Re-stabilization of Acoustic Parametric Instability for Downward Propagating Premixed Flames of *Le*>1 Mixtures

Ajit Kumar Dubey[1]*, Osamu Fujita[2]
[1]Mechanical and Industrial Engineering, Indian Institute Technology Roorkee, Roorkee, Uttarakhand, India
[2] Division of Mechanical and Aerospace Engineering, Hokkaido University, Kita-13 Nishi 8, Kita-ku, Sapporo, Japan

1 Introduction

Thermoacoustic instability culminating in high amplitude pressure oscillations is usually an unwanted phenomenon when occurring in gas turbine combustors or rocket engines. This is governed by Rayleigh criterion which states that pressure oscillations will increase in amplitude if it is in phase with heat release rate oscillations. One of the simplest experiments to study thermoacoustic instability in combustion systems is a premixed flame propagating in a tube [1]. This has been studied to outline basic features of the phenomenon. Two phases of acoustic instability are observed primary and secondary acoustic instability. Two coupling mechanisms were studied for the primary acoustic instability termed velocity coupling [2] and pressure coupling [3]. Velocity coupling is where heat release rate fluctuations are due to change in area of flame due to acoustic fluctuations and the flame area is also influenced by hydrodynamic instability. Pressure coupling is where heat release rate fluctuations are due to change in burning flux due to change in preheat zone temperature effected by acoustic oscillations. It was shown in our earlier study that the effect of geometrical parameters i.e., diameter and length of the tube on the thermoacoustic instability can only be explained if velocity coupling is dominant [4]. Pressure coupling is dominant when there is no change in the flame shape [5][6].

Secondary acoustic instability is generated as a result of parametric instability of the flame front [7]. In parametric instability, cells of a particular wavenumber are generated on the flame front. A critical diameter of secondary instability is experimentally found to be around 1 cm and independent of Lewis number of mixture [5]. At lower S_L, primary instability transforms to secondary instability through a planar flame if sufficient acoustic oscillations are generated due to primary instability. At certain critical S_L, primary instability directly transforms to secondary instability without occurrence of a planar flame [8]. In tubes of narrow diameter, new forms of acoustic and flame instabilities are observed [9]. A lot is now known about features and mechanisms of acoustic instabilities of downward propagating flames.

Generally, the tendency of parametric instability increases with increasing S_L. In our earlier work, a peculiar observation is made in mixtures of Lewis number greater than unity flames which has not yet been explained. The tendency to generate parametric instability shows a non-monotonic behavior, first increasing then decreasing and then again increasing with increasing mixture strength. Therefore, there is a range of mixture strength for which parametric instability is re-stabilized. This work attempts to explain this re-stabilization.

2 Experimental results

The experimental method has been already presented in our earlier works [4-5,8-9]. This section explains the general features of downward propagating flame experiments in a tube for the sake of completeness. Experiments were performed in an acrylic tube of diameter 5 cm and length 70.2 cm. The tube was filled with combustible mixture and ignited at the top end which was opened just before ignition. Downward propagating flames were captured using a high-speed camera.

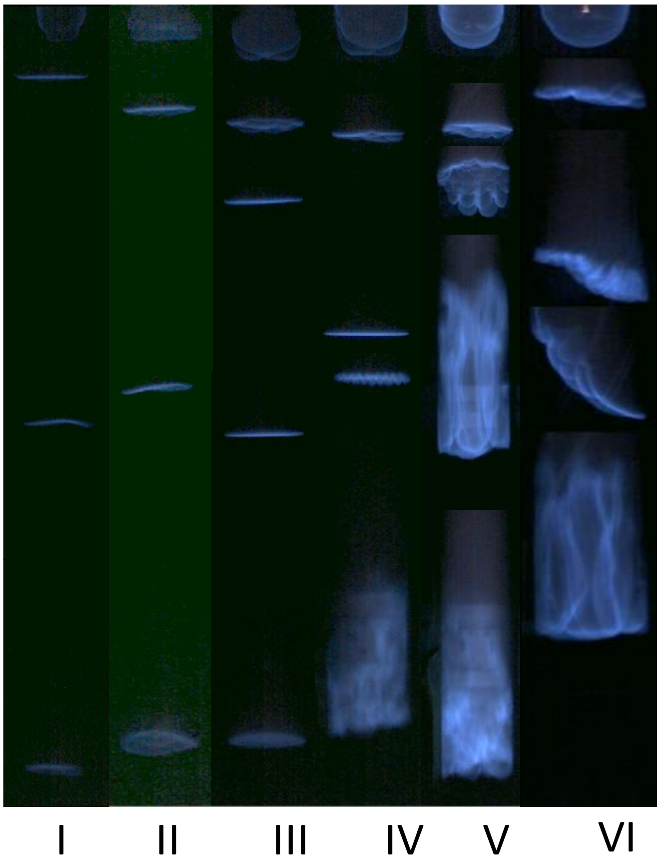

Figure 1: Images of flame at various instants of flame propagation for different regimes

Figure 1 shows representative images of various regimes of flame propagation at several instances. In regime I, a curved flame propagates downwards with no vibration. Pressure oscillations are also not observed. In regime II, a vibrating curved flame is observed, and pressure fluctuations can also be observed. The frequency of pressure oscillation and flame front oscillation corresponds to the fundamental mode of the tube. In regime III, a vibrating curved flame is observed which later transitions to a vibrating flat flame due to effect of acoustics on the flame. In regime IV, a curved flame transitions to a vibrating flat flame. After the pressure oscillations reach a certain amplitude corrugated structures appear on the flame due to acoustic parametric instability of the flame front. This instability creates strong secondary acoustic instability with high amplitude pressure oscillations, a high flame speed through turbulent flame structure. In regime V, a vibrating curved flame transitions directly to corrugated flame through parametric instability without transitions into a flat flame. Stability of the planar flame is lost in regime and effect of acoustics of any amplitude cannot turn the flame flat in regime V. In regime IV and V, fundamental mode parametric instability is observed. In regime II, III, IV and V pressure oscillations are of fundamental mode of the tube. In regime VI, higher mode of parametric instability is observed. A vibrating curved flame transitions to corrugated flame through first harmonic parametric instability and the pressure oscillations observed during this time are of first harmonic. As the flame travels downward first harmonic parametric instability transitions to fundamental mode parametric instability as in regime V. More higher modes can be observed where even higher modes can become active [10].

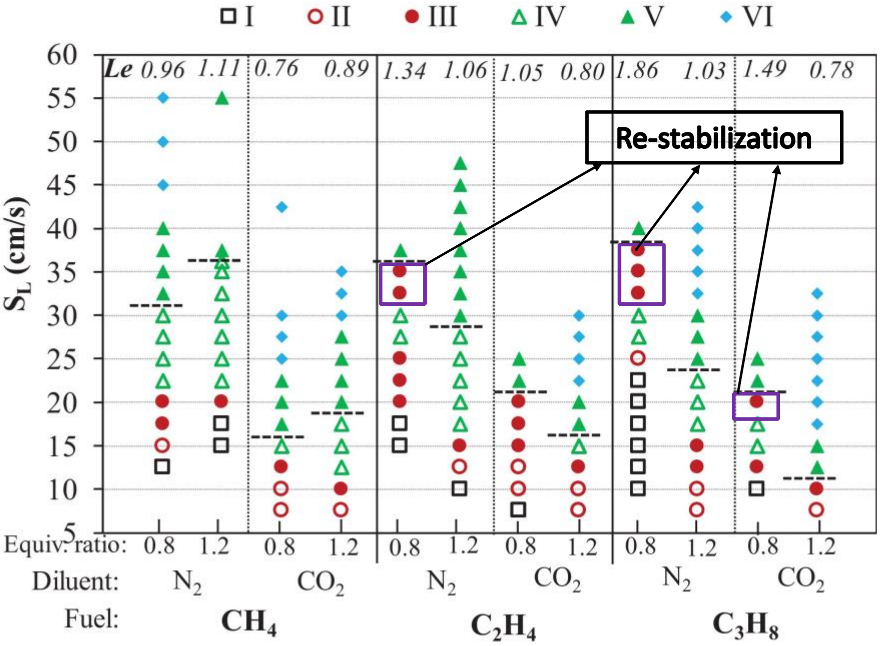

Figure 2: Regimes observed for several mixtures of different Lewis numbers (adapted from [8]). Re-stabilization is highlighted in purple boxes.

Figure 2 summarizes the regimes observed for several mixtures for different S_L. Generally, as the S_L increases regimes transition from I towards VI. However, for higher Lewis numbers (shown in purple boxes in Fig. 2), regime III is observed at S_L higher than one at which regime IV is observed. Consider Le=1.34, in which regime III appears at S_L=32.5 and 35 cm/s whereas regime IV appears at 30 cm/s and regime V appears at 37.5 cm/s. In regime III, parametric instability is not observed. This means parametric instability is suppressed or re-stabilized in a small range of S_L below and above which parametric instability can be observed. This phenomenon has not yet been understood.

3 Theoretical descriptions of parametric instability

A planar flame subject to acoustics fluctuations can be treated analytically. The equations have been described by Searby and Roechwerger [7] and method to solve has been detailed in our previous works [8]. This has not been detailed here due to space limit and can be seen from the references. The inputs to the system of equation are wavenumber (k), amplitude (Ua) and frequency of acoustic fluctuations and the mixture properties. A stability analysis gives stable/unstable regions on a k-Ua plane. This stable diagram is presented in Fig. 3. For lower Ua, hydrodynamic instability is observed. The range of unstable wavenumbers decrease with increasing Ua and at certain Ua hydrodynamic instability is completely stabilized and a planar flame which is dynamically stabilized can be observed in experiments as in regime III. As Ua increases further, a parametric instability is observed at a critical wavenumber. In the experiments, cells on the planar flame of this critical wavenumber are observed in the experiments in regime IV (Fig. 1 fourth image from the top).

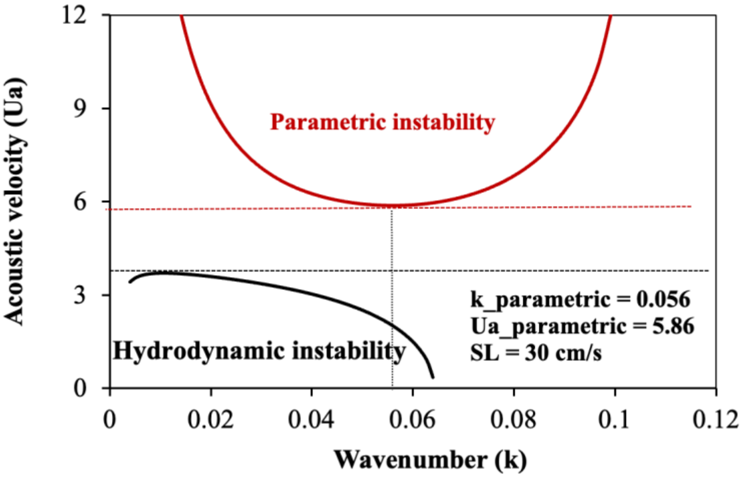

Figure 3: Stability diagram of $C_2H_4/O_2/N_2$ mixture of S_L=30 cm/s and Le=1.34 for tube length of 70.2 cm.

4 Reasons for re-stabilization

Now, we will try to explain why such re-stabilization occurs in high Lewis number mixtures by taking an example of Lewis number of 1.34. The onset of parametric instability happens when the acoustic fluctuations ahead of the flame front reach a certain amplitude. In the experiments, that acoustic amplitude is generated by the primary instability. There are two possibilities; first the acoustic fluctuations required show a minimum in the region of re-stabilization, second, the growth rate of primary acoustic instability shows a minimum in the region of re-stabilization. We will analyze both these situations one by one.

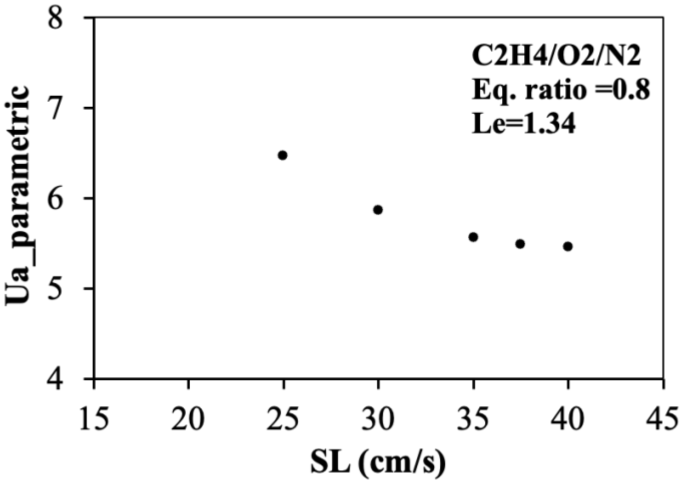

Figure 4: Variation of acoustic amplitude for parametric instability with S_L.

Figure 4 shows the normalized acoustic amplitude required to generate parametric instability with varying S_L. It is observed Ua required to initiate parametric instability decreases with increasing S_L and shows a monotonic behavior. Hence, this is not the exact reason for the re-stabilization. The only possibility now is that the acoustic amplitude required is not reached as the S_L increases in the region of re-stabilization. Before the onset of parametric instability, the flame is flat. The growth rate of acoustic instability is determined by velocity coupling if the flame is curved or cellular and if the flame is flat and thus no change in area of the flame, the growth rate is determined by pressure coupling. The growth rate of acoustic instability is proportional to zeldovich number as discussed by Clavin [3]

$$\frac{1}{\tau_{ins}} \approx \frac{\beta M}{\tau_a}$$

βM is a small number of the order 10^{-2} as discussed and presented by Yoon et al [6]. The cumulative effect of this growth rate over the residence time of flame in the unstable region creates the final acoustic amplitude. The distance covered by flame in the unstable region is related to the acoustic wavelength. The residence time is thus

$$t_{res} \equiv \frac{wavelength}{S_L} = \frac{\tau_a}{M}$$

Combining above two equations

$$\frac{t_{res}}{\tau_{ins}} \approx \beta$$

Hence, an initial perturbation of amplitude A_i will increase to a final amplitude A_f given by

$$\frac{A_f}{A_i} = \exp\,(\beta)$$

Hence the final acoustic amplitude is proportional to exp (β). Figure 5 shows variation of exp (β) with S_L. It can be observed that exp (β) shows a minimum in the region of re-stabilization. Hence, the re-stabilization is due to lower final amplitude of acoustic fluctuations which is not sufficient to cause parametric instability which in turn is caused by minimum of zeldovich number.

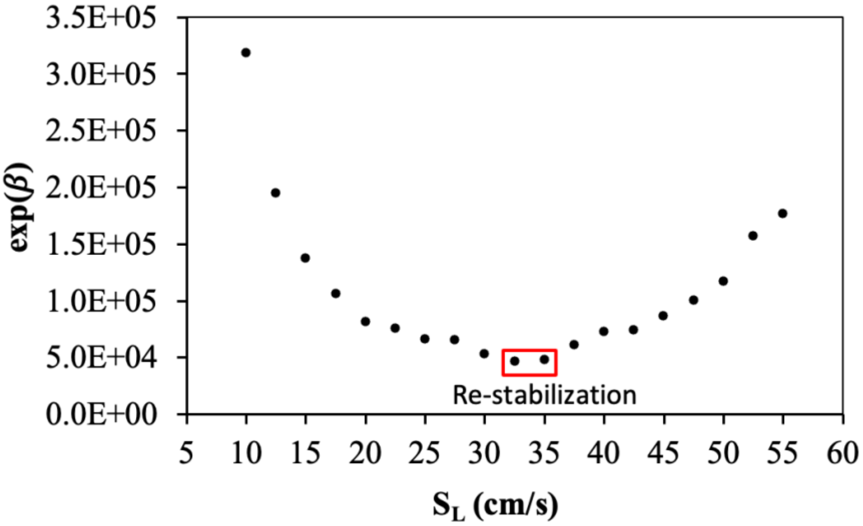

Figure 5: Variation of exp(β) with laminar burning velocity.

5 Conclusion

This work explains the re-stabilization of parametric instability observed in downward propagating flame experiments of large Lewis number mixtures as the S_L is increased. It is found that the final acoustic amplitude required to cause the parametric instability is not reached in the region of re-stabilization due to lower growth rate (lower zeldovich number) of primary acoustic instability.

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