Effects of Variation of the Flame Area and Natural Damping on Primary Acoustic Instability of Downward Propagating Flames in a Tube

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1 Introduction

This investigation was triggered from the experimental observations by Searby [1]. He reported four distinct regimes of downward propagating flames in a tube: (1) a cellular flame with no acoustic sound just after ignition, (2) a primary acoustic instability with a flat flame surface, (3) a violent secondary acoustic instability with a corrugated flame, and (4) turbulent flame. Here, the important problem which remains unsolved is the generation of primary acoustic instability. The approach on how to resolve this issue is generally to consider the Rayleigh criterion [2]: an acoustic wave will be amplified if the time integral of the product of the pressure and heat release fluctuations is positive over a pressure cycle. To prove this criterion, many previous researchers [3-7] have proposed a variety of mechanisms. In particular, a suggestion by Markstein [7] has been in the spotlight now [5, 6]. He has suggested that primary sound is generated where flames are sufficiently fast to be affected by fluid dynamics intability (or Landau-Darrieus Instability). An analytical analysis of this mechanism was performed by Pelcé and Rochwerger [5]. They demonstrate that the growth rate of the thermoacoustic instability is proportional to $(k_c a_0)^2$, where k_c is the critical wave number and a_0 is the peak-to-peak amplitude of the cellular flames. The basic reson for this may be understood from the Rayleigh criterion. The rate of heat released per unit cross-sectional area of the tube by the cellular flame is $q = \rho_u S_L c_p (T_b - T_u) S$, where ρ is the density, T is the temperature, subscript u and b refer to fresh and burned mixtures, S_L is the flame burning velocity, C_p is the heat capacity, and S is the relative area of the cellular flame: $S = 1 + 1/4(a_0 k)^2$. It follows that the fluctuations of heat release are proportional to variation of flame area δS. Thus we can expect that the acoustic sound which is generated by a large curved flame can overcome natural damping effect. However, when comparing therory and experiments, k_c and a_0 are very hard to control experimentally since the initial cellular flame is intrinsically unstable. To solve this problem, we utilize a novel method, the CO_2 laser irradiation method, to control the shape of freely propagating flames [8,9,10], because the ethylene gas used is the main absorption medium of CO_2 laser light. Therefore, one of the purposes of this paper is to provide experimental evidence regarding the effects of variation of the flame area on the primary acoustic instability of downward propagating flames in a tube. Another objective is to investigate the effects of acoustic losses on primary sound. Generally, the acoustic losses depend on the geometry of the combustion chamber and on the nature of the gaseous medium. We can only

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consider radiative and wall losses when the combustion tube with one end closed and the other end (ignition side) open is used. Thus, we present experimental observations of the generation of primary acoustic instability by changing the damping ratio and flame propagation velocity..

2 Experimental Procedure

We have conducted experiments with four different gas compositions in association with different acoustic losses and laminar burning velocities shown in Table 1. The cases 1 and 2 are chosen to study the effect of damping factor on acoustic losses. The comparisons of cases 1 and 3 as well as the cases 2 and 4 provide information on the effect of laminar burning velocity. The experimental apparatus is schematically outlined in Fig. 1. The propagation tube (transparent acrylic tube, inner diameter 50 mm and length 511 mm) is fixed vertically and is charged with tested gas at atmospheric pressure. To artificially change the flame area, we utilize the CO_2 laser irradiation method [7-9]. Carbon dioxide and nitrogen were selected as diluents to control properties of gases. There is an automatic opening system of the top lid of the tube powered by an electromagnet and a mechanical spring. When the spark igniter is activated, the top lid is simultaneously opened. The time-dependent behaviors of the downward propagating flame are captured by high speed cameras. A microphone is placed at the bottom to record the sound pressure fluctuation.

Table 1: Composition of the tested gas

Case	C_2H_4	O_2	CO_2	N_2	S_L (cm/s)	T_b (K)	α (cm^2/s)	ν (cm^2/s)	$1/\tau_{rad}$ (s^{-1})	$1/\tau_{wall}$ (s^{-1})	βM
1	0.07	0.24	0.69		21.51	2049	0.13	0.095	1.54	6.65	0.014
2	0.04	0.14		0.82	21.34	1832	0.21	0.154	2.02	10.69	0.008
3	0.06	0.20	0.74		9.66	1814	0.13	0.093	1.54	6.57	0.006
4	0.05	0.18		0.77	33.74	2092	0.21	0.153	2.02	10.66	0.017

S_L: 1-D laminar burning velocity (CHEMKIN3.7, Premix Code, USC-II).

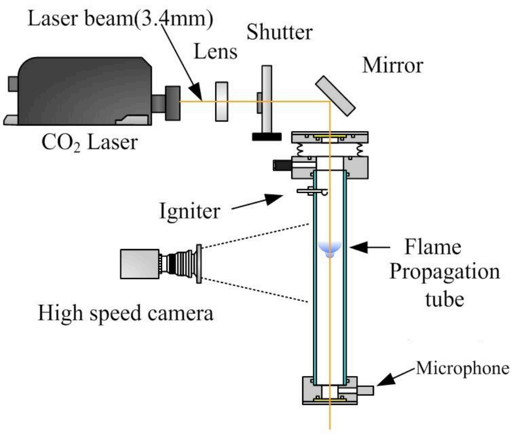

Figure 1. Schematic outline of the experimental setup.

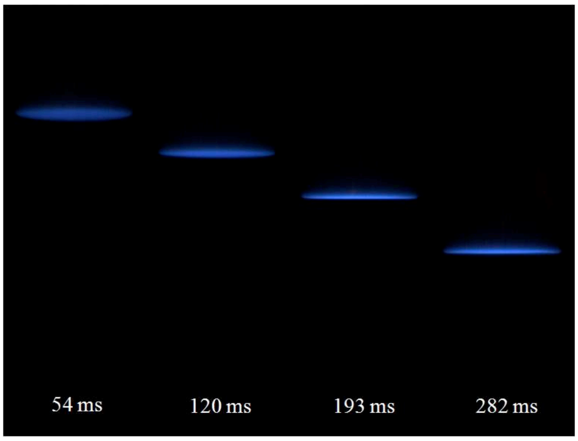

Figure 2. Still images of the temporal evolution of flame fronts without laser power.

3 Results and Discussion

3.1 Without Laser Power

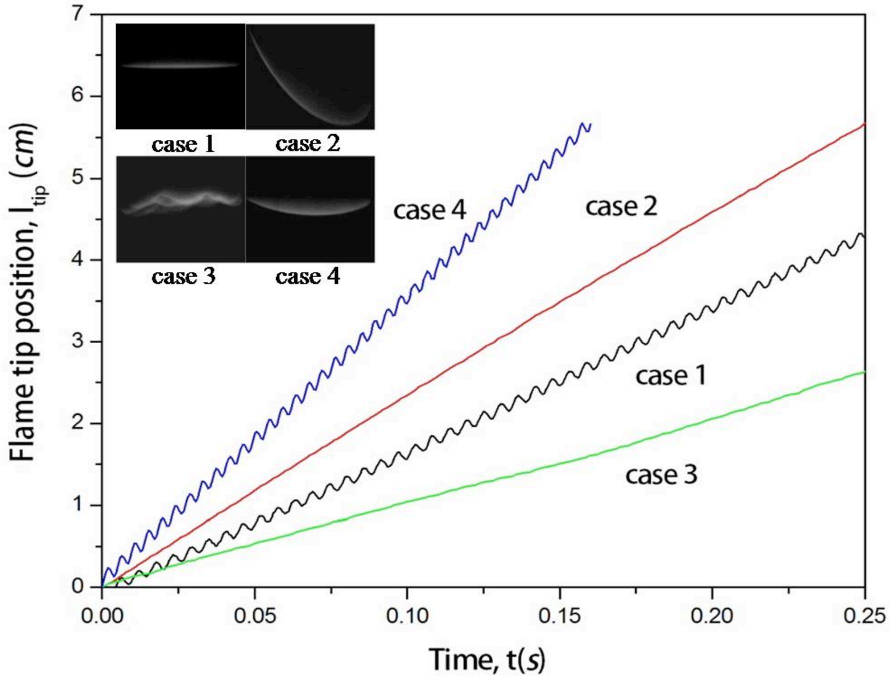

Figure 3. Flame tip position vs. time without laser, flame propagating downward.

Figure 2 shows typical downward propagating flame behavior in primary acoustic instability. After ignition, a curved flame front propagates downwardly due to hydrodynamic instability. And then, the flame becomes flat under the presence of acoustic sound in the propagation tube. Figure 3 depicts the temporal variation of the flame tip position with different gas compositions. Two distinct types of behavior are identified. First a regime of acoustic instability in which the flames are flat and vibrating as shown in case 1 and 4. Secondly, in the regime of acoustically stability, in case 2 and 3, flames are cellular and propagate without fluctuation. Comparing cases 1 and 2, the flame with relatively lower kinematic viscosity and thermal diffusivity (case 1) displays periodic vibration even with same laminar burning velocity. Also, the displacement flame velocity is lower than the case 2 because of the relatively small flame surface area. Comparing cases 1 and 3, the flame with higher velocity (case 1) can only be observed as a vibration behavior even though both cases are at the same kinematic viscosity and thermal diffusivity. In the same way, the comparison of cases 2 and 4 showed that the higher burning velocity tends to give vibration behavior with higher burning velocity. As a summary of the experiment, two facts can be pointed out: (1) larger kinematic viscosity and thermal diffusivity tend to suppress the acoustic vibration, and (2) larger burning velocity tends to cause acoustic vibration.

In general, the acoustic energy is dissipated at the open end of the tube through radiative losses and at the wall through diffusive losses. The characteristic times of acoustic losses can be expressed as follows (Landau & Lifshitz [11]).

Radiative losses: $1/\tau_{rad} = (\omega r)^2/(8cL)$, where ω is the angular frequency, r is the tube radius, c is sound speed and L is the length of the tube. The radiative losses are proportional to ω^2.

Wall losses: $1/\tau_{wall} = \sqrt{8}(\omega\alpha)^{0.5}[(\gamma-1)+\mathrm{Pr}^{0.5}]/r$, where α is the thermal diffusivity, γ is specific heat ratio and Pr the Prandtl number. The first term in the brackets is related to the thermal boundary layer and the second term to the viscous layer. The diffusive losses are proportional to $(\omega\alpha+\omega\nu)^{0.5}$. The total acoustic loss, $1/\tau_{loss}$, is given by $1/\tau_{loss} = 1/\tau_{rad} + 1/\tau_{wall}$.

Thus, heat transfer and viscous friction at the tube walls and acoustic radiation losses at the open end of the tube represent unavoidable dissipation i.e. natural damping processes. Since high thermal diffusivity leads to a gentle radial temperature gradient and an enhancement of the thermal penetration depth at the flame edge, the acoustic instability can be suppressed by acoustic energy dissipation with excessive heat-loss to the acoustic boundary layer. Also, acoustic energy losses due to viscous friction should increases when high kinematic viscosity causes a gradually-varying acoustic velocity gradient at the boundary layer along the wall. Therefore, it is probable that the flame cannot overcome natural damping with high thermal diffusivity and kinematic viscosity in case 2.

Clavin et al. [12] have theoretically shown that the flame whose activation energy is sufficient ($\beta M \geq 0.01$) may nearly overcome the natural damping effects, where M is Mach number and β is the dimensionless activation energy, $\beta = E(T_b - T_u)/(RT_b^{\ 2})$, E is the activation energy and R is the gas constant. In this respect, in the case 3, the energy input to the vibration system may be small enough in comparison with the natural damping effect because the laminar burning velocities and the activation energy are relatively small [12].

3.2 With Laser Power

Figure 4 shows the temporal variation of the flame tip position for different gas compositions with various laser powers. Laser light is irradiated to change flame propagation velocity artificially. For cases 2 and 3, these still represent a regime of acoustic stability despite the CO_2 laser irradiation. The flames appear smoothly curved front during propagation without fluctuation. As mentioned earlier, the rate of heat released per unit area is a function of flame surface area as $q = \rho_u S_L c_p (T_b - T_u) S$. Although it is expected that increasing of the flame surface area causes primary acoustic sound, the experimental facts show that the sustained growth of flame area is not always associated with onset of acoustic instability. Here, maximum value of $(k_c a_0)^2$ are 233.4 and 16 in case 2 and 3 with laser power of 18 W, respectively.

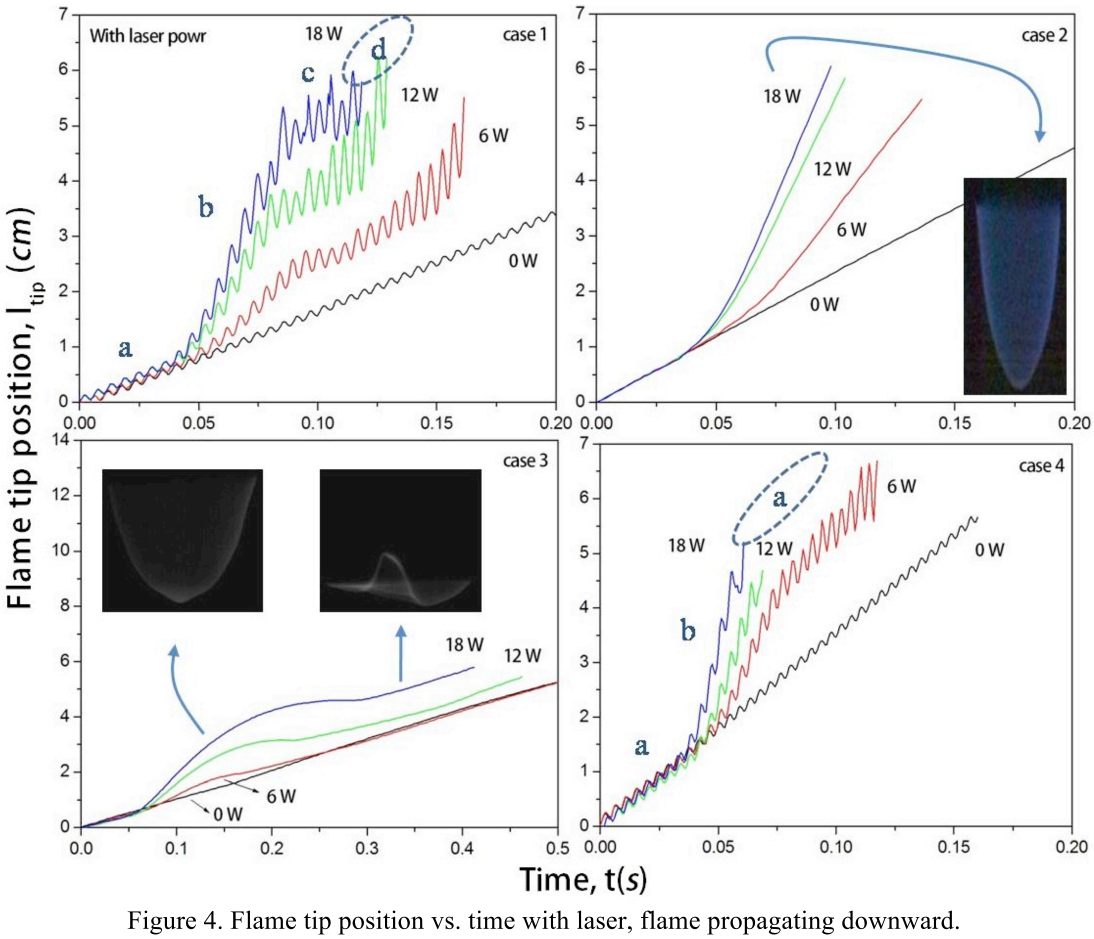

Figure 4. Flame tip position vs. time with laser, flame propagating downward.

Cases 1 and 4 are regimes of acoustic instability with laser irradiation. One can divide the results into four individual types of flame behavior in order to describe these regimes in detail. First, the flat flame corresponds to the primary acoustic instability in Fig. 5-a (upper). The flame appears in "ice-cream" like shape [9] as in the case of exposure to CO_2 laser light in Fig. 5-b (upper). After this, the flame exhibits a corrugated structure on increasing acoustic frequency in agreement with the secondary acoustic instability in Fig. 5-c (upper). Finally, explosive turbulent motion appears with strong noise in Fig. 5-d (upper). Interestingly, for case 4, we cannot observe turbulent motion because the ice-cream like flames again become flat flames even though the flames are continuously exposed to CO_2 laser light in Fig. 5 (lower). It is remarkable that the transition from the secondary acoustic instability to the primary acoustic instability takes place. This restabilization of the secondary acoustic instability may be caused by strong natural damping that suppresses the acoustic instability and prevents transition to turbulent motion.

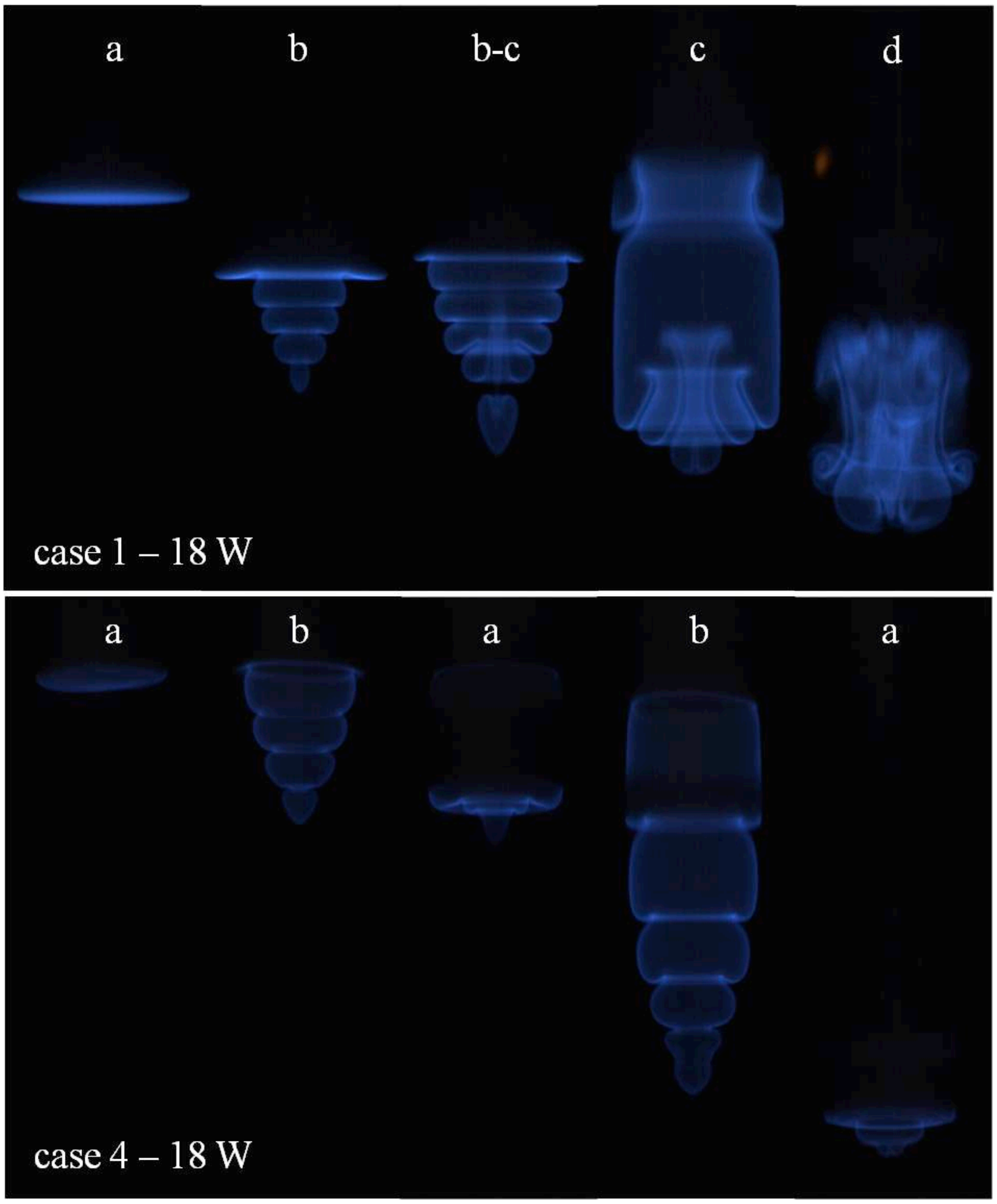

Figure 5. Still images of transient flame motion with laser power 18 W in cases 1 and 4.

4 Conclusion

This paper provides experimental evidence regarding the effect of the flame area and natural damping on primary acoustic instability of downward propagating flames in a tube. The conclusions are as follows:

1) Depending on the thermal diffusivity and kinematic viscosity of the mixture, two different cases, one with no acoustic vibration and the other with acoustic vibration, are found even for the same laminar burning velocity.

2) When laminar burning velocities and the activation energy are very low, primary acoustic instability does not appear. This might arise because the energy input to the vibration system is too small in comparison with the natural damping effect.

3) Although it is expected that the increase of the flame surface area causes primary acoustic sound, the sustained growth of flame area on laser irradiation did not contribute to the onset of acoustic instability in the present experiments.

4) The restabilization of the secondary acoustic instability was observed under certain conditions.

Acknowledgement

This study was supported by a Grant-in-Aid for Scientific Research (KIBAN (B) #26289042) from MEXT Japan.

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