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Experimental Investigation on the Role of Thermo-acoustics on Soot Formation

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Abstract – Combustion in itself is a complex phenomenon that involves the interaction and interplay of multiple phenomena, the combined effect of which give rise to the common flame that we see and use in our daily life applications from cooking to propelling our vehicles to space. The least thing that goes unnoticed about these flames is the effect of the various phenomena from its surrounding environment that affects its behaviour and properties. These phenomena cause a variety of energy interactions that lead to various types of energy transformations which in turn affect the flame behaviour. This paper focuses on experimentally investigating the effect of one such phenomenon, which is the acoustics or sound energy on partially premixed flames. The subject in itself is extensively studied upon as thermo-acoustics globally, whereas the current work focuses on studying its effect on soot formation of partially premixed flames. The said effect is studied in this research work by the use of a butane as fuel, fitted with a nozzle that houses 3 arrays consisting of 4 holes each that are placed equidistant to each other for entraining air and the resulting flame is impinged with sound from two independent and similar sound sources that are placed equidistant from the centre of the nozzle. The entire process is systematically video graphed using a 60 fps regular CCD and analysed for variation in flame heights and flickering frequencies where the fuel mass flow rate is maintained constant and the configuration of entrainment holes and frequency of sound are varied, whilst maintaining constant ambient atmospheric conditions. The current work establishes significant outcomes on the effect of acoustics on soot formation; it is noteworthy that soot formation is the main cause of pollution and a major cause of inefficiency of current propulsion systems. This work is one of its kinds and its outcomes are widely applicable to commercial and domestic appliances that utilise combustion for energy generation or propulsion and help us understand them better, so that we can increase their efficiency and decrease pollution.

Keywords**:** Thermo Acoustics, Entrainment, Propulsion System, Efficiency, Pollution.

1. Introduction

Combustion deals with exothermic chemical reaction by using fuel and oxidizer associated with a reaction zone. Fuel and oxidiser mix in required proportions and combustion occurs through an intricate sequence of reaction steps. Combustion is critically important and the resultant energy interactions and governing phenomenon sources close to 80% of the world energy requirements in form of like propulsion, heating, electricity production. This branch of physics is broadly classified into smouldering and flaming. The classification is based on the manifestation of flames resulting from highly exothermic reactions yielding high flame temperatures depending on the fuel-oxidizer ratio. Different types of flames can result from the way in which the fuel and oxidant are mixed. Combustion can occur in premixed or diffusion modes. Diffusion flame represents diffusion-controlled combustion with diffusion rate greater than the reaction rate. In diffusion flame, fuel and oxidiser concentration vanishes at flame front and the flame region is very thin. In premixed flames, fuel such as natural gas, commercial and industrial liquid fuels, usually termed fuel oils and air mixture kept in an open tube is lighted by a spark and the propagation of the flame is observed at a certain velocity. In comparison to the premixed flames (short and blue), diffusion flames are longer and yellow with higher stability range, luminosity, sooty and flame temperature is not very high. When the fuel flow rate is relatively low, the incoming gaseous flow of fuel and air is laminar, as is the flame however; high fuel flows may lead them to being turbulent.

Thus, flames are generally identified as to be laminar premixed, laminar diffusion, turbulent premixed or turbulent diffusion. In addition, they can also be categorized into stationary or propagating flames. Partially premixed flames contain a rich premixed fuel-air mixture in a stream, and, for complete combustion to occur, they require the transport of oxidizer from an appropriately oxidizer rich mixture that is present in another stream. The stationary flames are widely used in domestic or industrial burners, the propagating flames being involved in explosions. An important aspect of the combustion research is investigation of the behaviour of flames in response to numerous parametric variations and external influences. The premixed and diffusion flames had been extensively studied and explored owing to the strong physical presence and applications. Combustion systems are one of the most important and complex highlighting an interesting aspect of the presence of partially premixed flames as a coupled resentment between premixed flame and diffusion flame. Flames in most practical applications cannot be described as purely premixed or non-premixed. Understanding the behaviour of flame in response to multiple air-entrainments to fuel on its path to produce flame is important because of its wide range applicability i.e. ring pool fire, perforated liner in combustors, furnace burner rims, Bunsen burners, perforated exhausts and culinary flame torches. This study could be very effective for fire safety purpose of a multiple-windowed tall infrastructure.

The parametric study of flaming combustion characteristics for ring pool fires and perforated liners has been done by researchers for decades. Scientists have stratified, classified and quantified the traits of flame in influence of amount of passive air-entrainment, forced air-entrainment, variation of composition of fuel and oxidiser and induced instabilities. Sohrab and Law [1] studied characteristics of polyhedral flames of propane and butane in influence of burner rim aerodynamics by illuminating the effects of atmospheric entrainment, inner wall boundary layer, and conductive heat loss to the burner. They found burner tips are unable to to support polyhedral structure and rise in surrounding atmospheric Nitrogen enhances the propensity of polyhedral structure. The rotational speeds based linear velocities at times in excess of laminar propagation velocity corresponding to the same mixture. Wadia [2] gave a brief review on advanced liner cooling techniques focusing more on laminated porous wall cooling, angled-multihole (effusion) cooling and composite metal matrix liner by defining the concept of heat transfer considering material and fabrication problems associated with it. Jing and Sun [3] worked on and found that in a perforated liner in presence of a bias flow, significantly gives rise in absorption coefficient and effective absorption bandwidth. The plate thickness also has a major significance on acoustic reactance and thus on resonating frequency. Eldredge and Dowling [4] investigated on effectiveness of cylindrical perforated liner with mean bias flow in its adsorption of planar acoustic waves in a duct. Each aperture was subjected to a harmonic pressure difference resulting vortex shedding from the rim. When the system included in a duct whose termination allows most acoustic energy to reflect upstream for further interaction with the liner, can absorb as much as 83% of incident energy at certain frequencies, and prevent 100% of the outgoing energy from reflecting back to the source. Lei, et al. [5] worked for controlling combustion instability by the effects of perforated liners with bias flow and by analytically and experimentally found that perforated liners can largely supress the combustion instabilities. Heuwinkel, et al. [6] studied liner configuration under bias and grazing flow condition was performed in three different test facilities and with three different measurement techniques. Results show the influence of the flow dominates the damping behaviour of the circular module and plane configuration shows an additional resonance effect. Though, the behaviour outside of the resonance range is similar to the circular configuration. Rodrigues and Fernades [7] analysed methane and propane flame stabilization on matrix-hole plate burner optimising effects of hole diameter, distance between holes and number of holes of the flow distribution plate as function of the relative velocity gradient. Shows that flames are less stable as large is the distance between holes on the distribution plate and that the flame stability is almost insensible to the other number of holes of the plate and the hole diameter and finally characterised the reacting propane airflow around burner plate. Lei, et al. [8] investigated the detailed behaviours of the temperature, velocity (in axial and tangential directions) and air entrainment in fixed-frame type fire whirl plume. The radial temperature follows the decaying exponential function and the power exponent 'n' decreases from 2 to 1 with height in the intermittent flame and plume. In continuous flame, drop in increment rate of centreline axial velocity was observed comparative to buoyant flame. Recently Wang, et al. [9] studied the flame height and air entrainment coefficient of double buoyancy-controlled jet fires having two identical rectangular nozzles with same mass flow rate but varying distances. They found the flame height increases with the heat release rate, and it decreases with the distances between two nozzles if the distance is small. The flame height remains unchanged when the distance is large enough. Hu, et al. [10] experimentally investigated the evolution of flame height produced by line-source buoyant turbulent non-premixed jets with air entrainment constraint by two parallel side walls at various separation distances. Resulting in little flame height change with side walls separation distance when the longer side of the line-source nozzle is perpendicular to the side walls, flame height decreases with increase in side walls separation distance and finally approaches the value of a free jet when the separation distance beyond a critical value when the shorter side of the line-source nozzle is perpendicular to the sidewalls. In 2018, Tao, et al. [11] experimentally investigated on effects of various diameters for ring pool fire resulting flame height of ethanol changes slightly and for n-heptane, it increases with equivalent diameter. They also found a classic correlation for n-heptane and ethanol for plotting the evolution of flame height. The fuel flow rate and the extent of axial shear for fuel flow rates are major functions of soot emissions. Soot suppression increased along with higher external shear for all the fuel flow rates [12]. Deepika, et al recently observed that the soot suppression and flame area enhancement are contemporary following non-linearity, which reflects the flame to soot area variation across the magnitude of external shear for different fuel flow rates. Rahul, et al. [13] experimentally investigated on transitional flaming from premixed to diffusion flame with varying inlet air-entrainment area and varying orientation in first quadrant. Images of transitional flaming acquired and phenomenally presented. The results obtained clearly quantify flaming transition as a strong function of inlet air-entrainment enclosure area with linear dependence on orientation. Present work primarily focuses on simplifying and understanding the behaviour of flames with varying location and for various sets of locations of air-entrainment zones of equal enclosure area. The motivation for this work is initiated by the idea of understanding flames as a function of various air-entrainment enclosure locations and simultaneous multiple air-entrainment enclosure locations in varying sets and utilising it wide range applications of flames associated with perforated channels for stabilizing it and further exploration of flame dynamics. The specific objectives of the work are:

(a) To investigate the combined effect of varying entrainment area position and acoustics on flame height and flickering frequency.

(b) To study the effect of thermo-acoustics on soot formation.

2. Experimental Setup and Methodology

To address the subject, an experimental setup was upraised comprising of components as shown in figure 1 (1) Height reference chart, where each square box is 5mm, (2) Laptop connected to speakers with NCH tone generator software for sound generation of varied frequencies and laptop with 100% volume, (3) Two sound sources which are identical in dimensions, power input and output characteristics, (4) Cylinder holder apparatus, (e)Butane cylinder. The cylinder and the sound sources are calibrated in vertical and horizontal positions for same level using the lines as seen from top view (please refer to figure 2). The sound sources are placed 20cm from the centre of nozzle on either sides and totally 40 cm from each other. The speakers were checked and corrected for perpendicularity and symmetry in position about all three directions of space. Selected nozzle contains 3 sets of 4 holes each (diameter 4.87 mm each) for required air entrainment. The array of holes positioned at the start of the nozzle are named E1, the one in middle of the nozzle are named as E2 and the array of holes positioned at the end of the nozzle are named as E3 (as shown in figure 3a).The experiments were carried out in normal gravity ($9.81ms^{-2}$) and standard atmospheric conditions where temperature was maintained constant at 29^oC and 21% oxygen concentration environment. The fuel mass flow rate was maintained constant by measuring the velocity of fuel flow from the orifice at the start of the nozzle as depicted in figure.3b. The fuel mass flow rate was maintained at 1.217 mg per second. Different configurations of entrainment holes were achieved by closing 3 holes completely and half of the fourth hole in a single row by using paper and adhesive tape. A case where all the holes are open is achieved as shown in figure.3d. . The ignition through external source is done at the end of the nozzle outlet in all cases to maintain uniformity as shown in figure.3e. Using NCH tone generator software, the sound sources produced sounds of frequencies 100Hz, 500Hz, 1000Hz, 2500Hz, 5000Hz, 7500Hz and 10000Hz(as shown in figure 4). The orientation of the nozzle was always maintained perpendicular and equidistant from sound sources. The centre point of the sound source was aligned to be in line with the entry point of nozzle in all cases.

For each of the five entrainment hole configurations (only E1 open, only E2 open, only E3 open, all open and all closed) cases, firstly the fuel was calibrated to required level and ignited at the end of the nozzle and sound sources were switched on for the required frequency and allowed to impinge sound on the flame for 60 seconds, meanwhile a 60 fps camera was set in position to video graph the entire process (shown in fig.5). Later the video graph was shredded to obtain images at 12, 24, 36, 48 and 60 seconds time interval and the image is analysed for Gross flame length (GFL), Blue Flame Length (BFL) and Yellow Flame Length (YFL). After every case the flame was blown out and the apparatus was allowed to cool down for 10 minutes, so that the wall temperature of nozzle and atmospheric conditions remain constant throughout the experimentation duration. This process was repeated in all configurations of entrainment holes and each frequency of sound source.

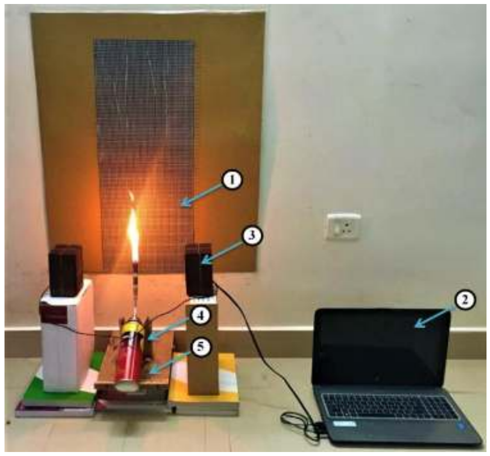

Fig. 1: Complete experimental setup.

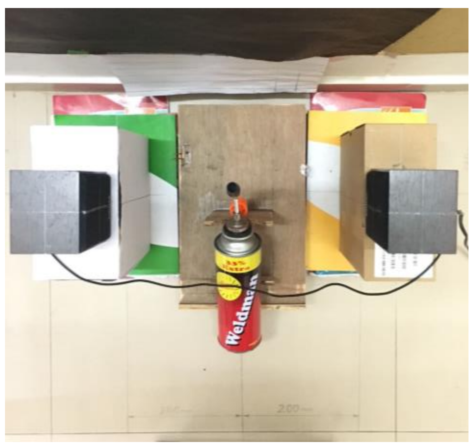
Fig. 2: Top view of experimental setup.

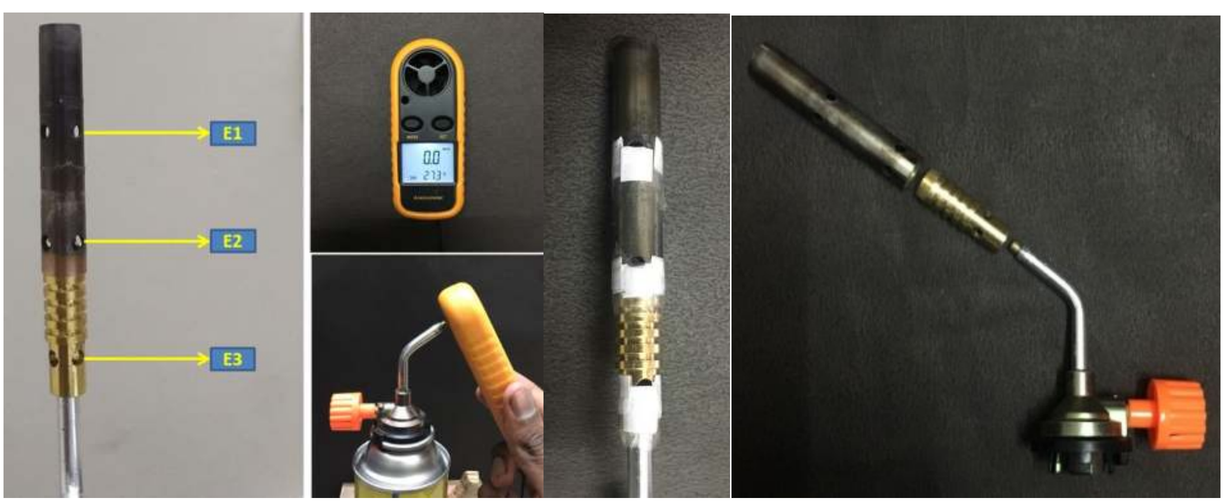

Fig. 3: (a) Nomenclature of array of holes, (b), (c) Anemometer and flow measurement.
(d) All open case, (e) Removable sub-parts of nozzle.


Fig. 4: Ignition from top.

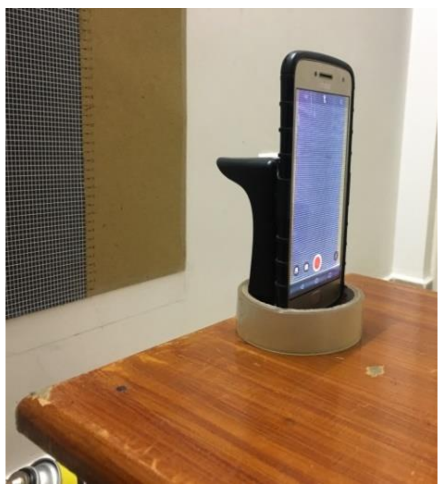
Fig. 5: Camera stand and holder

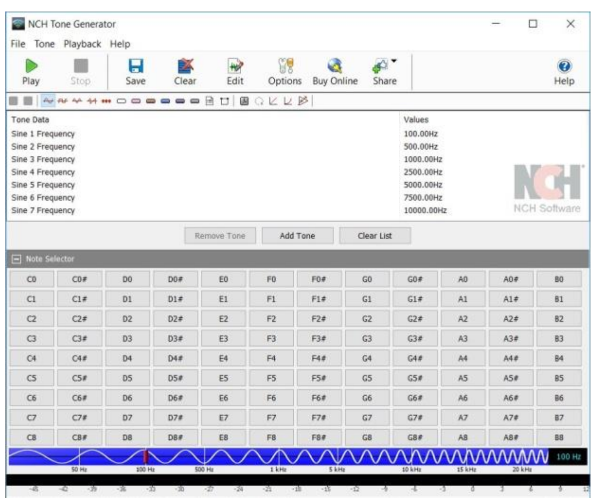

Fig. 6: Screenshot of NCH tone generator window.

3. Results

The experimentation was carried out step-wise and in an organised manner, firstly a base case was established with which rest of the cases could be compared. In this case only E1 is kept open (3 holes of E1 completely closed and one hole is half closed) and the other holes (E2 and E3) are completely closed and no sound interaction with environment was entertained. As the sooty flame emanated from the trailing edge of premixed blue coloured flame witnessed for the first time as we covered $3\frac{1}{2}$ out of 4 holes of E3 set. This case is referred as the base case for this study, where the longitudinal axis is fixed for alignment for the all the sets so that the $3\frac{1}{2}$ holes of each set could be positioned.

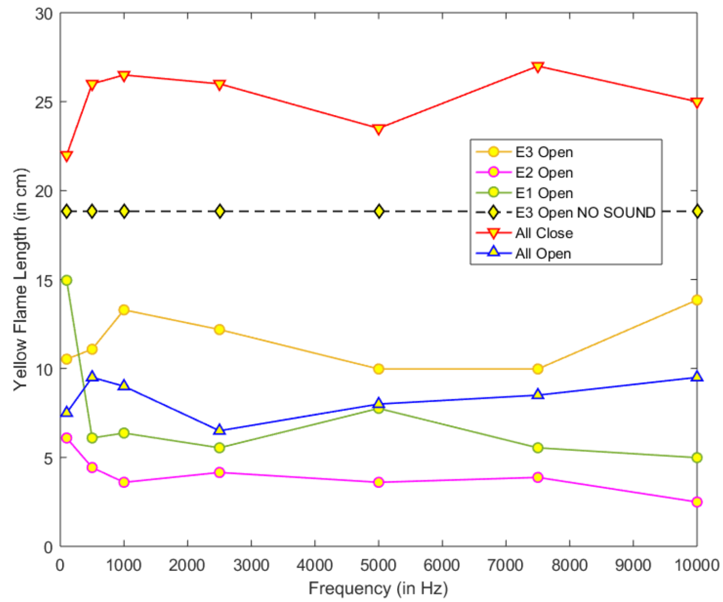

Fig. 7: Variation of Yellow Flame Length with Frequency.

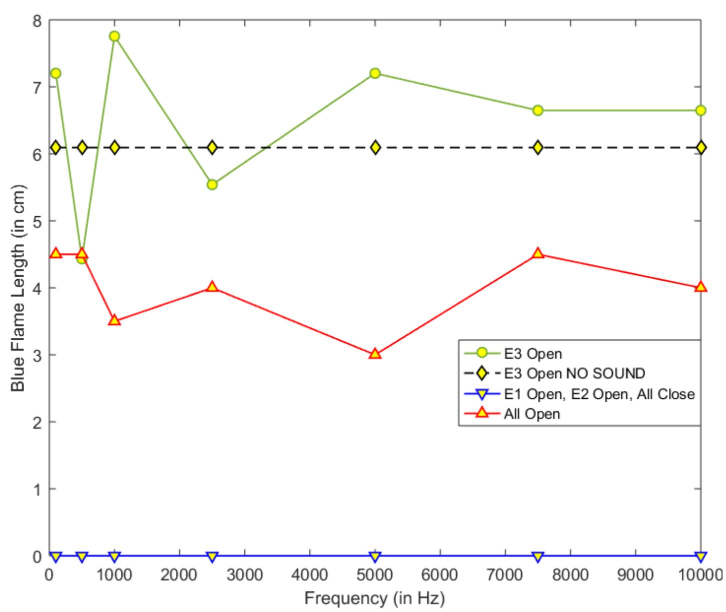

Fig. 8: Variation of Blue Flame Length with Frequency.

Fig. 9: Variation in flames with varying sound wave's frequencies for configurations as follows
(a) Only E3 Open (b) Only E2 Open (c) Only E1 Open (d) All holes close (e) All holes open.

On careful observation of images in Fig. 9 (d), which are the snapshots taken at equal intervals of 12 seconds from the 60 second video for the case where all the holes are closed. We can observe that the resultant flame in all the cases is an unsteady diffusion flame that is flickering, the flame shape is not constant and neither is the height. In this flame, the height of blue flame, which is visible to have formed at the base of the nozzle and at the beginning of the flame, is almost constant in height in all cases and its length, is very small compared to the length of the yellow flame. The diffusion flame is formed in this case because all the holes for entraining oxygen or air into the nozzle are blocked, which forces the out coming fuel gas from the nozzle to diffuse air from the surrounding atmosphere to mix with it at the exit of the nozzle. This entrainment zone being very near to the flame front doesn't allow much time for the fuel and air to mix well, this leads to incomplete combustion of fuel and thus leads to formation of the yellow part of flame which is actually the soot or the partially burnt carbon particles and radicals which are emitting electromagnetic radiation in the visible spectrum of yellow region due to the return of electrons from the higher excited states to the lower states, as the fuel particles moves to the end of the flame length. Due to unsteady heat generation, the sound generated due to combustion and vortices that are formed due to aerodynamic interactions between the flowing fuel gas and entrained air, which all interact with the flame we observe flickering behaviour. All the aforementioned phenomena interact with each other and also interact with the flame to cause pressure oscillations inside the nozzle which leads to flickering behaviour. Now by us externally trying to impinge sound on the flame is done so as to imitate practical scenarios where noise from environment interacts with the combustion based appliances and we try to find out how this sound effects and interact with the flame which in turn will affect the appliance in which it is being utilised.

The series of snapshots in Fig. 9 (e) are the cases depicting changes of flame structure and shape with change in various sound source frequencies for a fixed fuel flow rate and the configuration of entrainment holes where all the holes are open (3 holes completely closed and half of fourth hole closed in E1, E2 and E3). On careful observation we can observe that the flame in all the cases is a shorter flame compared to diffusion flame, and most of the flame is blue and towards the tip of the flame it is yellow. Also the flame is unsteady and is flickering. It can also be observed that in some of the cases the flame possesses an M-shape and bifurcated at the end. Almost three-fourth of the flame is blue which indicates its premixed strength, it signifies that most of the fuel is ignited completely whereas some of it is partially or incompletely burned which is visible as the yellow part of the flame which is also referred to as soot. In this case as almost most of the entrainment area is closed and only some of it is open for allowing air to enter and mix with the fuel in the nozzle, we observe a partially premixed flame. The flickering nature is again observed due to interaction between the unsteady heat generation, wall heat interactions, aerodynamic interactions of flow and sound energy from environment with the flame.

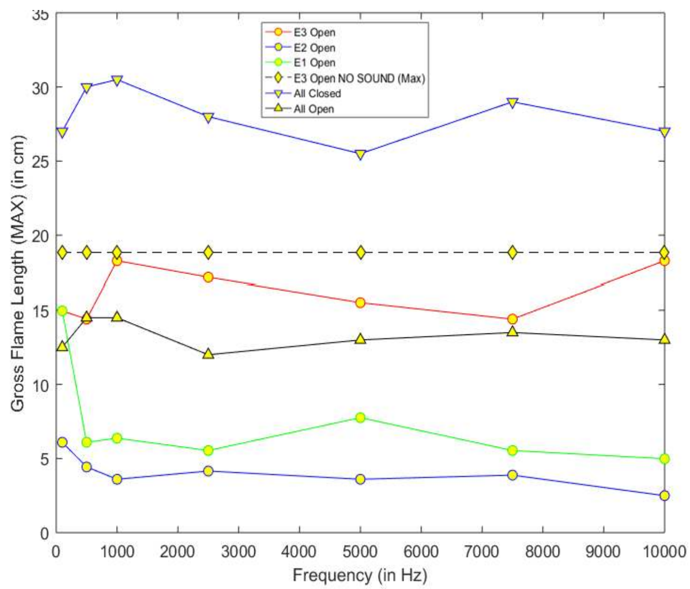

Fig. 11: Varying Maximum Gross Flame Length with frequency

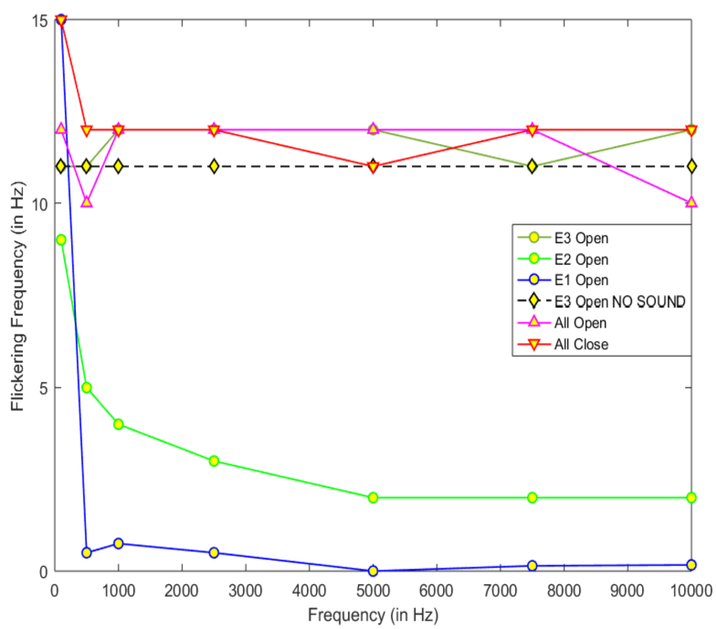

Fig. 12: Variation of Flame Flickering Frequency with Acoustic Frequency

The variation in Gross Flame Length (GFL) with impinging incrementing acoustic frequencies is represented graphically in Fig. 11, where the GFL of none of the cases reached the base case GFL except all holes closed case. All holes closed case GLF increased 43.34%-61.92% more than base case from range of 100-1000 Hz then decreased up to 35.38% more than base case reaching 5000 Hz and again it rose to 53.96% and dropped to 43.34% more than base case where it's initiated at 7500 and 10000 Hz, respectively. The fuel is lacking enough oxidiser at ignition in all entraining holes closed case, resulting in unburned fuels from exhaust referred as soot. This system to achieve energy conservation compensates entropy change with GFL in search of oxidiser for flame's sustainment. At 1000 and 7500 Hz the local maxima of GFL reached that means the pressure pulse waves formed in-phase constructive waves which have large amount of energy and a possibility is that it would lose energy to stable and it transferred the energy to flame which eventually helped flame to gain more stability and eventually decreased the GFL, which actually spreads its yellow portion (soot) flame. At 100, 5000 and 10000 Hz the vice versa takes place the impinging sound waves formed in-phase destructive wave which lacks energy to be stabilised so it withdraws energy from the flame and GFL rose to gain energy by shifting the process towards complete combustion by exposing flame to more oxidiser, thus the decreasing soot area. In all rest of the cases the GFL didn't reach till base case. For all holes open and E2 open case the trends are almost similar, till 1000 Hz the GFL continues to decrease and till 2500 Hz in all open case, then it continues incrementing up to 4 % relatively till 7500 Hz and almost stays constant till 10000 Hz. In E2 open case after 1000 Hz it almost stays constant till 10000 Hz. But in all open case and E2 open case the maximum GFL reached 57.35% and 67.64% less than base case. For E3 open case, 500 and 7500 Hz local maxima GFL decreased 23.53% than base case. For E1 open case at 100 Hz in local maxima decreased up to 20.59% than base case, 58.82% decreased than base case at 5000 Hz. At rest of the frequencies in E1 open case GFL maxima almost decremented 70% than base case. As the ignition takes place at the nozzle exit leads to flame formation and depending upon the oxygen diffused in fuel flow the flame tends to sustain by exposing it to more atmospheric oxygen by compensation of its height (and/or front area) via the systematic conversions of inter-energy between flame and corresponding flow just to not violet the law of net energy conservation and make the maximum possible rise in entropy change by the system. Results rise in unsteady flickering phenomenon occurs because of internal energy conversions in a flame. This flame eventually transfer its heat to low temperature fuel in downward direction through hot radicle transfers and though conduction by metallic wall of nozzle. This makes the walls hotter and the reduction in heat loss take place, so with time flame becomes more steady and structured.

The stability of a flame can be well optimized considering the flickering frequency as a function because the unburnt region of flame having less energy than blue flame, so sooty-flame transforms its shape very easily than blue flame. This reason relates the flame frequency with the sound wave's frequencies. So impinging sound waves do affect the stability of a flame by fetching variations in flickering frequency as consequence of interacting energies, and these are depicted in fig. 12 for separately E1, E2 and E3 open cases and the extreme cases of all holes closed and all holes open cases. For the case of E3 open, the frequencies overshoot the base case frequency by 9 % for impingement of 1000, 2500, 5000 and 10000 Hz of sound, by transferring pressure pulses' energy to the flame making flame excited and inducing much inter-energy conversions. But for 100, 500 and 7500 Hz the flame imitated the base case range of frequenting values. For only E2 open configuration, the flame frequency reduced by 18% for the highest frequency of case and it decreased up to 72.72% up to 2500 Hz and further up to 81.82% and stays constant as rise in acoustic frequency up to 10000 Hz. In case of only E1 open configuration 100 Hz sound wave impingement induces flame frequency 36.36% more than the base case but a drastic drop of flickering frequency observed up to 95.45% than base case at 500 Hz impingement and stays almost constant having error of $\pm$4% and at 5000 Hz impingement completely stationary flame occurred with no flame frequencies. But in case of all holes open 36.36 % flickering frequency rose than base case at 100 Hz and flame frequency of about 10 % more than the base case almost stays constant for all other sound frequency impingement in diverges the chances of getting a stable-structured flame. In all holes open configuration, the 10% more flickering frequency than base case observed for almost all cases except the impinging frequencies of 500 and 10000 Hz where about 10% lesser flickering frequency than base case was observed. *As optimized here, it is very difficult to drop the flickering frequency of flame having collinear-multi-entraining holes in either fully open or fully closed cases and even for the only opened case of closest air entraining hole to the reservoir. But for the cases of intermediate and farthest entrainment holes from reservoir impinging pressure pulses of sound for varying frequencies could be a great controlling parameter as it converge the frequenting flame towards stable-structured flame as sound frequencies increases.*

4. Conclusion:

A systematic experimentation methodology was followed to study the effect of effect of thermo-acoustics and position of air entrainment on the soot formation of flames. To manually induce sound energy in the environment of flame sound source was utilised that is capable of producing various frequencies of sound, and a nozzle with various sets of entrainment holes set at vertical position and equidistant from sound source were used to study the combined effect of this phenomena on soot formation characteristics. The thermal energy in this system is contained in two forms which are namely the external and internal form, where the internal form refers to the chemical kinetics and the external thermal energy is manifested in the form of localised velocity and temperature gradient fields along the nozzle wall, the impinging acoustic energy alters the external thermal energy, which is a cause of the internal energy, so thus with progress of time the acoustic energy alter the internal thermal energy which leads to other forms of energy interactions whose effect on the flame can be observed by observing the flame height, which is the key analysis parameter in this research work. Along with external acoustic energy, other energy interactions also affect the flame characteristics which are studied by varying the entraiment location. The major outcomes of this work are as stated below:

(i) The externally applied acoustics doesn't always aid in the soot reduction.

(ii) The energy interactions caused due to applied acoustic energy and thermal energy compete with each other and the resulting effect on flame is manifested in the form of soot formation and flame height.

(iii) Usually the flame characteristics are most influenced by the dominating effect that causes energy interactions, this effect can be seen by keeping one of the energies constant and observing flame characteristics.

(iv) But in this case it can be inferred that the two energies, that is thermal and acoustic energy compete with each other and jointly produce effects on the flame characteristics which is the soot formed.

(v) This case is the most realistic analysis that matches practical scenario where the combustion based appliance is exposed to multiple sources of external energy.

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