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Modulated Thermoacoustic Singularities on Lifted Premixed Flames

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Abstract

Efficient propulsion development is an area of major interest in space industry. Chemical propulsion-oriented rockets and space systems are well known to encounter acoustic instabilities. The modified heat fluxes, owing to wall temperature, reaction rates and non-linear heat transfer are observed. The thermoacoustic instabilities significantly result in reduced combustion efficiency leading to uncontrolled rocket engine performance, serious hazards to systems, assisted testing facilities, enormous loss of resources and every year substantial amount of money is being spent to prevent them. Appreciable work had been carried out in the past leading to a progressive stand however, the complexity of the problem has prevented a comprehensive solution. Present work attempts to fundamentally understand the mechanisms governing the thermoacoustic combustion in rocket engines using a simplified experimental setup comprising of a butane cylinder and an impinging acoustic source. The RL-10 engine generates a noise of 180 Db at its base. Systematic studies are carried out for varying fuel flow rates, acoustic levels and observations are made on the flames. The work is expected to yield a good physical insight into the development of acoustic devices that could effectively enhance combustion efficiency leading to safer missions and better fire safety.

Keywords: Lifted flames; Acoustic impingement; Combustion efficiency; Liquid rocket engines

Introduction

Combustion has a million years of history and its control is essential to our existence on this planet. Combustion essentially is an exothermic oxidation process with fuel, oxidizer and heat in proper proportion and occurs through an intricate sequence of reaction rates. The chemical reaction brings in controlled transfer and transformation of energy, mass and momentum. The systematic identification of mass and energy conservation is the basis for any reflections in combustion engineering. The sequence of processes includes, phase change, multiphase flow, large property gradients. The overall combustion rate is decided by the time scales for different sequential events. The phenomenon is important as owing to consequential part of the world's energy requirement. Combustion process is the biggest source of greenhouse gases and products viz., soot significantly results in extreme accidents. Combustion is broadly categorized in two forms viz., smoldering and flaming. The smoldering deals with the exothermic chemical reaction at the surface of the solid fuel whereas the flaming combustion involves the reaction in gaseous form surrounding the fuel visible as a flame. A flame is caused by a self-propagating exothermic reaction accompanied by a reaction zone. Flaming combustion is further sub-divided as premixed and diffusion flame combustion. In diffusion flames, fuel and oxidizer vapor forms an instantaneous mixture for combustion whereas, premixed flames are generated, when the fuel and oxidizer are mixed before entering the ignition zone. Diffusion flames are mostly diffusion controlled whereas, premixed flames are reaction controlled. Premixed flames are normally encountered in three forms as steady, lifted and flashback.

The classification is based upon the controlling parameters viz., mass flow rate 'U', flame speed 'S_L', flame cone angle 'α' (Figure 1a). A stationary conical flame results with the equality of the normal component of flow velocity 'U', and flame speed 'S_L' as '$S_L = U\sin\alpha$' which enables flames to be stabilized on a burner. Instability in premixed flames is defined in terms of lifted premixed flames and flashback phenomenon. Lifted premixed flames are defined for the fuel flow velocity exceeding the flame speed as '$S_L < U\sin\alpha$' and flashback with flame drifting towards the burner exit by '$S_L > U\sin\alpha$' (Figure 1b).

The lifted premised flame and flashback characterizes strong instabilities. Various flame theories attempt to predict the flame propagation from physical and chemical properties change however, a closed form solution is yet to be obtained. The study of flames is important from safety and engineering point of view with applications as propulsion, power generation, practical utilizations. In productive engineering applications, the combustion instabilities are widely associated with acoustics. Sound is a weak pressure wave that propagates through a medium causing variation in pressure across it forming compression and rarefaction zones. The energy carried by an

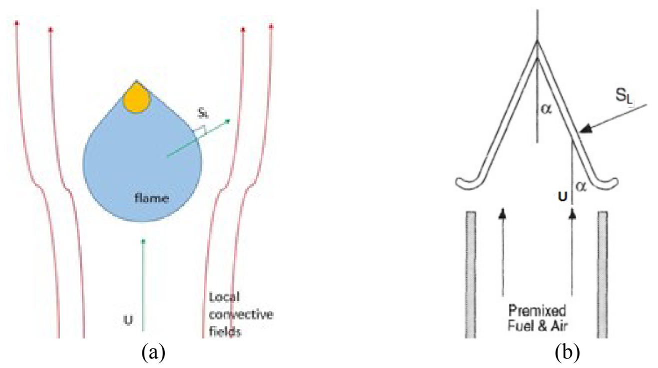

Figure 1: (a) Schematic of a lifted premixed flame (b) Flame cone angle and flame speed.

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oscillating sound wave converts back and forth between the potential energy of the extra compression of the matter, and the kinetic energy of the displacement velocity of particles of the medium. The resultant thermoacoustic largely accounts for a substantial economic loss to the aerospace industry and thus an imperative field of intensive research. Presence of acoustic field largely alters the properties of flame front, the localized temperature and velocity fields. The significant gradient changes consequences in uneven energy transfer which further adjusts the localized temperature fields thus useful energy feedback. The net energy loss to the environment also varies as:

$$G=H - T.S \quad (1)$$

where, '*H*' refers to enthalpy, '*G*' refers to Gibbs free energy, '*T.S*' refers to energy from atmosphere. It is important to note that the acoustic presence significantly alters the atmospheric energy, which results in varying '*G*' value. It is necessary to understand instability as lift-off phenomena of premixed flames in simplified manner, as the presence of such flames in gas burners reduce their efficiency by a considerable amount. Lifted flames potentially result in excessive fuel consumption and reduced adiabatic flame temperature resulting in loss of effectiveness of gas burners. This necessitates to put active research efforts into lifted premixed flames and thermoacoustic interactions to fundamentally understand the controlling physics. One of the predominant portions of combustion processes is the presence of acoustics.

The thermoacoustics interactions are broadly known to significantly affect the energy transfer. In order to access flame stabilization for unstable cases (here, lifted premised flame), the role of external acoustic field upon lifted premised flames is an aspect yet to be thoroughly explored. The external acoustic field is likely to alter the net energy interactions around the flame. The effects could result in stabilization, enhanced instability or neutralization of the lifted premixed flame. Significant research contributions have escalated the fundamental understanding of the thermoacoustic interactions with varying aspects and approaches. However, the heterogenous nature of the heat and mass transfer have prevented a thorough understanding.

Following the classical work of Chiu and Summerfield [1] on 'Theory of combustion noise' where, a unified theory of noise generation and amplification by turbulent combustion of premixed fuel and liquid fuel droplets was developed. The overall sound generation processes were classified in terms of the sound due to an isolated turbulent flame and that due to the interaction of a flame with its environment in a typical combustor. The analysis was focused on, parameters viz., far field noise characteristics, and the mechanism of sound generation, dispersion, and transmission near an open flame. The intensity of the intrinsic noise was found to be inversely proportional to the fourth power of the mean life time of the liquid droplet. It was stated that the noise amplification by acoustic instability contributes significantly to the combustion noise in high performance ducted spray combustors. Chinchao et al., [2] worked upon acoustically tuned lift-off flame with good repetition of the global flame stabilization process for detailed measurements and analysis using the line Raman spectroscopy and laser-induced fluorescence techniques. The laser diagnostic result showed that the flame base is found to locate in lean mixtures for all the phase angles, and water vapor of combustion products are found upstream of the flame base. The stabilization process of the flame propagation and recession of a lifted flame in an oscillation cycle was described by the evolution of the upstream large-scale vortex and the induced strain and dissipation rate on the flammable layer and the flame base. Cha and Chung [3] studied characteristics of lifted flames in non-premixed jets experimentally with emphasis on the effects of the entrained flow field which was varied by placing a plate near the nozzle and by confining the jet. Results showed that lifted flame behavior in a confined jet is drastically different from that of a free jet. In the confined jet, the liftoff height is linearly proportional to the nozzle diameter and the flow velocity, while the liftoff height is independent of the nozzle diameter in the free jet. The blowout velocity was found to be linearly proportional to the nozzle diameter in the free jet, whereas it was independent of the nozzle diameter in the confined jet. Chao et al., [4] investigated the feasibility of using external acoustic excitation with various frequencies and amplitudes to control the flame and pollution emission characteristics from a jet flame. Results indicated that appropriate acoustic excitation has obvious effects on enhancing the fuel-air mixing, flame stability, and even on switching the combustion modes in a jet flame. It was reported that the different diffusion and premixed combustion modes of attached, hysteresis and liftoff flames can be manipulated by applying different acoustic excitations. Prakash et al., [5] proposed a method for detecting and preventing lean blowout in a premixed, swirl stabilized combustor. The acoustic signal was filtered to detect localized extinction 'events', which increase in frequency as the flame equivalence ratio approaches lean blowout. The method directed that, as the flame becomes leaner, the lean blowout flame equivalence ratio can be effectively shifted to lower equivalence ratios by redirecting a fraction of total fuel into a central, premixed pilot. Kumar et al., [6] proposed a new flame extinction model based to predict the flame liftoff heights over a wide range of coflow temperature and O_2 mass fraction of the co-flow. The chemical time scale was derived as a function of temperature, oxidizer mass fraction, fuel dilution, velocity of the jet and fuel type.

The extinction model was tested for a variety of conditions viz., ambient co-flow conditions (1 atm and 300K) for propane, methane and hydrogen jet flames, for highly preheated co-flow, and for high temperature and low oxidizer concentration co-flow. It was observed that flame stabilization occurs at a point near the stoichiometric mixture fraction surface, where the local flow velocity is equal to the local flame propagation speed. Predicted flame liftoff heights of jet diffusion and partially premixed flames was found to be in excellent agreement with the experimental data for all the simulated conditions and fuels. Idahosa [7] carried out an investigation into the response of atmospheric, non-premixed swirling flames to acoustic perturbations at frequencies (0– 315 Hz) and swirl intensities (0.09 and 0.34) was carried out. The dependence of flame dynamics on the relative richness of the flame was investigated by studying various constant fuel flow rate flame configurations. The work provided the prevalence of gas turbines operating in primarily lean premixed modes of the need for lower emissions and increased efficiency. Navarro-Martinez and Kronenburg [8] consolidated Large Eddy Simulation-Conditional Moment Closure (LES-CMC) results by analyzing a wide range of lifted flame geometries with different prevailing stabilization mechanisms. The simulations allow a clear distinction of these mechanisms. It was corroborated that LES-CMC accurately predicts the competition between turbulence and chemistry during the auto-ignition process, the dynamics of turbulent flame propagation can be captured, however, the dynamics of the extinction process are not approximated well under certain conditions. The averaging process inherited in the CMC methods does not allow for an instant response of the transported conditionally averaged reactive species to the changes in the flow conditions and any response of the scalars will therefore be delayed.

Malanoski et al., [9] experimented on acoustic forcing effects on the dynamics of leading edge of a swirl stabilized flame. Vortex breakdown bubble dynamics were characterized using both high-speed particle image velocimetry (PIV) and line-of-sight high-speed chemiluminescence. A wide array of forcing conditions was achieved by varying forcing frequency, amplitude, and acoustic field symmetry. The results showed significant differences in instantaneous and time averaged location of the flow stagnation points. They also showed motion of the flame leading edge that were of the same order of magnitude as corresponding particle displacement associated with the fluctuating velocity field. The observations suggested that heat release fluctuations associated with leading edge motion may be just as significant in controlling the unsteady flame response as the flame wrinkles excited by velocity fluctuations. Qureshi et al., [10] subjected a 1-D premixed laminar methane flame to acoustic oscillations to investigate the effects of acoustic perturbations on the reaction rates of different species, with a view to their respective contribution to thermoacoustic instabilities. Acoustically transparent non-reflecting boundary conditions were employed. The flame response was studied with acoustic waves of different frequencies and amplitudes. The integral values of the reaction rates, the burning velocities and the heat release of the acoustically perturbed flame were compared with the unperturbed case. Results directed that the flame's sensitivity to acoustic perturbations is greatest when the wavelength is comparable to the flame thickness. It was concluded that acoustic fields acting on the chemistry do not contribute significantly to the emergence of large amplitude pressure oscillations. Ruan et al., [11] analyzed DNS data of a laboratory-scale turbulent lifted hydrogen jet flame to show that the flame has mixed mode combustion not only at the base but also in downstream locations. The mixed mode combustion was observed in instantaneous structures as in averaged structure, in which the predominant mode was found to be premixed combustion with varying equivalence ratio. The non-premixed combustion in the averaged structure was observed only in a narrow region at the edge of the jet shear layer.

Chen and Zhang [12] carried out an experimental investigation to study the nonlinear coupling characteristics of a propane/air flame with acoustic standing waves, using chemiluminescence emission and phase locked PIV measurements. A variety of coupling modes were observed for the excitation source with combustion instability oscillations and its harmonics and sub-harmonics. The frequency analysis showed that flame/acoustic coupling behavior results in complex non-linear coupling. The coupling behavior was found to be weak at lower excitation intensities (0.3V). At a voltage amplitude of 2V, the results showed that the excitation frequency is only coupled with the sub-harmonic frequency for the premixed flame. However, for the diffusion flame, more complex frequency components were observed. It was found that all the nonlinear phenomena that were observed occur because of the coupling between buoyant and acoustic excitation and create complex nonlinear frequency couplings. Brouzet, et al., [13] reported proper orthogonal decomposition (POD) method of a Direct Numerical Simulation (DNS) dataset of a turbulent premixed flame. The POD results showed that the combustion process is the dominant source of noise at low frequencies, whereas the inlet noise becomes an increasingly important source at higher frequencies. It was also shown that the first three POD modes, that are mainly associated with the noise produced by the flame, can provide a reasonable estimate of the DNS spectra at low frequencies. Mitsutomo et al., [14] developed a novel technology to reduce soot by utilizing a high-frequency standing wave of 20 kHz applied to a methane-air lifted jet flame base. The amount of soot was measured using the transmitted light attenuation method. A mixing profile of the fuel jet was visualized using acetone planar-laser-induced fluorescence to measure the mixing status when the ultrasonic wave was applied. The blow-off and reattached limit were increased by the standing wave. Soot was also clearly decreased under some conditions.

In recently, Kypraiou, et al., [15] experimentally studied the effect of forced oscillations on the behavior of non-premixed swirling methane flames close to the lean blow out limits using experiments in a lab-scale burner. Two different fuel injection geometries, non-premixed with radial -NPR- and non-premixed with axial -NPA- fuel injection, were considered. The flame behavior was studied using 5 kHz OH chemiluminescence and OH Planar Laser Induced Fluorescence (OH PLIF) imaging. In both systems, acoustic forcing was noted to reduce the stability of the flame, and, the stability was found to decrease with the increase in forcing amplitude. Flame lift-off was observed in both configurations, with the magnitude of the effect of forcing depending on the fuel injection configuration. The results provide insight on the effect of superimposed flow field fluctuations in systems operating close to the lean blow out limits and offer useful data for the development and validation of numerical models for the prediction of the dynamic behavior of flames of industrial interest. Appreciable scientific research work had been done but the complexity of the problem has prevented a comprehensive understanding owing to heterogenous heat and mass transfer. The present works aims to address an unstable lifted premixed flame phenomenon by alternate method of energy interactions. The heterogenous energy system is simplified with energy interaction between a flame and an external acoustic energy source. A steady lifted flame was chosen as the base case for the present work. It is expected that impinging acoustic will bring variation in lifted flame properties. The sound is likely to affect the lifted premixed flame in three modes that are either reducing the flame instability or increasing it or having no effect on the flame. The specific objectives of the study are:

- To understand the acoustic effects on the flame front of a lifted premixed flame.
- To examine the role of governing parameters.
- To deduce the strength of controlling inter-relation between the acoustic and thermal energy interactions.

Experimental Setup and Solution Methodology

An experimental setup was upraised for the present study comprising of (a) hard thermocol with angles marked on it and firmly supported on a table (Figure 2) butane gas lighters (Figures 3b and 3c) frequency generator software (d) notable speakers and (e) Marked dark sheets for observing the flame height which was digitally video graphed (Figure 3a). To simulate the flame instability in gas burners of the experiments have been scaled down and systematically conducted on butane gas lighters (Figure 3b). Lifted flame was obtained by blocking the lighter's nozzle with ink from a ball point pen. The speakers (Figure 3a) were placed diametrically opposite to each other and 20 cm apart

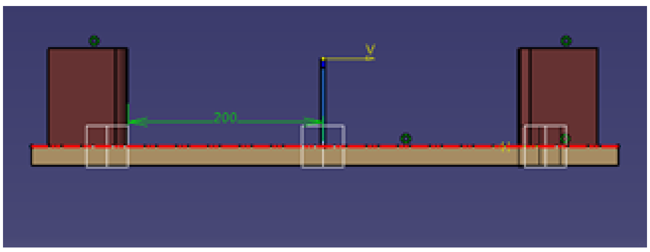

Figure 2: Schematic of the complete experimental setup.

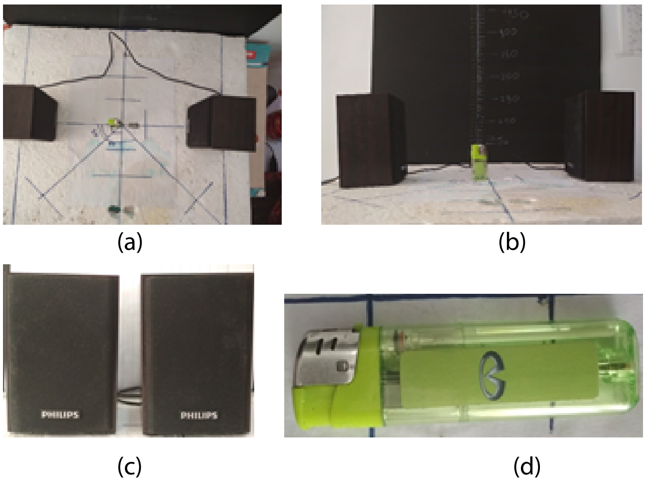

Figure 3: Pictorial view of the experimental setup (a) Top view of the setup (b) Front view of the setup (c) Acoustic sources (d) Butane lighter.

from the lighter. Fuel was ignited by exposing it to a pilot flame and special care is taken to remove the moisture which can affect ignition. The experiment is carried out in a quiet atmosphere and repeatability was ensured (Figures 3a-3d).

The experiments were thoroughly carried out in a quiescent room under normal gravity conditions and thoroughly video graphed. It is important to note that all the data presented represents repeatability. An optical setup was made to obtain shadowgraph of the ignition front. Dark sheets were used for flow visualization to capture the flame movement pattern. Stopwatch was used to measure the split times across the marker and entire experimentation was video graphed. Every experiment was carried out within 5 minutes to bring room atmosphere back to normalcy.

To quantify the instability induced in the flame, a new parameter '*GFL*' (Gross flame length) as the algebraic sum of '*FL*' (flame Liftoff distance) and '*FH*' (flame height) was defined (Figure 4). The instability parameter '*GFL*' can be formulated as:

'*GFL*' varies with the variation in '*FH*' and '*FL*' and variation in '*GFL*' represents variation in acoustic instability. The flame is stable when '*FL*=0' and '*GFL*=*FH*' i.e., flame is on the burner. A decrease in '*FL*' denotes the flame stabilization and vice versa. '*FL*' and '*FH*' both become 0 when the flame extinguishes. Hence '*GFL*=0' which depicts the flame no longer survives (Figure 4). The investigation was carried out experimentally and primarily focused on the variation of following parameters:

- Acoustic frequency (Hz).
- Flame extinction time (sec).
- Flame flickering frequency (cycles per minute).
- Re-stabilization time (sec).

The flame shapes were analysed for varying cases and responding effects were noted.

It is important to note that the external flow velocity over the fuel is the same at all the surface orientations and all the readings presented here, represent repeatability of the order three.

Results and Discussion

Prior to the main study, the experimental predictions were validated for a reference base case. Initialization was done by establishing and identifying the behavior of a lifted premixed flame as a base case (Figure 5). The respective images were taken 10 sec apart. The parameters (*FL* and *FH*) were observed and noted constant throughout the experimentation for all sound frequency indicating that without any external influence the parameters are unlikely to vary. The base case (without acoustics) was employed as a validation for all the other cases. Figure 6a shows the different flame lengths viz., *FL, FH and GFL*. The base case comprises of *FL*=2 cm, *FH*=3 cm and consequently, *GFL*=5 cm, with time. Looking at the plot, one can note that, *GFL* remains constant without acoustic impingement. The base lifted premixed flame was noted to not extinguish neither stabilize. So, the experimental setup is expected to provide a good physical understanding of the acoustic effects on lifted premixed flame. The base sets a standard limit for validating other cases. The base case here is an unstable case where flame is already lifted.

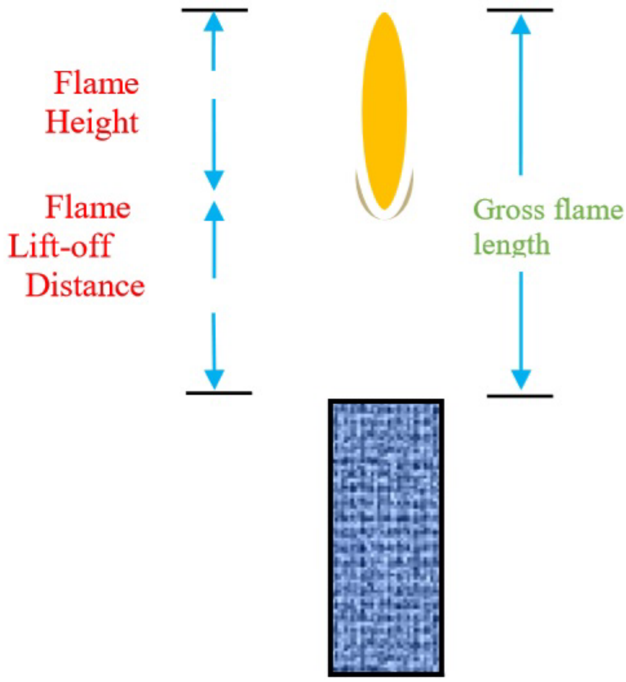

Figure 4: Schematic showing defined flame length scales for a lifted premixed flame.

Next, the effect of acoustics frequency variation on the *GFL* was investigated. Figure 6b shows maximum and minimum variation of *GFL* with varying acoustics in comparison to the one without acoustics. For the next set of experiments, acoustic of varying frequency was impinged on the reaction front of the flame from two external sources placed diametrically opposite and separated by 20 cm from the butane lighter. GFL_{max} was noted highest when sound wave of frequency 100 Hz is impinged (220% rise) and lowest GFL_{max} was observed for acoustic frequency of 800 Hz (30% drop). Non-monotonic nature of the curve can be attributed to the unprecedented energy interaction between acoustic waves and local temperature and velocity gradient field of the flame.

The curve for minimum *GFL* vs frequency is also non-monotonic thus fulfilling the trend of unpredictable energy interactions. It can be said that each frequency interacts uniquely with the flame that generate different flame parameters for each frequency. The parameters change as for every case a unique magnitude of energy is either extracted or added to the flame form the sound wave. These energy interactions

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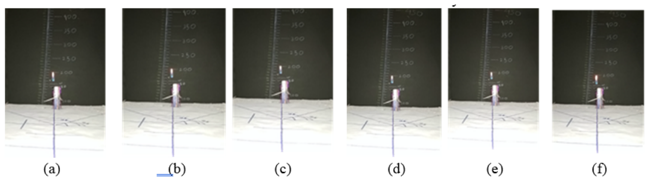

Figure 5: Pictorial representation of the features of the base flame (without acoustics) with constant GFL (a) 10 sec, (b) 20 sec, (c) 30 sec, (d) 40 sec, (e) 50 sec, (f) 60 sec.

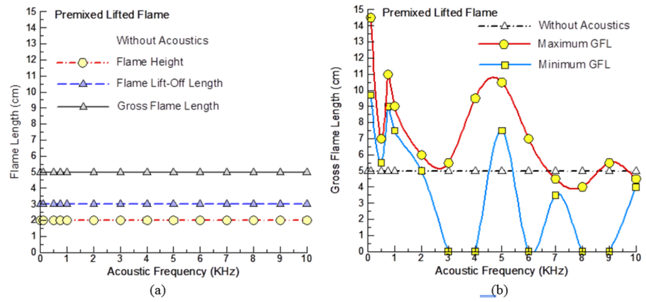

Figure 6: (a) Variation of base flame length(s) with acoustic frequency for reference case, (b) Maximum and minimum variation of gross flame length (*GFL*) with the acoustic frequency.

follow no specific order or trend hence a non-monotonous curve is obtained. The maximum GFL_{min} was observed for at 100 Hz (94% rise) and lowest GFL_{min} was registered as 0 which represent flame extinction. This can be attributed to the fact that acoustic waves pull out excessive energy from the combustion front, owing to parametric gradient between the flame field and sound wave. To understand the change in '*GFL*' next the variations of '*FL*' and '*FH*' was investigated. Figure 7a highlights the variation of flame lift-off length with the impinged acoustics. The flame lift-off length is highest again for 100 Hz (600% rise) and minimum FL_{max} was observed at 6000 Hz (75% drop). The non-monotonic nature of the curve indicates the non-linear nature of the flame. The FL_{min} was observed at 100 Hz (350% rise). FL_{min} represent 2 cases viz., flame-restabilizing and extinction. The acoustic frequencies of 500 Hz, 2000 Hz signify '*FL*' becoming zero as the flame reaches the burner and for other cases '*FL*'=0 denotes the flames extinction. The non-monotonous nature of the curve represents the non-linearity in energy interaction between the sound wave and local gradient field of the flame field. Figure 7b highlights the variation of flame height with the impinged acoustics. Looking at the plot one can the curve is of different nature from the *GFL* and *FL*. This indicates the distinct and diverse order of energy interaction for different thermoacoustic cases. The lowest FH_{min} was achieved for 100 Hz (83.33% drop) highest FH_{min} was achieved at 5000 Hz (183.33% longer). The maximum of FH_{min} was observed at 2000Hz and minimum was recorded at 0 for 3000Hz and 4000Hz where the flame could not survive.

To study the instability induced, the intensity of flame flickering frequency was observed. Figure 8a exhibits the variation of flickering frequency with impinged acoustics. Flame flickering was observed to be highest for 5000 Hz lowest was noted for 8000 Hz. The flickering was noted to be higher in the presence region of the acoustic spectrum. The periodic nature of flickering frequency can be interpreted as integral multiples of a frequency induce similar thermoacoustics instability. Flickering occurs due to inter energy transformation within the reaction zone which causes energy surge in the flame and makes it jump over the burner. Acoustic energy brings alteration in inter energy conversion which varies with frequency. In general, these conversions do not follow any specific trend but in presence of sound the conversions become periodic depicting dominance of acoustic energy over thermal.

The subsequent cases of neutralization (no change), re-stabilization and enhanced instability were observed due to these conversions. Figure 8b shows the temporal variation of above-mentioned effects with the acoustic frequency. The stabilization time 'T_s' and extinction time 'T_{ex}' reflect the heterogenous nature of the phenomenon. The cases of acoustics frequency causing flame stabilization and extinction varies distinctly with time. This defines a zonal acoustics frequency system which has significant effect on existing unstable flame. The longest extinction time was noted for 9000 Hz (59 sec) and the lowest as 0 if the flame doesn't extinguish. The longest stabilization time was noted for 2000 Hz (50-sec) and the lowest as 0 if the flame remains unstable. The lower zone frequencies from 100 Hz to 750 Hz either re-stabilize viz., 500 Hz or neutralizes the lifted flame. The midzone frequencies between 750 Hz to 2000 Hz also stabilize (2000 Hz) and neutralizes (750, 1000 Hz). The high zone frequencies from 2000 to 10000 Hz were noted to either extinguish or neutralize the flame. Furthermore, the acoustic effects at varying frequency were formulated by visual inspection stepwise at subsequent 10 second gap. For the case of 100 Hz acoustic frequency, it was observed that '*GFL*' kept varying nonlinearly with time. Figure 9 shows the pictorial variation of flame for subsequent 10 seconds. Initially '*GFL*' increased with time and then dropped as the experiment proceeded till it became stationary. Induced thermoacoustic instability was registered to be 12 cycles per minute. Acoustic frequency of 100 Hz showed a neutralizing effect on the flame. For this case the

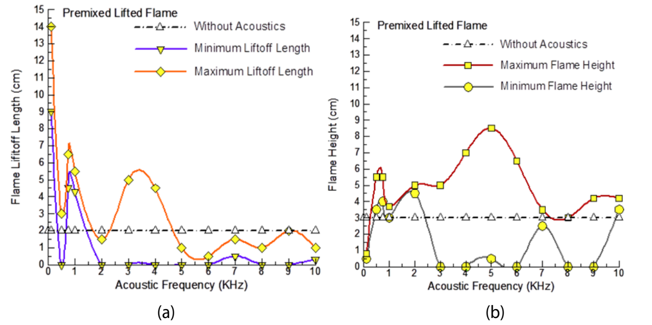

Figure 7: (a) Flame Lift-off distance variation with the acoustic frequency, (b) Flame height variation with the acoustic frequency.

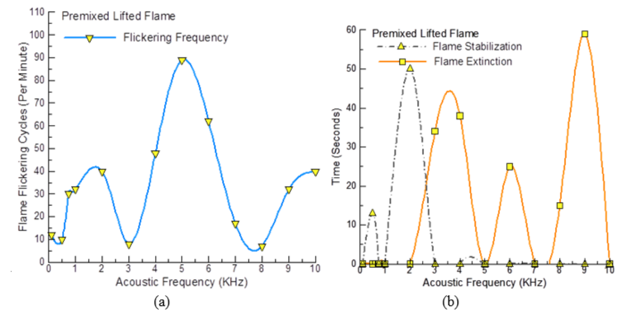

Figure 8: (a) Variation of the flame flickering frequency with the acoustic frequency, (b) Flame extinction and flame stabilization time variation with the acoustic frequency.

flame height was much lower than '*FL*' whereas '*FH*' varied from 8-5 mm and '*FL*' varied from 140 to 90 mm. The flame shape resembled a flat cone. The neutralization of the flame on impinging sound of 100 Hz may be attributed to same energy addition and extraction by the sound wave from the flame field owing to no existent parametric gradient. The case of 500 hertz acoustic waves was observed to make the flame stable (Figure 10). Flame lift-off length initially was noted to have a positive value which abruptly drops to zero after 12 seconds of sound impingement thus making '*FH=GFL*' which marks stability. After 50 seconds the flame lifts again and *FL* regains a positive value from 0 to 30 mm. '*FH*' varied from 55 to 35 mm thus '*GFL*' varied from 70 to 55 mm. Acoustic induced flickering was observed to be 10 and the flame re-stabilization followed by the destabilization can be attributed to the variation in magnitude of Gibbs free energy. A system is stable when it is in its lowest possible energy state so for the flame to be stable energy must be extracted in form of '*T.S*' (environmental energy). when the flame touches the burner the soundwave extracts energy from the flame making it stable, as '*U*' is constant at all time stability can be attained only by change in 'S_L' flame speed which can be altered by external influences and nonlinear energy interactions.

The flame is lifted when '*U*' is greater than 'S_L' and on the burner when '$U=S_L$' so when the flame lifts up '*T.S*' energy again is added to the gradient field of the flame causing increment in 'S_L'. This explains all cases that showed increment in flame height. For the case of 750 Hz, the acoustics was dominantly observed to neutralize the flame (Figure 11). No significant change in the variation of '*FL*' and '*FH*' and thus '*GFL*' was observed. '*FL*' and '*FH*' varied from 65 to 45 mm and 55 to 40 mm respectively and '*GFL*' varied from 110 to 90 mm. Figure 12 shows the flame variation for 1000 Hz. It can be observed that acoustics slightly stabilizes the flame as noted from the variation of '*FL*' and '*FH*'. As '*FL*' reduces, and '*FH*' increases thus keeping '*GFL*' slightly constant. Acoustic induced flickering cycle was noted to be 30 which indicates the different levels of internal energy conversions are occurring as the combustion reaction progress. The variation in '*FL*' and '*FH*' can be justified by saying energy addition is slightly higher than energy extraction. '*FH*', '*FL*' and '*GFL*' varied from 43-55, 37-30 and 90-75 respectively. 2000 Hz acoustic frequency represents a case where the flame re-stabilizes and touches the burner again (Figure 13). '*FL*' linearly reduces to 0 and the same increment in '*FH*' was observed keeping '*GFL*' constant. The flame re-stabilization occurs due to the extraction of energy from the flame front local gradient field by the sound wave.

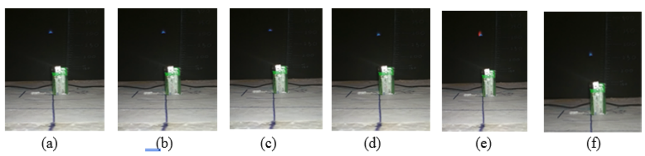

Figure 9: Pictorial representation of the flame for 100 Hz (a) 10 sec, (b) 20 sec, (c) 30 sec, (d) 40 sec, (e) 50 sec, (f) 60 sec.

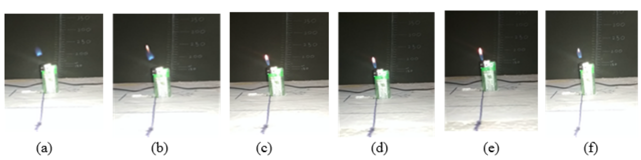

Figure 10: Pictorial representation of the flame for 500 Hz (a) 10 sec, (b) 20 sec, (c) 30 sec, (d) 40 sec, (e) 50 sec, (f) 60 sec.

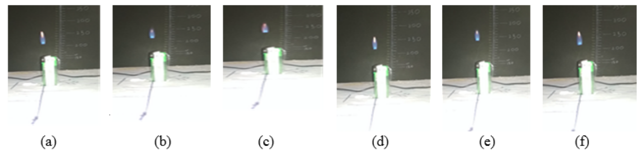

Figure 11: Pictorial representation of the flame for 750 Hz (a) 10 sec, (b) 20 sec, (c) 30 sec, (d) 40 sec, (e) 50 sec, (f) 60 sec.

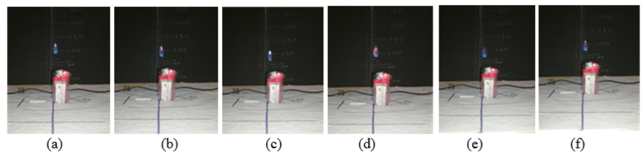

Figure 12: Pictorial representation of the flame for 1000 Hz (a) 10 sec, (b) 20 sec, (c) 30 sec, (d) 40 sec, (e) 50 sec, (f) 60 sec.

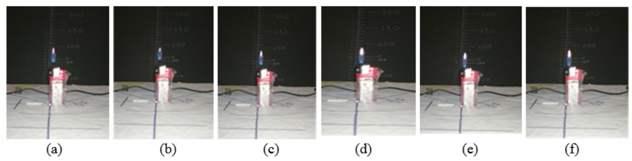

Figure 13: Pictorial representation of the flame for 2000 Hz (a) 10 sec, (b) 20 sec, (c) 30 sec, (d) 40 sec, (e) 50 sec, (f) 60 sec.

Flickering cycles was noted to be 40/min. '*FL*' varied from 0-15 mm and '*FH*' from 45-50 mm and making '*GFL*' variation from 60-50 mm. For the case of 3000 Hz acoustics, the flame extinguishes due to excessive energy extraction (Figure 14). '*FL*' and '*FH*' both remain constant until the flame extinction and becomes zero as the flame extinguishes. Energy conversion at different level take place in the flame resulting in flickering frequency of 8. Flame extinction occurs since energy is extracted in larger magnitude from the flame localized pressure and temperature field by the acoustic wave thus reducing the forward heat transfer to a level where combustion cannot be sustained. Whereas, the flame for 4000 Hz flickers heavily and bounces off the burner owning to huge internal energy transformations (Figure 15). '*FL*', '*FH*' and '*GFL*' vary non-linearly due to this transformation. The '*FL*', '*FH*' and '*GFL*' variation was noted from 50-0, 60-0 and 65-0 respectively. The flame is initially stabilized by the wave, followed by re-stabilization after 47 sec. The sound wave extracts enough energy to extinguish the flame. The 5000 Hz case represents inter energy conversions like the 4000 Hz, as the flame again is flickering heavily, the flame touches the burner and bounces off it (Figure 16). The instability induced in the flame tries to neutralize itself when acoustic waves are impinged as the wave draws out energy from the flames gradient zone but due to the internal energy transformation into the flame, instability are induced again in the flame and there is a competing effect between the interconversion energy and acoustic energy. The flame for 6000 Hz extinguishes after 24 seconds owing to the strong parametric gradients (Figure 17). '*FL*' remains constant with time '*FH*' changes due heavy trailing edge flickering '*GFL*' varies accordingly from 70 to 55 mm the flame extinguishers due to excessive unfavourable energy transfer from the flame front to the sound wave. 7000 Hz acoustics was observed to neutralize the flame (Figure 18). There was no significant change in the variation of '*FL*' and '*FH*' and thus '*GFL*' showed no observable variation. '*FL*' and '*FH*' varied from 15 to 5 mm and 35 to 25 mm respectively and '*GFL*'

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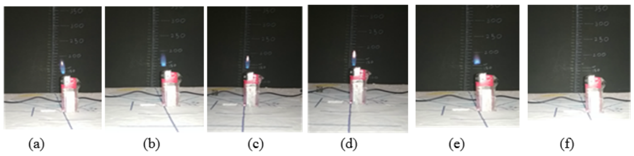

Figure 14: Pictorial representation of the flame for 3000 Hz (a) 10 sec, (b) 20 sec, (c) 30 sec, (d) 40 sec, (e) 50 sec, (f) 60 sec.

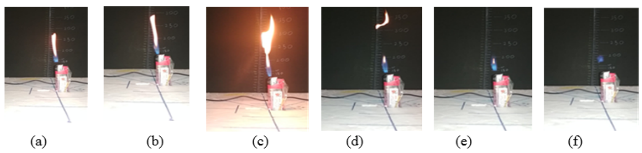

Figure 15: Pictorial representation of the flame for 4000 Hz (a) 10 sec, (b) 20 sec, (c) 30 sec, (d) 40 sec, (e) 50 sec, (f) 60 sec.

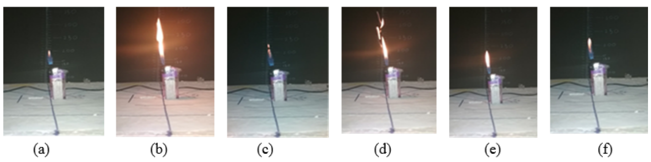

Figure 16: Pictorial representation of the flame for 5000 Hz (a) 10 sec, (b) 20 sec, (c) 30 sec, (d) 40 sec, (e) 50 sec, (f) 60 sec.

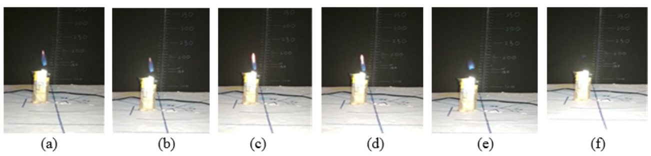

Figure 17: Pictorial representation of the flame for 6000 Hz (a) 10 sec, (b) 20 sec, (c) 30 sec, (d) 40 sec, (e) 50 sec, (f) 60 sec.

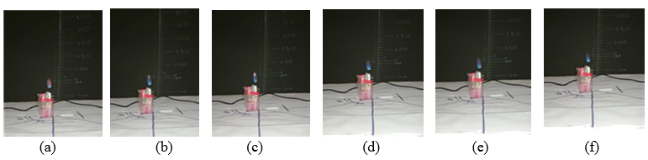

Figure 18: Pictorial representation of the flame for 7000 Hz (a) 10 sec, (b) 20 sec, (c) 30 sec, (d) 40 sec, (e) 50 sec, (f) 60 sec.

varied from 45 to 35 mm. For the 8000 Hz acoustics, the flame again extinguishes due to excessive energy extraction (Figure 19). '*FL*' and '*FH*' both remained constant until the flame extinction and become zero as the flame extinguishes. Energy conversion at different level take place in the flame that results in flickering frequency of 7. 9000 Hz acoustic, represents the flame extinction due to excessive energy extraction (Figures 20 and 21). '*FL*' and '*FH*' both remain constant until the flame extinction and becomes zero as the flame extinguishes. Increment is flickering before extinction. Energy conversion at different level take place in the flame that results in flickering frequency of 32.

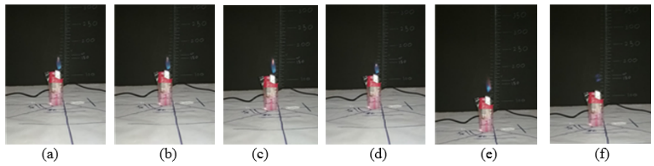

Figure 19: Pictorial representation of the flame for 8000 Hz (a) 10 sec, (b) 20 sec, (c) 30 sec, (d) 40 sec, (e) 50 sec, (f) 60 sec.

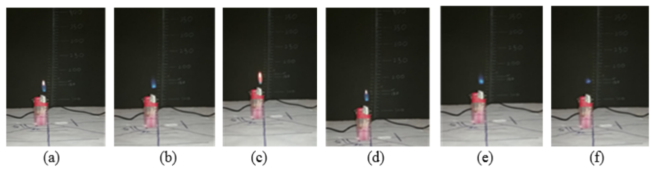

Figure 20: Pictorial representation of the flame for 9000 Hz (a) 10 sec, (b) 20 sec, (c) 30 sec, (d) 40 sec, (e) 50 sec, (f) 60 sec.

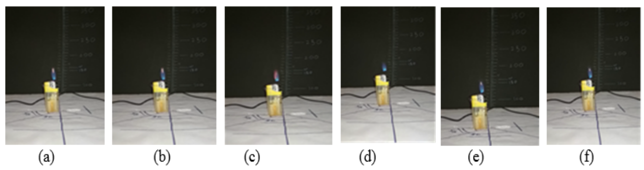

Figure 21: Pictorial representation of the flame for 10000 Hz (a) 10 sec, (b) 20 sec, (c) 30 sec, (d) 40 sec, (e) 50 sec, (f) 60 sec.

Conclusions

An experimental exploration was carried out on butane gas lighters to identify the merits of acoustic effects on lifted premixed flames. The controlling parameters viz., sound g frequency, sound source distance flame height and flickering frequency. The specific conclusions of the study details that:

- The lifted flame is severely affected by the presence of external energy source in its vicinity here which is an impinging sound source. Sound significantly affects the progression of flames.
- Formation of strong gradient grounded localized temperature and velocity fields in the immediate vicinity of flame controls the relevant energy transfer and consequently the chemical reaction rate decides the acoustic effect outcome under subjected condition.
- The thermoacoustic instabilities significantly result in reduced combustion efficiency leading to uncontrolled liquid rocket performance, serious hazards to systems, assisted testing facilities, enormous loss of resources and every year substantial amount of money is being spent to prevent them.
- Based on the observations the acoustic frequencies can categorized into a zonal system viz. High mid and low frequency zone. Each zone has its characteristic effect on the flame.
- Acoustics is observed to change flame characteristics and behavior. Both flame stability and flame extinction can be achieved by impinging acoustics.
- Acoustic losses are always present in combustion chambers. Impinging acoustics can suffice for these losses and bring in gradient change to alter the convective field of the reaction zone.
- Acoustic brings in changes in inter-energy conversion and

alter the reaction rates. The modified heat fluxes, owing to wall temperature, reaction rates and non-linear heat transfer are observed.

- The non-linearity in inter energy conversion involved with lifted premixed flames change when acoustic is impinged which makes flame flickering frequency periodic.
- The work explores a simple practical approach in addressing problems related to complex phenomena of flame lift-off instability.

Applications of the Present Work

The results of the following work can be effectively utilized to yield a good physical insight into the development of acoustic devices that when coupled with the present propulsive devices could effectively enhance combustion efficiency leading to better and safer missions. Designing acoustic inducers that could alter and affect the combustion efficiency and stability of a Gas turbine as well rocket engine, which in turn improves the specific fuel consumption and specific impulse of engines. Owing to the change in combustion parameters, combustion chambers properties change thus altering the performance of liquid rocket engines. Develop acoustic based fire safety devices and flame stabilizers that could be installed in rocket engines. Can form the ground work for subsequent studies related to flame instabilities. Results can directly be applied to space as well as terrestrial applications.

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