Combust-o-Acoustics: Energy Transition and Implications

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Abstract. Acoustics is an integral constituent of most of combustion processes. While combustion advancements have revolutionized human life, acoustics induced combustion also represents a dominant form of instability. Thermo-acoustics, as an intense area of scientific research, covers a wide range of applications viz., industrial (electricity generation), transportation (jet and space propulsion), engineering (system efficiency and operations) and scientific research. The presence of such inept working systems with instability is likely to result in significant loss of resources, infrastructure, property, mankind, nature, with huge amount of money being spent on research activities. Appreciable work has been done before however; the heterogeneous nature of the problem has prevented comprehensive understanding. Thus, the need to investigate and characterize the acoustics imbibed combustion processes to suggest better combustion alternatives/ enhance effectiveness and to minimize the resultant hazards. Present work, attempts to resolve the low effectiveness of combustion systems by classification of thermal acoustics and related major hazards. A simple experimental setup was upraised comprising of butane cylinder with nozzle and systematic experimentation was carried out to explore the phenomenon of energy transition in combustion with acoustics. The exploration was carried out for varying fuel mass flow rates, L/D ratios, material of tubes, interspace distance and counter acoustics impingement. The results were observed with acoustics measurement, along with type and structure of flames. The work is primarily motivated by the need to have technologically enhanced combustion understanding and for fire safety applications. The results exhibit that presence of external enclosures have significant effect on thermoacoustics and with coupled redundancy effect, a special pattern noted was both the controlling parameters results in reduction in maximum acoustics rise and increase in maximum drop levels this contributing significantly to enhancement of system efficiency. The results can be of pertinent significance for the testing, validation of conventional systems and designing of the efficient and safer futuristic propulsive systems.

1. Introduction
Combustion is one of the most defining phenomena of physics and sustains to control large part of world’s energy requirement. Combustion oriented power generation is the only established sources for wide range of industrial, engineering, practical, functional and scientific applications. The phenomenon is widely observed and studied in the form of flaming and smoldering combustion. This classification is based on the presence of the nature of hot gases emulating. Flaming combustion signifies the burning process with temperature dependent hot gases as visible interactions. The flaming
combustion is classified as the premixed flame and diffusion flame. This classification is based on the category of hot gases coming out as products of combustion in the form of soot. Diffusion flames are formed when fuel and oxidizer are mixed instantly and signify unstable burning with presence of soot, yellow in color, lower flame temperature but higher stability range. The premixed flames represent premixing of the oxidizer and fuel before the reaction occurs. There is no soot formation and the maximum temperature attained by them is high. The notable features of premixed flames being, blue in color and, less luminous and higher stability range (figure 1). The notable applications exist in the form of aerospace propulsion with gas turbine engine and space propulsion. Like every natural phenomenon, combustion is bound by instabilities. Instabilities may cause unnecessary noise which arises due to this energy transition. The amount of sound and its characteristics (like frequency) associated with the flame changes with the internal and external sources. One of the most dominant form of instability in combustion process exists in the form of acoustics. The acoustic energy increase due to the instable heat release of the flame being greater than the acoustic losses energy from the system leads to thermoacoustic instabilities to occur. These instabilities may be caused by a number of external and internal factors and incur effects on the flame e.g. lift off, flash back, turbulent flames etc. There also arises the question of energy transition and energy losses due to which the efficiency of combustion reduces. For centuries, scientists and inventors have been looking for ways to eliminate energy losses and obtain mechanisms with optimized efficiencies.

One of the major energy-transitions in this case is heat-to-acoustic energy transfer. Most of these losses occur due to redundant and uncontrolled energy transitions. Thus, it is important to estimate and compute the acoustic induced instabilities. The applications of studying this energy transfer are vast and can be used to design better and more efficient combustors and other thermal mechanisms in a wide range of fields. As one of the primary applications, the gas turbine combustor often pact with the acoustics and flame agitations. Owing to these interactions, combustion chamber burners play a deciding role in setting up the instabilities (figure 2).

The redundant coupling of acoustics with unsteady perturbations is expected to cause persistent complications in combustion chambers. One aspect which is yet to be comprehensively tested is utilization of external source(s) in minimization of the instability behaviour. Present work aims to focus on the losses that occur in combustion processes due to heat-to-acoustic energy transfers. The external sources that are used here are mild steel hollow cylindrical tubes of different dimensions that are placed above the flame in different positions to study the change. The variations are observed considering varying frequencies of these sounds with respect to time, distance between flame and pipe
opening and different dimensions. The applications include aircraft engines, power plants, missiles, rocket engines and also the daily use transport.

![Figure 2. Pictorial representation of premixed flame (a) combustor, (b) burner (*www.science.com).](image)

Following the classical work of Norris and Streid [1] on the laminar flow heat transfer coefficients for ducts, appreciable work on understanding the rooted thermoacoustic instabilities had been done. The reviews can be found in [1-13]. Wibulswas [2] worked on numerical solutions for laminar heat transfer for rectangular ducts of different aspect ratios. The work resulted in reasonable well marked agreement for different Graetz numbers for conditions of persistent wall temperature and heat input. Leyer and Manson [3] experimented with the vibratory flame propagation development in short closed tubes and vessels. Results showed that the primary flame interaction with the side walls is augmented by variations in the flame structure. The growth of the vibratory phenomena was detected to be inclined by the characteristics of the walls. Pelce and Clavin [4] worked on premixed laminar flames spreading downwards in an even reacting mixture and developed a diagnostic theory for the steadiness features. The study presented that the gravitational acceleration related with the diffusion mechanisms inside the front can counterbalance the hydrodynamical instability. Oyediran et. al., [5] reviewed the problem of combustion related acoustic instability on a variety of practical combustion devices. Investigations on the unsteady heat release rate were performed, based on trepidations in the fuel delivery system particularly for rocket instabilities. Lieuwen and Yang [6] provided stimulating review of the scientific activities carried out and issues to be addressed in the engineering, administrative, and theoretical societies with combustion instabilities in low-emission gas turbines. The review examined the essential mechanisms besides the modeling and regulation methods. The results were compiled that addressed the various planes of the issue. Allam and Abom [7] experimented with acoustic liners for overpowering engine sound by inlet and exhaust. The transfer matrix measurement was made using the two-microphone technique. It was deduced that sub-millimetre size perforations offer themselves adequate acoustic resistance and low acoustic mass reactance required for a wideband absorber. Campa and Camporeale [8] carried out experimental tests on single burner arrangements for the design of a full-scale combustion chamber, owing to the interaction of the local flame oscillations with the pressure waves of wavelength of the same magnitude as main chamber. The heat release variations were characterized through a flame transfer function (FTF) model and the transfer matrix method for modelling the burners. In the last decade, Richecoeur et. al., [9] studies stabilization of a partially premixed spinning propane–air flame. In the premixing tube, reactants were inserted indirectly to generate the swirling flow. Results exhibited that the premixer and combustion chamber can be considered as acoustically decoupled for small values of the acoustic coupling index. Campa and Camporeale [10] carried out full scale numerical study using a 3-D code for the eigenvalue investigation of the thermoacoustic instabilities modeled through the Helmholtz equation. Spatial distributions for the heat release intensity and time delay were used for the linear flame model. The results exhibited noteworthy impact of the 3D dispersal of the flame on the modes. Bauerheim et. al., [11] analysed the advances in combustion chambers experimentally, numerically, and theoretically with Longitudinal low-frequency thermoacoustic unstable modes. The
work advocated study of azimuthal modes in modern annular gas turbines. The evaluation offered development in the field with Galerkin and network models in both the temporal and frequency framework. Kim et. al., [12] experimentally investigated the combustion instability and its attenuation characteristics in the lab-scale swirl stabilized premixed combustor. Distinct importance was accorded to the effects of the acoustic cavity length on the stabilization. Results presented that the model combustor with the porous dump plane and the acoustic cavity exhibited dramatic attenuation of the pressure oscillation intensity by up to about 40%. Rashwan et. al., [13] carried out three set of numerical investigations on the consequence of air-fuel equivalence ratio on stimulating thermoacoustic instabilities in a partially premixed swirl combustor. The first set offered assessment between the present numerical study and preceding experimental work. The second simulation set was done to predict the reacting and non-reacting flows with regard to pressure fluctuations, power spectral density, and the sound pressure levels. The third simulation set measured the implication of the air-fuel equivalence ratio on the acoustics and combustion characteristics. It was resolved that the equivalence ratio details a vital rule on stirring combustion instabilities at various amplitudes and frequencies due to increase the heat release rate. From the noted literature survey, one can note that predicting thermoacoustic instability remains difficult owing to modelling and uncertainty of the physical parameters of process. The present work attempts to perform quantification for thermoacoustics. The work is motivated by the need to comprehend flame stabilization in a gas turbine engine under varying conditions.

The specific objectives of the work are:

a) To investigate the acoustics alteration produced by premixed flame in presence of external circular hollow metal tube(s) of varying dimensions.

b) To investigate the change in acoustics formed with external circular hollow metal tube(s) with:

i. One end open

ii. Both ends open

iii. Varying temporal conditions

c) To recognize the part of key governing constraints.

2. Experimental setup and Solution Methodology

A simple experimental setup (figure 3) was upraised to fulfil the selected objectives comprising of (a) Butane Gas Cylinder placed (figure 3(b) on custom-made stand (figure 3(c)) such that the nozzle is perpendicular to the ground, (b) Anemometer (figure 4(c)), (c) External hollow circular pipes made up of mild steel with varying L/D ratios (figure 4(a)) and (d) Sheet metal box kept over pipe to cover upper opening (figure 4(b)). A scaled black background was setup vertically to minimize external visual disturbances and to enhance clarity of flame image.

![Figure 3](image-url)
A specially designed soft board stand was made to hold the butane gas cylinder such that the nozzle stays perpendicular to ground. The external enclosures (here pipes) with varying length and diameter combinations of equal thickness of 1.5 mm were serially marked from 1-5. The corresponding L/D ratios selected are 7.89, 7.93, 9.52, 11.11 and 12 respectively. The external enclosures were held with an adjustable pipe holder, specifically designed to hold all five pipes firmly. A stand with transverse mechanism was used to hold the pipe holder in place. A least count of 1mm ensured greater accuracy in holding the pipes at a specified height. To cover one of the ends of the tubes, a mild steel sheet metal box was used. The flame front was digitally video graphed with an optical setup. Multiple mobile phones were used to measure the acoustic strength, to capture videos & photos and to record corresponding audio. Cardboard boxes with markings and slots were used as stands to hold the phones in place. A stopwatch was used to measure time intervals in which readings were taken. A transverse mechanism was placed in front of a scaled black background. A specially designed pipe holder was attached to the transverse mechanism with the help of a spanner. Pipes were firmly held by the pipe holder with the help of screws. A gas-cylinder-holding stand, which was specially designed to hold the
gas cylinder’s nozzle perpendicular to the ground was placed below the pipe holder. The gas cylinder, which was attached to the nozzle, was placed on the gas-cylinder-holding stand such that the nozzle was exactly below the pipe and their central axes aligned. A setup was raised at a distance of 120 mm from the nozzle to place two devices to measure acoustics and to capture the respective audio. To capture the videos and photos, a camera was placed at a distance of 1018 mm from the nozzle such that the whole setup along with the black background was visible in the frame. Ignition process is mostly owing to energy transition in a self-sustained reactive combustion. The noteworthy aspect from the phenomenon is the behaviour of the output (the system efficiency) which varies differently owing to presence of varying system acoustic energy. The governing acoustics energy is expressed as:

\[ I_s = p \times v \]  \hspace{1cm} (1)

\[ P_s = I_s \times A \]  \hspace{1cm} (2)

\[ P_s = p \times v \times A \]  \hspace{1cm} (3)

The net accessible energy in the system is given by:

\[ E_{net} = E_{gen} - E_{loss} \]  \hspace{1cm} (4)

where,

- \( I_s \) = Acoustic Intensity Level (W/m²)
- \( p \) = Sound pressure (N/m²)
- \( v \) = Particle velocity (m/s)
- \( A \) = Area (m²)
- \( E_{net} \) = Net Energy
- \( E_{gen} \) = Energy Generated
- \( E_{loss} \) = Energy loss

System efficiency = Net Available Energy / Energy Input  \hspace{1cm} (5)

Equations (4-5) highlight the effect of presence of system acoustics on useful energy available. One can note that any alteration in the acoustic levels is very likely to affect the operating system efficiency. (9%)

A nozzle setup was attached to the butane gas cylinder. The anemometer was used to measure the velocity of the butane gas by holding it at the mouth of the nozzle. At a desirable value, the nozzle knob was marked for later use. For every reading, the nozzle knob was set at that mass flow rate and the burner was ignited using a lighter and aligned below the pipe. For cases in which only the bottom end of the pipe was supposed to be kept open, a sheet-metal box was placed over the pipe to cover the top end. With the help of a stopwatch, the acoustic readings were noted at every 30th and 40th second from the instant the flame was ignited. At the same time, audio recordings, video recordings and photos were taken. During the whole process, it was made sure that there was minimum external acoustic disturbance. The flame was only ignited for about 45-50 seconds because after that, the purely blue flame would start turning into a yellow flame. The flow of butane gas from the cylinder was stopped and the nozzle, pipe, pipe holder and the sheet metal box (if used) were allowed to cool off. The yellow flame is mainly observed due to heating of the channel through which the gas flows. Moreover, properties of materials (here, material of pipe) also experience change when heated. Due to these reasons, the apparatus was allowed to cool off before re-using it. It is important to note that thorough environmental normalcy was maintained in experimentation and data represents necessary repeatability.

3. Result and Discussions

A systematic experimentation was carried out on basic premixed flame without external influence (enclosures). This was done in order to establish the base condition. This forms the primary condition with which all the other conditions under the influence of the external energy field was compared.
From Figure 6(a), we can compare the change in acoustic energy with respect to the base case when the L/D ratio of the enclosures is varied (Refer Figure 9). There is a continuous variation in the acoustic intensity level with increase in L/D ratio. Initially, it increases to reach a maximum (L/D=7.94) which is 3.93% greater than the base case. Then, it is seen that there is a fall in the acoustic intensity level up to a minimum (L/D=11.11) which is 4.89% lesser than the base case. After this, there is a small rise in the acoustic intensity (L/D=12.0) which is still 2.5% lesser than the base case. Interestingly, the enclosure with L/D ratio (L/D=7.89) gave an acoustic intensity 2.15% lesser than the base case. For the L/D ratio of 9.52, the acoustic intensity is seen to be closest to the base case which is just 0.95% lesser than the base case. The line representing the variation of acoustic intensity exactly takes the value of the base case around the L/D ratio of 9.25. Since our main goal is to identify is optimum L/D ratio to obtain minimum acoustic intensity levels, according to Figure 6(a) where the observations were recorded 30 seconds after the flame was ignited when the flame was with the enclosure, the L/D ratio of 11.11 is the optimum choice.

Figure 6(b) highlights a continuous variation in the acoustic intensity level with increase in L/D ratio, however the nature of the graph is reversed compared to Figure 6(a). From the minimum L/D ratio, it a percentage drop of 6.56% from the base case at the L/D ratio of 7.93 was observed. The Acoustic intensity was noted to take a slight dip to attain a peak at an L/D ratio around 8.4. Further, a steady increase crossing the base case value at the L/D ratio of 10.45 was noted. After this, it reached a maximum at the L/D ratio 11.6 and experienced a slight dip after the peak at L/D of 12. The maximum acoustic intensity was found very close to L/D of 12 which is 5.01% higher than the base case. The value of acoustic intensity at the minima is quite close to the value of acoustic intensity at the L/D ratio of 7.94 which is 6.56% lesser than the base case value. Since our main goal is to identify optimum L/D ratio to obtain minimum acoustic intensity levels according to figure 6(b), where the observations were recorded 30 seconds after the flame was ignited, when the flame was in the enclosure, the L/D ratio of 8.4 is the optimal choice.
Figure 7. Variation of Acoustic intensity level with L/D ratio for the cases of (a) enclosure effect with flame location, (b) partially opened enclosure effect.

Figure 6(a) and 6(b) represent variation in acoustic intensity with respect to increasing L/D ratio of the enclosures considering two different cases of flame positions with the observations recorded at 30 seconds from the point of ignition of flame. In figure 7(a), the similar cases of flame positions recorded at 40 seconds from the point of ignition of flame were analyzed. It was observed that the nature of the variation in acoustic intensity remains broadly similar in nature with respect to its temporal variation. The maxima and minima remain constant. From the figure 7(a), we can note that the curves for flame outside and for flame within the enclosure coincide at an L/D ratio of 9.6. This can be considered equivalent to 1.25% decrease (average of percentage decrease values at L/D ratio of 9.52 since they are the closest values). Figure 7(b) represents the change in acoustic intensity level when the vertical distance between the flame tip and the enclosure is varied. The figure shows two curves that represent cases in which the enclosure’s one end is kept open and both ends are kept open. One can note that the nature of the two curves is quite similar i.e., both experience a drop in the acoustic intensity levels from where it increases rapidly. It can be advocated on the results that the acoustic intensity for an enclosure with bottom end open is always greater than that of the enclosure with both ends open (refer figure 10 and 11). The maximum recorded percentage difference between the enclosures was found to be 7.34% at a vertical distance of 20 mm. The minimum acoustic intensity level that is attained by a one-end-open enclosure was found at 5 mm from the flame tip. Similarly, the minimum acoustic intensity level attained by both ends open enclosure occurred at 14 mm from the flame tip and at 23 mm, the acoustic intensity attained by the arrangement in which the enclosure has bottom end open is equal to the acoustic intensity without any enclosures. For the arrangement in which the enclosure with both ends open, this acoustic intensity is attained at a vertical distance 29.5 mm. The acoustic intensity kept increasing up to 16.67% for enclosure with bottom end open and up to 14.81% for enclosure with both ends open.

Figure 8(a) represents the variation of acoustic intensity for the case when the flame was taken with the enclosure comparing acoustic intensity at the two instants of time viz., 30 seconds and 40 seconds after the ignition of flame. The nature of the variation was noted to be similar and one can see the temporal variations clearly. Initially, the acoustic intensity level rises above the base case to attain a maximum, then drops down to attain a minimum and finally, increases and comes close to the base case value. The deflection between the two curves is not constant and was observed to be maximum at the point of first maxima (L/D=7.94) i.e. acoustic intensity at 40 seconds is 2.52% greater than the acoustic intensity at 30 seconds. The minimum deflection was noted at L/D ratio of 9.52 where
acoustic intensity at 30 seconds is 0.12% greater than its value at 40 seconds. It was also observed that between each L/D ratio that was taken into consideration, there is a point of crossover at each L/D ratio, the deflection is positive and negative alternately when acoustic intensity at 30 seconds and 40 seconds is compared. At the point of minima, i.e. at L/D ratio of 11.11, the acoustic intensity observed at 40 seconds was found to be lesser than that observed at 30 seconds by 11.44%.

Likewise, figure 8(a) represents the variation of acoustic intensity for the case when the flame is inside the enclosure comparing acoustic intensity at the time instants of 30 seconds and 40 seconds. It was observed that, the temporal variation is similar. Initially, the acoustic intensity levels decrease to attain a minimum and gradually increases with respect to cross the base case value to attain a maximum and experiences a small dip. The deflection of curve representing values at 40 seconds with respect to curve representing values at 30 seconds is not constant. The maximum recorded deflection was at L/D ratio 9.52 i.e. value at 30 seconds is 3.77% lesser than the value at 40 seconds. Considering the recorded observations, there are two points of intersection of the curves – one just before and one just after L/D ratio of 9.52. At the L/D ratio of 7.93 where the respective minimum acoustic intensities were observed, the acoustic intensity at 30 seconds is 1.4% lesser than that at 40 seconds (value at 30 seconds taken as reference).

Likewise, figure 8(a) represents the variation of acoustic intensity for the case when the flame is inside the enclosure comparing acoustic intensity at the time instants of 30 seconds and 40 seconds. It was observed that, the temporal variation is similar. Initially, the acoustic intensity levels decrease to attain a minimum and gradually increases with respect to cross the base case value to attain a maximum and experiences a small dip. The deflection of curve representing values at 40 seconds with respect to curve representing values at 30 seconds is not constant. The maximum recorded deflection was at L/D ratio 9.52 i.e. value at 30 seconds is 3.77% lesser than the value at 40 seconds. Considering the recorded observations, there are two points of intersection of the curves – one just before and one just after L/D ratio of 9.52. At the L/D ratio of 7.93 where the respective minimum acoustic intensities were observed, the acoustic intensity at 30 seconds is 1.4% lesser than that at 40 seconds (value at 30 seconds taken as reference).

Figure 8. Variation of Acoustic intensity level with L/D ratio for the cases of enclosure with temporal effect (a) open flame, (b) flame inside enclosure.

Figure 9. Pictorial representation of setup at different cases, (a) base case (b) flame tip touching enclosure (c) flame inside the enclosure.
Figure 10. Pictorial representation of experimentation with enclosure 1 (L/D ratio of 7.89) when the bottom of enclosure is touching the tip of the flame and only bottom end is open from the time of ignition of flame (a) 0 seconds (b) 10 seconds (c) 20 seconds (d) 30 seconds.

Figure 11. Pictorial representation of experimentation for enclosure 1 (L/D ratio of 7.89) with the bottom of enclosure touching the tip of the flame and both the ends are open from the time of ignition of flame (a) 0 seconds (b) 10 seconds (c) 20 seconds (d) 30 seconds.

4. Conclusions
Through systematic experimentation, an investigation was done to understand the modulated thermo-acoustics effect on instability analysis. From the results obtained, following conclusions can be drawn:

1) Presence of enclosures do affect the system acoustics significantly. The presence and type of enclosures affect the system acoustic intensity levels leading to the alteration of the system energy output. The acoustic intensity levels vary with L/D ratios of enclosures. The overall maximum acoustic energy change i.e. the maximum acoustic power gain noted was 5 % at an L/D ratio of 12. This resembles the case with overall minimum jet engine efficiency. The overall minimum acoustic energy change i.e. the maximum acoustic power loss measured was 7.867 % at an L/D ratio of 7.94, which is the case with overall maximum jet engine efficiency.

2) Presence of enclosure location is an important parameter as the maximum rise and maximum drop in acoustic energy levels were observed for the cases of enclosure with flame inside. The location of the enclosure with respect to the flame, has significant effect on the acoustic power levels, and hence the efficiency.

3) Combustion timing was verified to invite unsteady effect on acoustic intensity. In problems pertaining to system instability timing presents notable effects. As noted with experiments, for both the cases of flame inside and flame outside, as control time increases, the maximum rise in acoustics drops and maximum drop in acoustics increases.
4) With coupled redundancy effect, the variation of enclosure location was observed to have stronger bearing on the change in acoustics levels than the change offered by the change in timing. A special pattern noted was both the controlling parameters results in reduction in maximum acoustics rise and increase in maximum drop levels this contributing significantly to enhancement of system efficiency.

5) The results were validated with a new cylinder under similar conditions and matched reasonably well thus the results are expected to offer stimulating physical insight to better validation, testing and designing of the thermal systems.

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