Some Features of Oscillating Downward Propagation Flames Induced by External Laser Irradiation

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1 Preliminary considerations

The occurrence of flame instabilities has been extensively discussed in recent years, because it is a basic process in turbulent flames involving wrinkled flame surfaces, flame bulges, and local flame extinction (flame holes)[1] . The propagation of premixed flames in tubes is widely used to investigate the genesis of flame front behaviors, and there are many reports of propagating flames in tubes showing a variety of flame shapes along the direction of propagation (curved, flat, wrinkled, tulip, and cellular shapes) [2, 3]. It has been proposed that the formation of these shapes could be caused by the combined effects of a number of factors such as non-slip conditions at the wall surface, reverse flow in the vicinity of central parts of a flame, Darrieus-Landau instability, and acoustic waves.

Recently, Tsuchimoto et al. have conducted experiments to investigate oscillation phenomena in upward propagation flames [4, 5]. They had flames with a convex structure towards the unburned mixture on freely propagating flames using CO_2 laser irradiation, where the flame could undergo positive flame stretch. The intentionally-formed flame surface could modify the subsequent flame propagation behaviors, and it was possible to induce unstable motions in the flames. The external laser irradiation preheats the unburned mixture locally in front of the reaction zone, and the flame propagation velocity increases locally, here the flame front acquires a strongly curved shape which is sensitively subject to Lewis number effects. In this paper, we report transient phenomena in tubulization of downward propagating flames triggered by CO_2 laser irradiation. The preheated mixture induces flame instability, and then the increased flame surface enhances the burning rates over that of stable flames. Due to the procedures, the burned gas flow behind the reaction zone could show sudden pronounced changes. Once the higher flow rate of burned gas in a tube is induced, the flame propagation is susceptible to acoustic influences [2]. Figure 1 shows examples of flame fronts during flame propagation inside a transparent tube without CO_2 laser irradiation, showing the downward travel of a flat flame attained under the condition (see Table 1) mainly dealt with in this paper. This flame is selected as the default flame to observe the turbulization starting from the deformed flame that is induced by laser irradiation [5].

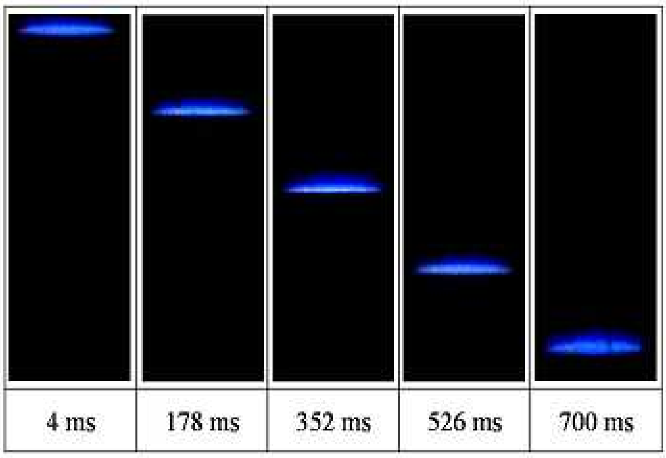

Fig. 1 Still images of the temporal evolution of flame fronts without laser power.

2 Experimental configuration

The experimental apparatus used in the present study is schematically outlined in Fig. 2. The propagation tube (transparent acrylic tube, inner diameter 50 mm and length 450 mm) is filled with the tested gas. There is an automatic opening system powered by an electro-magnet and a mechanical spring at the upper end of the tube. When the igniter is activated, the exhaust part is simultaneously opened. The premixed gas in the tube is exposed to the laser beam (beam diameter 3.3mm, SYNRAD Firester v20) in the time 0.6 seconds after ignition, and the time-dependent behaviors of oscillating flame fronts are captured by a high speed camera (500 fps, exposure time 2ms). To establish the flame position, the luminosity of individual pixels was measured from JPG files.

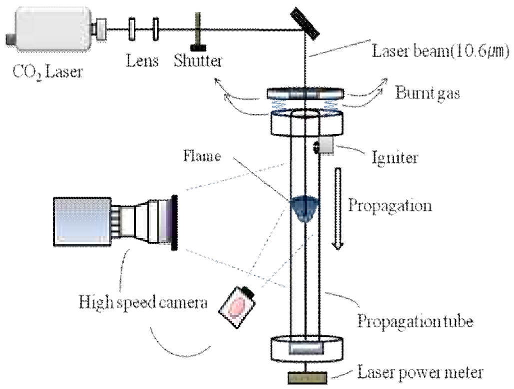

Fig. 2 Schematic outline of the experimental setup.

C_2H_4	O_2	CO_2	Φ	Le	S_L(cm/s)
9 %	21 %	70 %	1.29	0.84	25.1

Table 1 The tested gas composition(Φ: equivalence ratio, Le:Lewis No., S_L:1-D laminar burning velocity).

3 Results and discussion

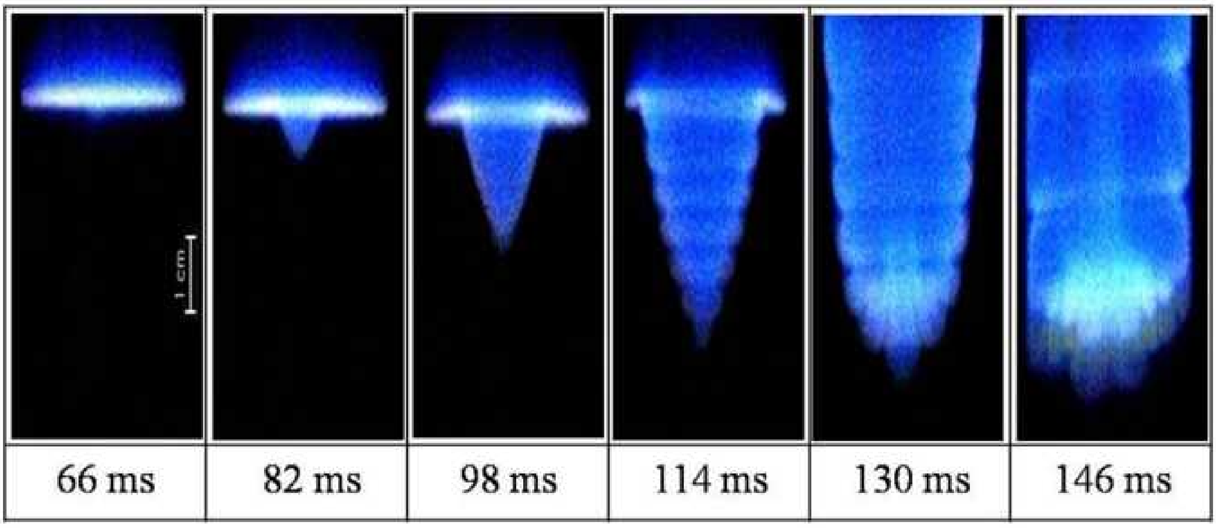

Fig. 3 Still images of flame shapes at the time instants 66; 82; 98; 114; 130; and 146ms after irradiating CO_2 laser with a laser power of 12 W

Figure 3 shows sequential images of the downward propagating flames observed at the arrows on the green curve in Fig. 4 with a laser power of 12 W. The flame front is strongly curved and the deformed flame front is gradually augmented, accompanied by a remarkable acceleration of the flame until 130 ms as shown in Fig. 4. When the apex of the flame is highly deformed and has a high curvature (convex towards the unburned mixture), the flame surface could focus deficient reactants (by mass diffusion) in the vicinity of the flame tip, resulting in high local temperature locally. Also, the presence of defocusing heat (heat loss) could reduce the temperature at the flame tip, but this influence is relatively small in comparison with the influence of mass diffusion (non-equidiffusion effect, Le<1). The above physical processes are the background to the approximately 160Hz "oscillatory-propagation-behaviors [4]" measured from Fig 4. Turning to Fig. 3, special attention should be paid to transversely propagating motion of the wrinkled surface around the center that was

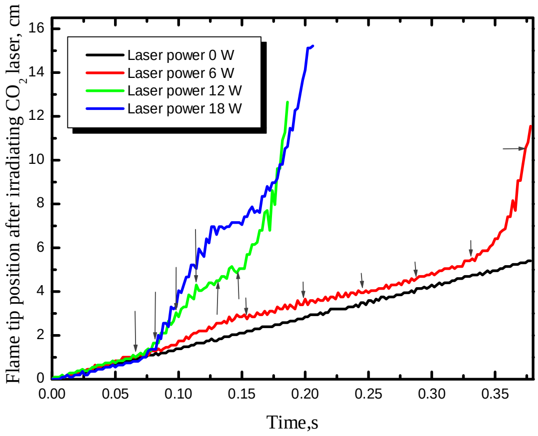

Fig. 4 Flame tip position vs. time with various laser power inputs.

generated by flame tip oscillation. At 114 to 146 ms after the irradiation, the evolution of second bulges on the flame front becomes more active than that at flame tip, and there is a gradual formation of concave structures between the individual cells. After these moments, the corrugated flame front is finally established, and there is a sudden decrease in flame velocity. The increase in the area of the flame surface makes it susceptible to inducing acceleration of burned gas, and the buoyancy works on the accelerating downward propagation, additionally. The following stage of the flame behaviors, secondary acceleration (acoustic instability) will be discussed latter in this paper. Figure 5 displays sequential images of the temporal evolution of a flame front with a laser power of 6 W, which can be referred to in Fig. 4 respectively (solid arrows on red line). During the propagation, the lower laser power increases the local flame velocity, the flame tip gradually degenerates into unstable behaviors due to thermal-diffusive instability at 202 ms. At 290 ms, the locally preheated mixture located beneath of the flame is subject to the buoyancy influence and relatively strong upward flow is generated, overcoming the local flame velocity at the center. The flat flame front is observed between 246 and 290 ms. Finally, the concave flame shape towards fresh mixture is clearly attained at 334 ms. It can be proposed that for Le <1, this negative flame stretch reduces the velocity at the flame tip, and that other portions of the flame surface around the flame bulge propagates to the center axis transversely (reestablishing smoothness). Once these procedures are repeated, the resulting flame surface would be wrinkled with smaller cell sizes than those induced by the convex. When the flame surface is perturbed by the unstable behaviors, it is more than likely that this increased flame surface expedites the burning rate in the reaction zone. For the enhanced states of burning in Fig. 5, there may be a considerable influence on the flame propagation by acoustic waves. As shown in Fig. 5, after the saturation of the wrinkled surface induced by concave surface (334 ms), a secondary acceleration (378 ms) with acoustic instability is triggered suddenly as shown in Fig 4 and Fig 5, akin to the phenomena observed in cellular flames [6]. The above discussed unstable flame behaviors induced by active controls on the flame shape without external flow disturbances. To investigate the tubulization [2] of premixed flames, the position of the flame tip, its velocity, and still images of transient flame motion with the laser power 18 W are shown in Fig. 6. After the primary acceleration, the flame tip has almost paused in regime (A). During this regime (A) flame development, the flame front becomes flat roughly with the development of concave structures. Then, it is suddenly accelerated in regime (B), accompanied with noise. It must be noted that the concavity facilitates

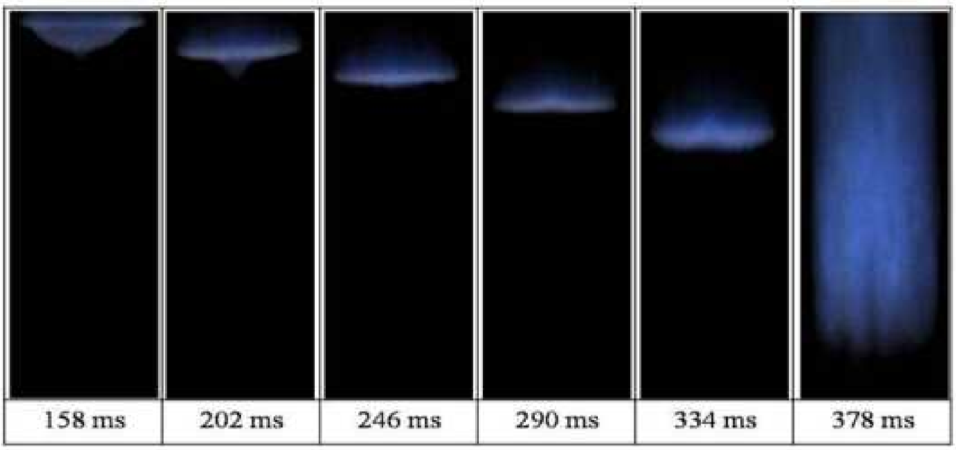

Fig. 5 Still images of flame shapes from 158 ms to 378 ms with laser power 6 W.

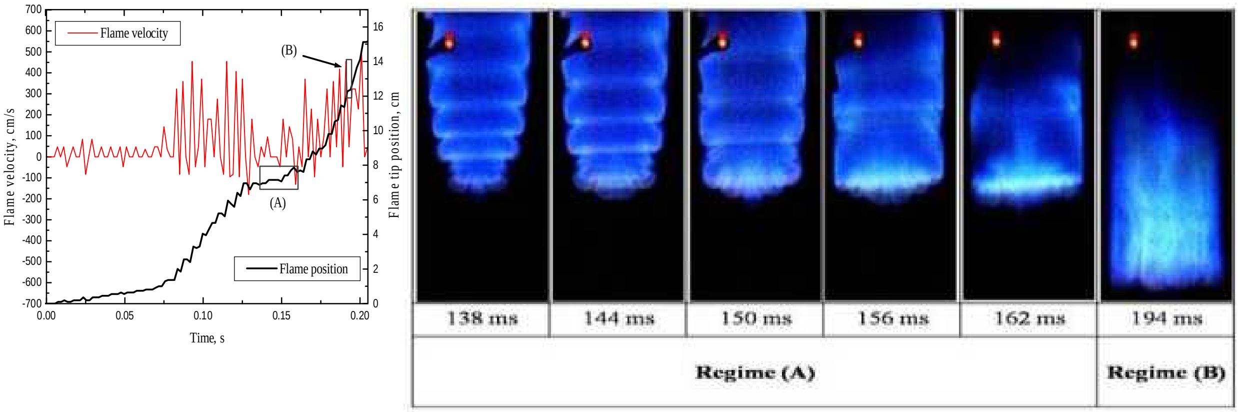

Fig. 6 Variations in the flame position and velocity (left) and still images of the flame motion(right) with a laser power of 18 W.

the small scale structures of wrinkled surface in Fig. 5. These appearances could also be observed with laser powers of 12 and 18 W. The experimental results with the unstable behaviors obtained in the paper make it possible to suggest that the turbulization [2] of propagating flames in tubes could be initiated by artificial controls on flame shapes (e.g., CO_2 laser irradiation in this study).

4 Concluding remarks

Experimental studies of premixed flames propagating downwardly were conducted to elucidate transient motion toward turbulization of laminar premixed flames induced by artificial controls of the flame shapes, which have not previously been observed. The observation showed different, unique phenomena depending on the laser power input. The importance of the flame shape could suggest that a corrugated flame structure has a strong effect on the dynamic behaviors of propagating flames in tubes. Mechanisms explaining the observation are proposed in the present study, however further investigations would be necessary to validate the discussion.

5 Acknowledgements

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References

[1] Lyons K.M et al. (2005). On flame holes and local extinction in lifted-jet diffusion flames. Combust. Flame. 142: 308.

[2] Aldredge R.C, Killingsworth N.J. (2004). Experimental evaluation of Markstein-number influence on thermoacoustic instability. Combust. Flame. 137: 178.

[3] Gonzalez M. (1996). Acoustic instability of a premixed flame propagating in a tube Combust. Flame. 107: 245.

[4] Tsuchimoto M et al. (2008). Effect of gravity and beam diameter on flame oscillation phenomena induced by external laser absorption. Combust. Sci. Tech. 180: 1.

[5] Tsuchimoto M et al. (2009). Research on the relation of flame front curvature and oscillatory flame propagation by external laser irradiation method. Proc. Combust. Inst. 32: 1003.

[6] Kadowaki S et al. (2005). The unstable behavior of cellular premixed flames induced by intrinsic instability. Proc. Combust. Inst. 30: 169.