However, our previous prediction was based on the one-step reaction model [6], and this model might be questionable to be applied to "ignition-like behavior" for which the chemical effect plays an important role. In this study, for the purpose to validate the previous predictions, ignition-like behavior is obtained experimentally and its characteristics are investigated accordingly.

2 Experimental setup

To obtain ignition-like behavior caused by interaction of curved diffusion flames, four slot burners are used to form four fuel-oxidizer interfacial planes in the combustion zone as shown in Fig. 1 schematically. Two "combined" (slot) burners are made; each one consists of two (single) aligned slot burners. Then these burners are crossed to form a stagnation-point flow. The fuel is injected from the diagonally located streams, and the oxidizer is injected from the other two. Eventually, four "crossed" shape fuel-oxidizer interfacial planes are formed between the upper and lower burners. With this burner system, two curved "hyperbolic" diffusion flames are successfully obtained.

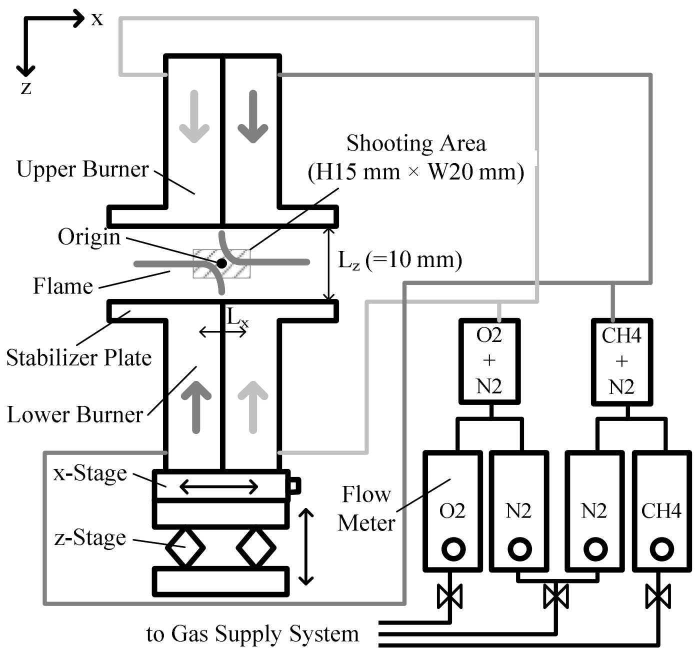
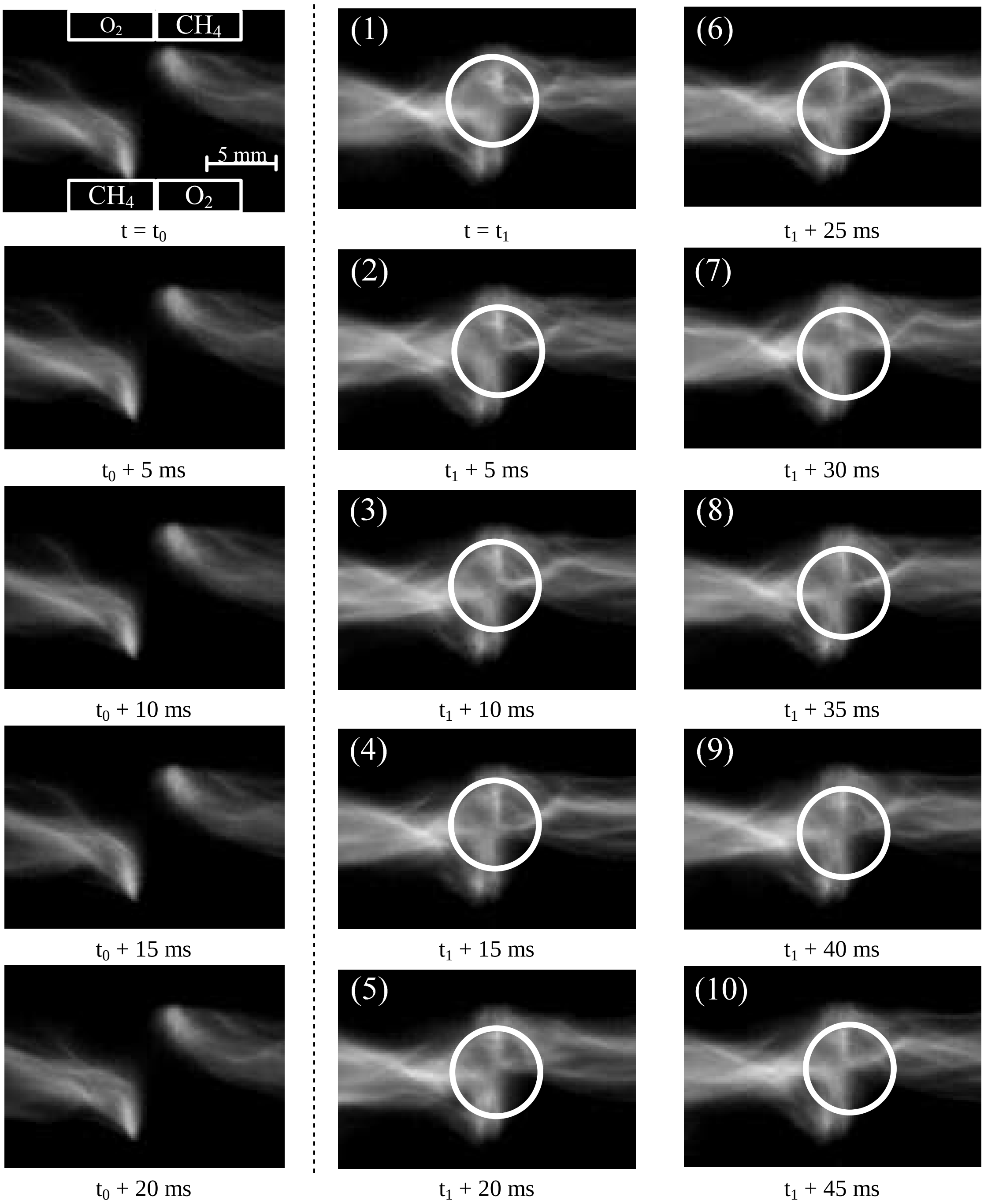


Fig. 1 A schematic illustration of burner system

The upper/lower burners are made of stain-less steel with a thin metal sheet inside it to separate the volume in half, which is identical to the two aligned slot burners. At all burner ports, a rectangular piece of sintered metal (SMC EBS-100M; 5 mm thickness, 8 mm in width (x) and 50 mm in depth (y)) is installed to eject uniform flow into the combustion domain. The upper burner is connected with the outer frame, whereas the lower burner is placed over the mechanical stage (xz) to enable adjustment of the "offset (x)" and "gap length (z)" between the two burners. With this stage, interaction degree of two curved diffusion flames can be changed easily. In this study, offset (L_x) is changed to -2 mm or 0 mm, gap length between the two burners (L_z) is set to 10 mm. The flow rate of fuel and oxidizer are controlled by flow meters (KOFLOC RK1650 series). After the flow control system, gases are distributed into the four burners. The fuel and oxidizer used in this study are methane and oxygen, respectively, and the diluents are nitrogen. Throughout the study, the ratio of the induced amount of fuel is set to 26.7 % in volume and oxygen is set to 80 % in volume, and the ratio of the total volume flow rate of fuel and oxidizer flow is set to unity. To avoid any disturbance caused by the buoyancy-induced flow, a stabilizer plates is placed near each burner. The gas flow velocity (U) is varied to change the flame interaction degree. A microphone (Onosoki MI-1432) and a high-speed camera (IDT MotionXtra N3 (maximum 61000 fps @ 1280 × 12); 1000 fps, shutter speed : 1.4 ms) are put in front of the shooting area (H15 mm × W20 mm) from the distance of 280 mm and 1400 mm, respectively, to acquire flame sound and movie.

3 Results and discussion



(a) Stable flames (L_x = -2 mm) (b) Instable flames due to the ignition-like behabior (L_x = 0 mm)

Fig. 2 Time-sequence of curved diffusion flame behavior (κ = 200 s^{-1})

Fig. 2 indicates time-sequence of curved diffusion flame behavior from the time t = t_0, t_1 at a condition of κ = 200 s^{-1}, where κ is the bulk velocity gradient of the curved diffusion flames which could be represented by $\kappa = (U_{upper} + U_{lower}) / L_z$ [3]. (a) shows stable flames at a condition of L_x = -2 mm and (b) shows instable flames due to the ignition-like behavior at a condition of L_x = 0 mm. From (a), it is confirmed that two curved "hyperbolic" diffusion flames exist stably and are completly independent. That means there is no interaction between two flames. In terms of (b), on the other hand, reaction zone is observed between two flames at the center of the combustion domain, and two flames interact with each other. Focusing on the flame tip of the right side flame, it is also confirmed that flame fluctuates to the direction of center of the combustion domain periodically. In odd-numbered images, a small amount of methane is leaked through the flame tip and merged at the center, where hot vitiated oxidizer gas is present, and finally the ignition-like behavior occurs [4]. After occurrence of the ignition-like behavior, flame tip is returned to the position where flame can exist stably as shown in the even-numbered images. Moreover, compared with the stable flames shown in (a), periodic change of the flame luminance can be also observed in instable flames shown in (b). This can be also confirmed with Fig. 3, which shows average luminance of the central part of the instable flame images against the time.

Fig. 4 shows power spectrum of sound, which is induced by interaction of curved diffusion flames, against the sound frequency (Hz) given by a microphone. (a), (b), (c) shows at a condition of κ = 183 s^{-1}, 192 s^{-1}, 200 s^{-1}, respectively. As indicated, a strong peak of power spectrum of the sound can be confirmed at each condition. When curved diffusion flames interact with each other, unburned methane penetrates the flame and leaks to the center of the two curved flames, where hot vitiated oxidizer gas is present, eventually ignition-like behavior occurs [4]. Generally, ignition induces severe volume expansion of gases

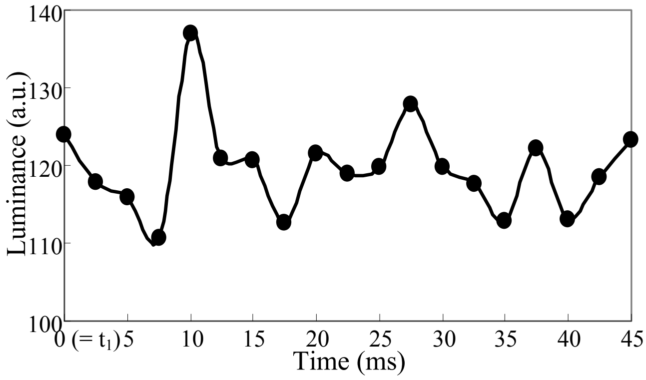


Fig. 3 Average luminance of the image of the instable flames vs. time

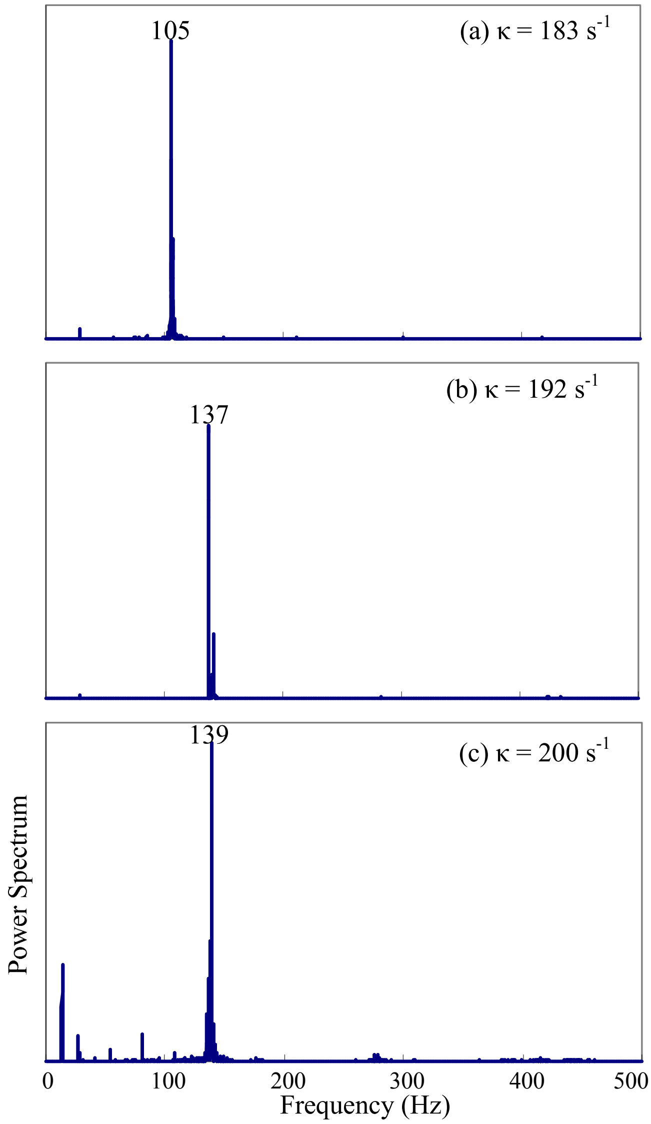


Fig. 4 Power spectrum of sound induced by interaction of curved diffusion flames

and eventually pressure wave occurs. This pressure wave is caught as a “sound” by microphone. So, it can be considered that the strong peak in Fig. 4 is related to the sound induced by ignition-like behavior. That means ignition-like behavior occurs not only numerically but also experimentally.

Fig. 5 depicts frequencies of the sound of ignition-like behavior and the flame fluctuation by means of the bulk velocity gradient, κ, which is the same as a strain rate in the present stagnation-point flow. ● means the frequency of sound which refers to Fig. 4. □ means the flame fluctuation frequency which is calculated by the flame movies obtained by a high-speed camera. It is shown that frequency of sound of ignition-like behavior increases with an increase of κ, and is found that almost linear relation exists between the frequency of the sound and κ. In other words, frequency of ignition-like behavior is proportional to the characteristic flow time τ_f. This is because that the time for the deformed flame shape due to the ignition-like behavior to get back to the shape before the occurrence of the ignition-like behavior is equal to the characteristic flow time τ_f, according to previous studies [7]. Moreover, tangent of the approximate line of the plot is 0.82. This value coincides with the previous numerical prediction [4].

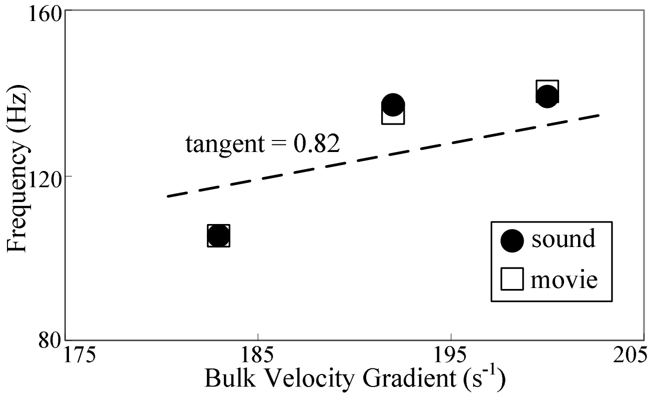


Fig. 5 Frequency of ignition-like behavior vs. given bulk velocity gradient (strain rate)

Concerning the flame fluctuation frequency, this is also proportional to κ, and moreover, flame fluctuation frequency shows a good agreement with the frequency of the sound of ignition-like behavior at the same κ. This means that fluctuation induced by interaction of curved diffusion flames, which was indicated in the author’s previous work [4], is induced by the ignition-like behavior.

From all of the discussions above, previous numerical prediction about “ignition-like behavior” caused by interaction of “curved” diffusion flames is revealed to be validity with flame fluctuation, change of flame luminance and frequency of pressure wave. It is also convinced that the mechanism of “ignition-like behavior” can be understood with the estimation of the local reaction rate at the maximum curvature point of the flame, which was indicated in author’s previous works.

4 Conclusions

For the purpose to validate the previous numerical predictions, abrupt temperature increase caused by the interaction of “curved” diffusion flames, which we call “ignition-like behavior”, is obtained experimentally and its characteristics are investigated accordingly.

From the strong peak of the power spectrum of the sound induced by curved diffusion flames which interact with each other, ignition-like behavior is confirmed to occur experimentally, which was only realized in the numerical analysis before. The frequency of ignition-like behavior is proportional to the bulk velocity gradient, which is identical to the characteristic flow time. Tangent of the approximate line of the plot of the ignition-like behavior frequency against the bulk velocity gradient is 0.82. This value coincides with the previous numerical result. According to the flame movie given by high-speed camera, frequency of flame fluctuation, which is induced by interaction of curved diffusion flames, also shows a good agreement with the frequency of ignition-like behavior at the same condition of bulk velocity gradient.

Finally it is concluded that previous numerical prediction about “ignition-like behavior” caused by interaction of “curved” diffusion flame is revealed to be validity. It is also convinced that the mechanism of “ignition-like behavior” can be understood with the estimation of the local reaction rate at the maximum curvature point of the flame, which was indicated in author’s previous works.

Acknowledgments

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