Interaction between Propagation Speed and Flame Structure in Downward Cellular Propagating Flame in a Combustion Tube with CO_2 Laser Irradiation

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1 Introduction

All flames are intrinsically unstable. This instability is due to hydrodynamic and thermo diffusive effects. The hydrodynamic instability is the result of the density change across the flame, between the burned and the unburned gas, and affects all flames no matter the fuel composition or the mixture characteristic [1]. The thermo diffusive effects are related to preferential diffusion because of (1) the difference in the molecular weight of the reactants and (2) when the thermal diffusivity of the mixture is smaller than the mass diffusivity of the deficient reactant [2]. One of the most interesting ways these instabilities develop is as cellular structure, the subject of present investigation. In our previous research, Park et al. [3] have experimentally studied the transition from laminar flat flames to turbulent motion, induced by external laser irradiation, proving that this is a promising technique to study the relation between flame shape and flame instability in detail. In the present study, we focus in understand the effect of changing the propagation speed of the flame, on the flame structure. We use the CO2 laser irradiation method since it is a technique that allows us to vary the flame speed during propagation and consequently the occurrence of the transitions described here. Three main motions are reported and detailed: transition from cellular flame to convex structure towards the unburned mixture; transition from convex structure to concave structure towards the unburned mixture; and the return to the initial cellular flame.

2 Experimental Set-up

The experimental set up is outlined in the Fig. 1. A vertical propagation tube made of transparent acrylic, with a 50 mm inner diameter and 450 mm long is filled with premixed gas, described in Table 1, at atmospheric pressure and ambient temperature. There is an automatic opening system of the tube upper end. After the top end is opened, the igniter is immediately activated and flame front propagates towards the unburned mixture while it is exposed to stepwise CO_2 laser power input. CO_2 laser is irradiated through the center of the tube after the cellular flame is formed. Two high-speed cameras capture the behavior of the flame, bottom and side view of it. The onset of CO_2 laser irradiation is taken as t=0 for the present study.

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Table 1: Composition of the premixed gas

C_2H_4 (Vol. %)	O_2 (Vol. %)	CO_2 (Vol. %)	Le	Φ	S_{fl} (cm/s)
9	20	71	0.79	1.35	20.25

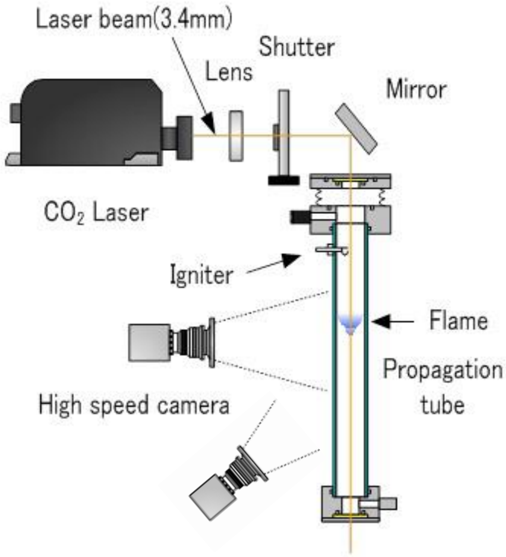

Figure 1. Experimental set-up.

3 Experimental Results

Experiments have been conducted for three CO_2 laser powers of 2, 4 and 6 Watts with continuous irradiation. Once the igniter is activated, a cellular flame is formed and propagates downwardly to the unburned mixture. Then, CO_2 laser is irradiated along the tube, deforming the flame. The combustion velocity locally increases while the unburned mixture ahead of the flame front is preheated in the path of the laser beam. In the sequential pictures of Fig. 2 one can observe the temporal variation of the flame front. Firstly, transition from cellular structure to a big one smooth cell convex to the unburned mixture, occurs within 0.17 second for laser powers of 2 and 4 Watts and within 0.16 second for 6 Watts, after CO_2 laser irradiation has started. This one cell is maintained for short time and then it evolves into the concave structure that appears in the center of the flame, where the laser beam is irradiated. At the same time, the return of cellular flame around this concave structure occurs. As the laser power is increased, the time for the appearance of the concave structure takes place earlier and the depth of this concave structure is larger and the size of the new cells around it is bigger.

4 Discussion

4.1 First Transition

Previous studies have shown that cellular flames are the product of the competition among the hydrodynamic instability due to the density change across the flame; destabilizing thermo diffusive effects when the Lewis number is less than unity; and stabilizing effects of gravity under a given flame velocity. Moreover, the growth rate of the hydrodynamic instability is given as a function of the flame velocity [4]:

$$\sigma \approx u_l k,$$

where u_l is the laminar flame speed and k is the modulus of the wave vector. This is the solution of the analysis done by Darrieus and Landau, they considered that there is a perturbation of the flow velocity, ahead of the flame, produced by the front wrinkling equal to the derivative of the flame position respect to the time, the flame velocity, and this perturbation will have the same sign as the deformation of the flame. Hence, for the phenomena described in the present study, u_l is being increased with the CO_2 laser irradiation, intensifying the hydrodynamic instability specifically at the center of the flame, where CO_2 laser is irradiated, enhancing just one wrinkle and generating the big smooth cell, convex towards the unburned mixture.

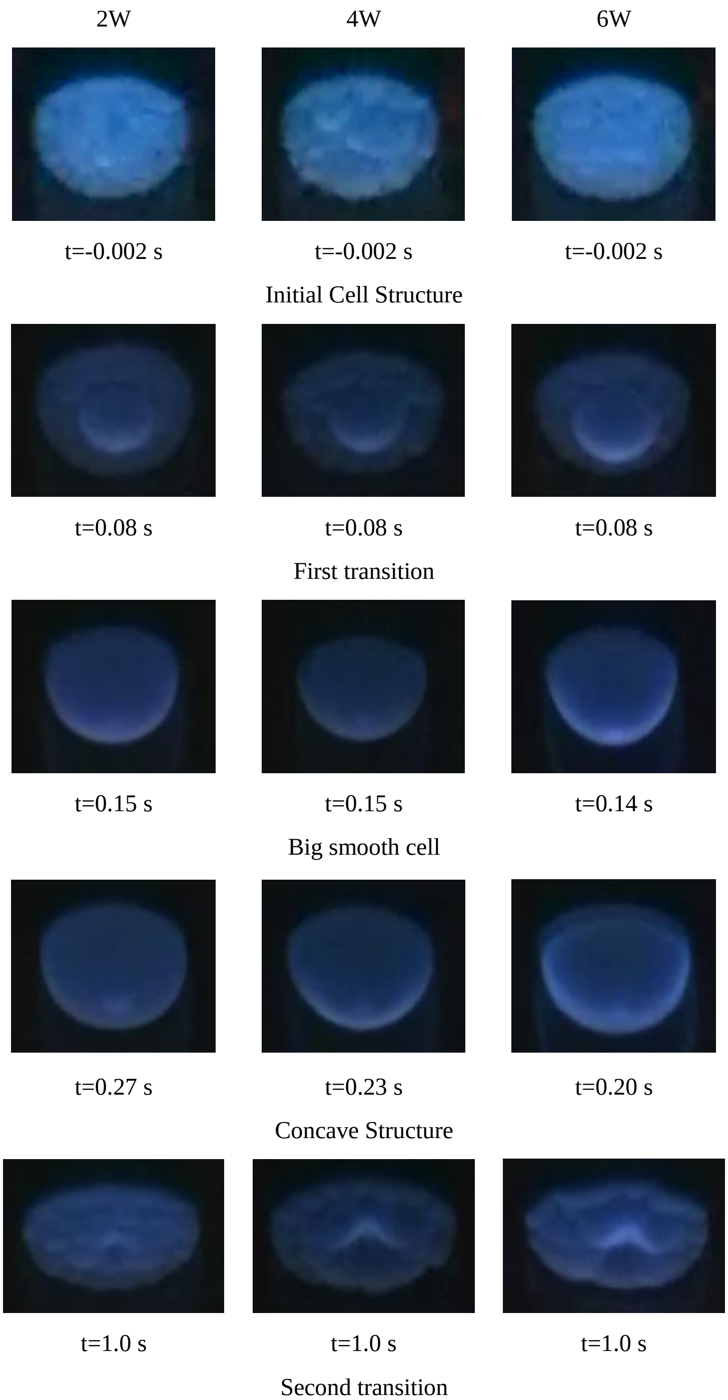

Figure 2. Temporal variation of the flame front with external time controlled CO_2 laser irradiation.

4.2 Second Transition

However, CO_2 laser irradiation not just locally increases the combustion velocity but also preheats the unburned gas ahead of the flame front, decreasing its density in the path of the laser beam and causing the upward motion of the flow because of buoyancy effects. Comparison between the induced flow velocity due to buoyancy and the acceleration of the flame velocity because of preheating effect is done in order to describe the appearance of the concave structure. The induced flow velocity because of buoyancy effects is estimated through calculation of the buoyancy force:

$$F_b = (\rho_{u0} - \rho_{u1}) g l A,$$

where F_b is the buoyancy force; ρ_{u0}, the density of the unburned gas; ρ_{u1}, the density of the unburned gas in the path of the laser beam; g, gravity; l, distance from the bottom of the tube to the flame front; and A is the front area of the preheated volume corresponding to the diameter of the laser beam. By making equation of motion from the buoyancy force identical to Newton's second law definition, we can find the dynamic change of the induced flow velocity by the following equation:

$$u = \int \frac{g(\rho_{u0} - \rho_{u1})}{\rho_{u1}} dt,$$

where u is the induced flow velocity and t is the time. Fig. 3 shows the values of u and the flame velocity, S_{fl} as a function of time. The flame velocity, S_{fl}, is obtained as in previous studies [5]. First, since the absorption coefficient of the burned gas for CO_2 laser wavelenth is negligible, compared to the one from ethylene, we assumed the absorption of CO_2 laser takes place only in the unburned gas and is simply described by the Beer's law, which yields the temperature distribution in the unburned mixture. Then, we use CHEMKIN (with GRI-Mech3.0) to predict the flame velocity dependance on the temperature to account the preheating effect because of the CO_2 laser irradiation. Also, the displacement of the flame front due to its own motion, is considered in the calculation. From Fig. 3 one can observe that the combustion velocity increases with a nonlinear trend due to preheating effects until it reaches the steady state. On the other hand, the buoyancy induced flow velocity, noted as u in Fig. 3, monotonically increases with time and it overcomes the combustion velocity causing the appearance of the concave structure. The cross point observed in Fig. 3 represents the moment of the appearance of the concave structure and matches with the visual observation of the experimental pictures. At the same time that the one big smooth cell evolves into the concave structure, new cells are formed around it since the buoyancy effects are overcoming the local increment of the combustion velocity in the tip of the flame, decelerating it close to the value of the initial cellular flame speed causing the return to its original cellular structure. In the results presented in this study one can observe 3 regimes: (I) transition from cellular flame to one big smooth cell; (II) transition from this one big smooth cell to concave structure; and (III) final motion of concave structure with the return to cellular flame around it. Propagation speed for every regime, including the case with no laser irradiation, has been calculated from the temporal variation of the flame front position shown in Fig. 4. Table 3 describes how the propagation speed changes in the regimes observed. Once CO_2 laser beam is irradiated, propagation speed increases and the difference between this increased value and the initial flame velocity also escalate according to the laser power as observed in Table 3. Then, when concave structure appears, propagation speed is small as the initial velocity since combustion velocity is overcome by the buoyancy effects.

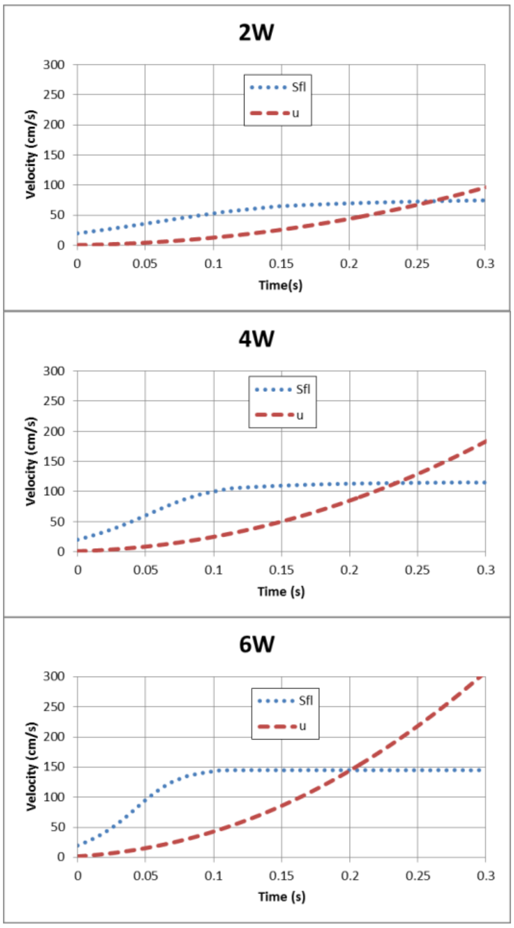

Figure 3. Plots of the induced flow velocity and the flame velocity as a function of time.

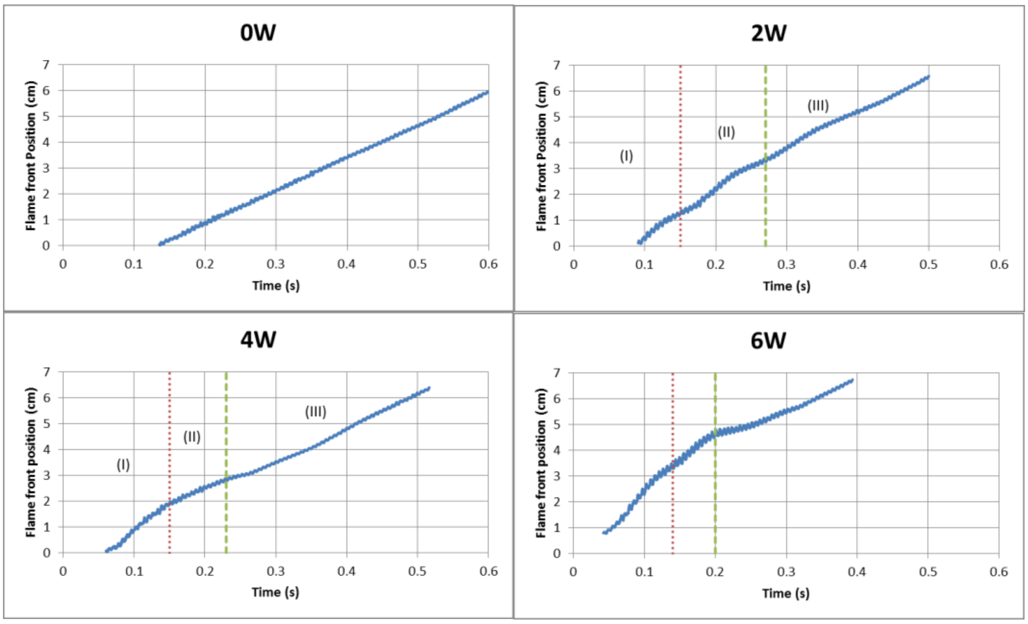

Figure 4. Temporal variation of the flame front position. Dotted line indicates the time for the formation of the one big smooth cell and dashed line, the time for the appearance of concave structure.

Table 3. Propagation Speed

Laser power (W)	Cellular flame (cm/s)	Regime (I) (cm/s)	Regime (II) (cm/s)	Regime (III) (cm/s)
0	12.7	-	-	-
2	12.7	19.8	18.7	13.4
4	12.7	20.8	12.5	11.4
6	12.7	22.2	18.6	9.9

5 Conclusions

The transient deformation of a downward propagating cellular flame in a combustion tube with external laser irradiation has been studied in order to explain the interaction between the propagation speed and the flame structure. Several motions have been observed: transition from cellular structure to one big smooth cell because of the enhancement of the hydrodynamic instability; appearance of the concave structure because of upward motion of the flow produced by buoyancy effects; and the return to cellular flame around this concave structure as a result of the change in the propagation speed. The estimation of the induced flow velocity due to buoyancy effects in order to compare with the combustion velocity of the flame, suggests that buoyancy effects can control the flame structure and that evolution of the concave structure is induced by buoyancy driven flow overcoming the propagation speed. This is for low laser power (lower than 6 Watts) condition, while for higher laser power, CO_2 laser irradiation leads to the convex structure and transition to the turbulent motions as described in our previous work [3] and [5]. These experimental results allow thinking that CO_2 laser irradiation is the unique technique to modify the flame structure varying just one parameter, propagation speed.

6 Acknowledgment

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