SPECTRAL ANALYSIS OF DIFFUSION FLAME DYNAMICS WITH FUEL EXCITED AND ITS INTERACTION WITH AN ACOUSTICALLY RIJKE TUBE

Hajer M. Mayo, Hanan M. Edawi, Saad I. Al-Bourki and Salem A. Farhat*

Aeronautical Engineering Department-University of Tripoli -Libya
*Mechanical and Industrial Engineering Department-University of Tripoli -Libya

E-mail : salemfarhat_t@yahoo.co.uk

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ABSTRACT

The instability of combustion processes in heat engines, particularly those with continuous fuel injection such as gas turbines and jet engines, poses significant challenges impacting efficiency, fuel consumption, and engine life. A critical factor contributing to this instability is the interaction between fluctuating heat release from combustion and acoustic pressure fluctuations within the combustion chamber. Rayleigh criteria have been pivotal to understanding this instability, particularly in settings like the Rijke tube, where acoustic excitation plays a crucial role. In recent experimental studies, the dynamics of diffusion flames within a vertical Rijke tube were investigated extensively. In this paper, the Rijke tube is acoustically excited at first three harmonics mode of 74 Hz, 222 Hz and 370 Hz, and fuel is excited with frequencies from 30 Hz to 300 Hz. Measurements included acoustic pressure via microphone system and flame chemiluminescence emissions via light cell system have been analyzed. Notably, at a fuel excitation frequency of 90 Hz, significant flame instability was observed, influencing both flame appearance and spectral characteristics. Under excitation, the initially laminar flame transitioned to turbulence, characterized by a change in flame color to blue and a distinctive V-shaped flame structure with rotational behavior. Increasing excitation further led to flame lift-off and extinction, akin to scenarios with increased fuel flow rates. Spectral analysis revealed a transition from a dominant frequency of 13 Hz (typical for laminar flame) to higher frequencies as instability progressed towards flame blowout. Moreover, experiments within the Rijke tube demonstrated strong interactions between fuel excitation and tube harmonics, notably at the first harmonic frequency where anti-node pressure fluctuations were most pronounced. This interaction significantly affected flame stability, evident in RMS values peaks of chemiluminescence emissions, while decays indicated instability or extinguishment. Acoustic pressure fluctuations, particularly at the first harmonic frequency, exerted a significant destabilizing effect, whereas lesser effects were noted at higher harmonics, where acoustic velocity fluctuations are high. Cross-correlation analysis between acoustic pressure and flame chemiluminescence emissions highlighted clear distinctions between stable and unstable conditions. These findings underscore the complexity of combustion instability and its sensitivity to acoustic conditions and fuel excitation frequencies. Such insights are crucial for developing effective stability control systems, whether active or passive, aimed at enhancing engine performance and reliability in diverse operational conditions.

KEYWORDS: Thermo-acoustic Instability; Chemiluminescence Emissions; Rijke Tube; Power Spectrum

الملخص

عدم استقرار عمليات الاحتراق في المحركات الحرارية ذات حقن الوقود المستمر مثل التربينات الغازية والمحركات النفاثة يشكل تحديات كبيرة تؤثر على كفاءة واستهلاك الوقود وعمر المحرك. إحدى العوامل الهامة التي تسهم في عدم الاستقرار هو التفاعل بين تذبذب الحرارة المنبعثة من عملية الاحتراق والتذبذب في الضغط السمعي داخل غرفة الاحتراق. لقد كان معيار رايلي هام

في فهم عدم الاستقرار السمعي الحراري في غرف الاحتراق، حيث تلعب الإثارة السمعية دورًا مهما في عدم استقرار اللهب. في هذه الورقة تمت دراسة معملية لديناميكية اللهب الانتشاري داخل أنبوبة رايجك المثارة سمعيا عند الترددات التوافقية التالية 74، 222 و370 هرتز, وترددات إثارة الوقود من 30 إلى 300 هرتز. تم قياس اشارة الضغط السمعي داخل الانبوب بواسطة نظام الميكروفون, وانبعاثات اللهب الضوئي الكيميائي بواسطة نظام الخلية الضوئية لحظياً. لوحظ بشكل واضح في اللهب النفث الحر, عند اثارة الوقود بالتردد 90 هرتز كان عدم استقرار للهب عالي جدا، مما أثر على مظهر اللهب والخصائص الطيفية له. تحت الاثارة السمعية للوقود تحول اللهب الرقائقي في بداية الاضطراب الى اللون الأزرق وبنية اللهب أخذت شكل حرف V مع سلوك دوراني حول محوره. عند زيادة سعة الاثارة ازدادت شدة الاضطرب, وارتفاع اللهب عن فوهة الحارق تم حدث إطفاء للهب نتيجة لشدة عدم استقراره، هذه التغيرات لها نفس السلوك عند زيادة معدلات تدفق الوقود. من التحليل الطيفي للهب قبل الاثارة للوقود كان التردد السائد هو 13 هرتز (نموذجي للهب الرقائقي) وعند زيادة سعة موجة الاثارة الصوتية ازدادت شدة عدم الاستقرار الى ان حدث اطفاء للهب. اما عند وضع اللهب داخل انبوبة ريجك مع ظروف مختلفة للإثارة, أظهرت التجارب ان هناك تفاعلات قوية بين إثارة الوقود والترددات التوافقية للأنبوب، لا سيما عند التردد التوافقي الأول حيث كانت تذبذبات الضغط ببطن (anti-node) الموجة الواقفة أكثر وضوحًا. أثر هذا التفاعل بشكل كبير على استقرار اللهب، وهو ما يتضح في مخطط قيم RMS لإشارة الانبعاث الضوئي الكيميائي. عند قمم (peaks) إنبعاثات التوهج الكيميائي كان اللهب مستقرا تماما, بينما أشارت الانخفاضات (decays) إلى عدم الاستقرار أو الانطفاء خاصة عند التردد التوافقي الأول للأنبوب, في حين لوحظت تأثيرات أقل عند التوافقيات الأعلى حيث كانت تذبذبات السرعة السمعية هي السائدة. أبرز تحليل الارتباط المتبادل بين التذبذب في الضغط السمعي وانبعاثات الضوئي الكيميائي للهب الفروق الواضحة بين الظروف المستقرة وغير المستقرة. تؤكد هذه النتائج على مدى تعقيد عدم استقرار الاحتراق وحساسيته للظروف الصوتية وترددات إثارة الوقود. تعتبر هذه الأفكار ضرورية لتطوير أنظمة فعالة للتحكم في الاستقرار، سواء كانت نشطة أو سلبية، تهدف إلى تعزيز أداء المحرك وموثوقيته في ظروف التشغيل المتنوعة.

INTRODUCTION

Fossil fuel combustion remains crucial for generating thermal energy in heat engines such as gas turbines and jet engines, necessitating high operating temperatures exceeding 1000°C. Despite its prevalence, the environmental impact of fossil fuels, including toxic emissions like carbon monoxide and nitrogen oxides, as well as greenhouse gases such as carbon dioxide, underscores the need for enhanced engine efficiency and reduced emissions. One strategy to achieve these goals is operating engines on very lean fuel-air mixtures. Lean combustion processes offer several advantages, notably lowering combustion temperatures, which mitigates the formation of nitrogen oxides in the air [1]. This approach not only curtails pollutant emissions but also enhances thermal efficiency and lowers specific fuel consumption. However, running engines on excessively lean mixtures presents challenges. Moreover, lean mixtures can lead to combustion instability within engine chambers, posing operational risks and impacting engine performance reliability [2].

Combating combustion instability is critical in the operation of continuous fuel injection for combustion engines processes. Addressing this issue involves advanced engineering solutions such as optimizing fuel injection systems, adjusting air-fuel ratios dynamically, and improving combustion chamber designs to promote stable and efficient combustion. Efforts to improve heat engine performance must strike a balance between achieving lean combustion benefits and managing associated challenges. Ongoing research focuses on developing technologies that enhance combustion stability while maximizing efficiency and minimizing environmental pollutant emissions. Innovations in materials, fuels, and combustion control systems are pivotal in advancing towards cleaner, more efficient fossil fuel utilization in heat engines, ensuring sustainable energy solutions for future generations.

Combustion instability encompasses various oscillatory behaviours observed in combustion systems, posing significant challenges due to reduced efficiency, increased emissions, and potential damage to equipment. A critical manifestation of this instability is thermo-acoustic instability, where acoustic oscillations interact with heat release dynamics, leading to amplified pressure oscillations within the system [3]. Understanding these phenomena involves detailed study of flame characteristics. This includes analyzing flame dynamics to determine oscillation frequencies, measuring pressure oscillation intensities, and assessing correlations in emitted chemiluminescence emissions waves under varying conditions. Positioning the flame within the combustion chamber and controlling parameters such as fuel flow rate are crucial factors influencing instability.

Previous studies have extensively addressed the mitigation of thermo-acoustic instability, employing two primary techniques: Passive Instability Control (PIC) and Active Instability Control (AIC). These approaches are discussed in relation to their effectiveness in managing combustion dynamics. Additionally, the study reviews the concept of chemiluminescence emission, detailing methods for quantifying flame chemiluminescence emissions relevant to this investigation.

Thermo-acoustic instability in combustion arises from the interplay between acoustic pressure waves and fluctuating heat release within the system. This dynamic coupling leads to self-sustained oscillations known as thermo-acoustic instabilities. These instabilities occur when the acoustic feedback amplifies certain frequencies, creating a resonance that can significantly affect combustion efficiency and stability. Understanding thermo-acoustics is crucial in engineering combustion systems to mitigate these natural instabilities, which can cause fluctuations in temperature, pressure, and ultimately affect performance and safety.

In 1859, Rayleigh [4] provided the foundational explanation for the emergence of heat-driven oscillations, laying the groundwork for understanding combustion instability. His insight centred on the delicate balance between acoustic dissipation and excitation within combustion systems. This balance is crucial as it determines whether small perturbations can grow into sustained oscillations, often leading to undesirable consequences such as increased engine noise or even mechanical damage. Since Rayleigh's pioneering work, numerous attempts have been made to develop analytical models that predict combustion instability in terms of its amplitudes and frequencies. However, the complexity of engine noise and the intricate interactions between heat release and pressure oscillations often defy straightforward analytic techniques. Early models focused on correlating heat-release dynamics with pressure fluctuations over time, seeking to establish criteria for the onset of instability. Rayleigh's criterion for instability underscores the critical role of feedback mechanisms in amplifying oscillations within combustion systems. It highlights the sensitivity of these systems to initial disturbances and the nonlinear responses that can occur as a consequence of dynamic coupling between heat release and pressure variations. In contemporary research, while sophisticated computational tools have advanced our ability to simulate and predict combustion dynamics, the fundamental insights from Rayleigh's work continue to inform efforts to mitigate instability and enhance the efficiency and reliability of combustion processes in various industrial and transportation applications.

Rayleigh’s criterion has been used in combustion instability studies, which is the coupling between unsteady heat release and acoustic pressure. This criterion states that if the local unsteady heat release q'(t) is in-phase with local pressure fluctuation p'(t), the pressure wave associated with the fluctuation will be locally amplified. In 1953, Putnam and Dennis [5] formulated Rayleigh's hypothesis for heat-driven oscillations into a mathematical expression known as the Rayleigh integral form. This formula describes the coupling between unsteady heat release (q(t)) and acoustic pressure (p(t)) in combustion instability studies. According to Rayleigh's criterion, when the local unsteady heat release is in-phase with local pressure fluctuation, the pressure wave associated with the fluctuation can be locally amplified. The Rayleigh integral form provides a quantitative framework to analyze and predict the conditions under which combustion instabilities driven by the interaction between heat release and acoustic waves may occur. The Rayleigh integral form is:

$$\int_0^T p^{'}(t)q^{'}(t)dt > 0$$

Where p is the pressure, q the heat release, T the time of one period of a cycle and the symbol ' denotes the fluctuating quantities. The equation above states that the product of the heat release and the sound pressure fluctuation is integral over a period of oscillation T. If the integral of state is positive, then the oscillation is amplified, if it is negative, damping occurs. In other words, the phase difference or time lag between the heat release rate and the pressure oscillation determine whether the instability grows or decays. This approach has led to the widespread adoption of phase shift controllers as a dominant combustion control strategy. These controllers detect pressure within the combustion chamber and introduce a time delay (phase shift) to the signal before feeding it back into the acoustic system via a loudspeaker installed for dynamic system control. Putnam's experiments in 1971 [6] echoed Rayleigh's criteria, providing insights into pressure oscillations within combustion chambers.

Acoustic waves interact with flames directly within the flame zone, where they encounter steep gradients in gas properties at the flame front. These waves can scatter and potentially amplify due to the flame's response to perturbations, highlighting a critical area of interaction influencing combustion stability and dynamics. Indirect interactions in flow fields, irrespective of flame type (diffusion or premixed) manifest consistently. Studies show acoustic perturbations induce velocity fluctuations in non-reacting jets or flows [7], highlighting their influence beyond specific combustion dynamics.

In Lieuwen's comprehensive review (2003)[7] the interaction between flames and acoustic waves is categorized based on their impact on the flame's internal structure or global geometry. Acoustic disturbances influencing local burning rate are linked to pressure-coupled mechanisms, while those affecting global flame dimensions like length or area typically involve velocity-coupled mechanisms, Figure (1) shows the acoustic disturbances classification. This classification underscores how acoustic waves can distinctly modify flames: either by altering their internal combustion dynamics or by influencing their overall shape and size in the presence of fluctuating pressures or velocities. Understanding these mechanisms is crucial for controlling combustion stability and efficiency in practical applications.

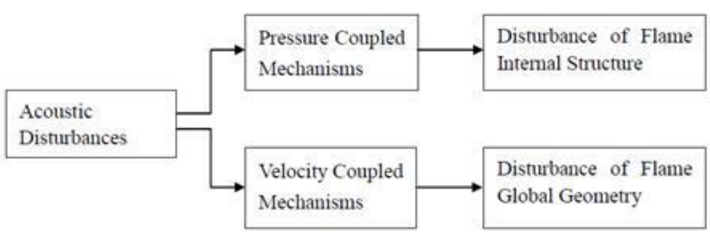


Figure1: Acoustic disturbances classification.

Camilo (2023) [8] explored thermo-acoustic instability in gas turbines, exacerbated by lean combustion technologies. Traditionally, these instabilities were attributed solely to acoustic cavity modes, inherent to the combustion system's geometry. The sensitivity of lean premixed flames to acoustic environments highlights the increased occurrence of such instabilities in modern turbine operations. Heckl et. al (2022) [9] derived an integral equation for the acoustic field using a Green's function tailored to a 3-D rectangular box with hard-wall boundaries. they solve this equation through two methods: an iterative approach in time to track acoustic velocity history and a Laplace transform method to determine eigen-frequencies and growth rates of thermo-acoustic modes, their results, focused on 2-D scenarios, highlight how flame orientation and position significantly influence thermo-acoustic instability and mode interference. King et. al. (2023) [10] introduce a novel actuator concept for combustion control using sub-breakdown electric fields and flame plasma properties. This technology enables variable flame distortion and bidirectional heat release control, crucial for suppressing thermo-acoustic instability. Demonstrating a 27 dB reduction in sound pressure level within 60 ms, the concept operates at low power (40 mW for a 3.4 kW flame) without moving parts, showing promise for widespread use in combustion applications. Yongqing et. al. (2024) [11] develop a Helmholtz method to predict self-excited thermo-acoustic instabilities in gas turbine combustors. They incorporate flame describing functions, measured damping rates under firing conditions, and non-uniform spatial parameter distributions. Results show lower damping rates in hot conditions versus cold, with predicted Eigen-frequencies and velocity fluctuations within 10% error. They observe mode shapes and velocity fluctuations influenced by equivalence ratio, air flow rate, and combustor length, highlighting effective instability prediction. Huimin Guo (2011) [12] investigated the stability of laminar diffusion flames and their interaction with acoustic waves within an acoustically excited cylindrical tube. This study explored intriguing phenomena related to the effects of infrasound and sound on flame dynamics and structure. When a cylindrical tube burner is acoustically excited at one end, it induces a standing wave along the burner's length. Guo applied a programmable signal from a generator to drive a loudspeaker, generating acoustic waves of varying frequencies and intensities to excite the flame. This manipulation can lead to diverse outcomes such as increased stability, instability, or even flame blowout. The research employed methods from both the frequency domain and time domain to analyze how acoustic waves affect flame stability. By varying the frequency and intensity of the acoustic waves, Guo examined changes in flame behaviour and stability. In this paper the fuel feeding the diffusion flame will be excited by a loudspeaker, and interacts with an acoustically excited cylindrical tube.

The excitation of fuel with known frequencies from signal generators allows researchers to study the coupling between acoustic waves and flame dynamics, providing insights into instability mechanisms. Ultimately, comprehensive investigation into flame behaviour under different operating conditions is essential for developing strategies to mitigate combustion instability, ensuring safer and more efficient combustion processes in industrial and transportation applications. In this paper, the chemiluminescence signal from the flame and its relationship to the acoustic signal of the diffusion flame inside an acoustically Rijke tube will be analyzed. This analysis is represented in terms of spectral analysis of the optical and acoustic signals and also a calculation of the cross-correlation between the two signals. The aim of this analysis helps in controlling the phenomenon of combustion instability. Therefore, studying the interaction between sound waves and flame dynamics is the crucial step to understanding thermo-acoustic instability, monitoring, avoiding, and reducing or possibly eliminating its effects.

EXPERIMENTAL SETUP

The experiment setup consists of two different techniques: the microphone system technique to measure the acoustic signal and the other technique is the light cell system to measure the chemiluminescence emission from the flame. These two systems are installed on a high-speed data collection system with a speed of up to 1.25 M samples per second, and analyzed using the LabVIEW software from National Instrument Company. Figure (2) shows the over view of the experimental setup used to analyze the dynamics of the flame excited by the two acoustic excitation units.

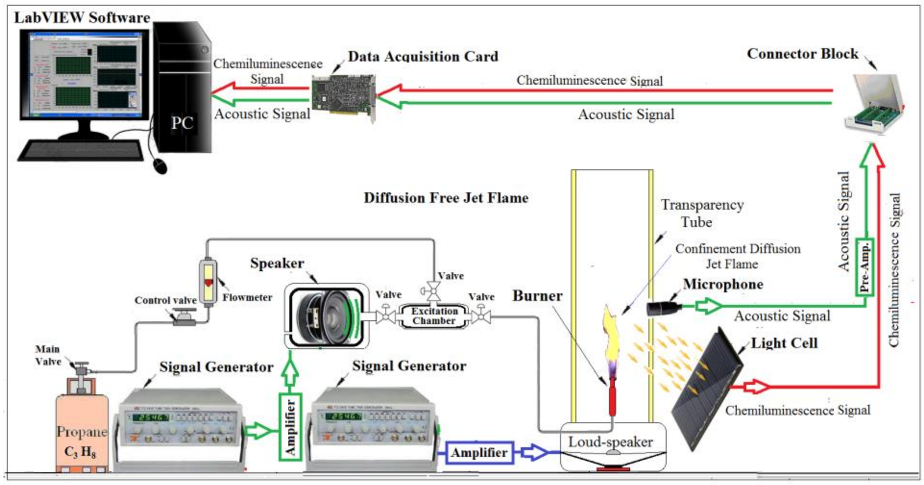


Figure 2: Fuel excited confinement diffusion jet in an acoustically cylindrical tube with an enclosed baffle loud-speaker mounted at the bottom end.

The rig has three units: acoustic waves generating unit, burner unit, optical and acoustic measurement unit. Acoustic wave generating unit by using a controllable frequency signal generator is used to excite the fuel feeding the burner with a frequency range from 30 to 300Hz, and the other is used to excite the air inside the cylindrical tube (Rijke tube), loudspeaker and power amplifier are used for excitation units. The rear side of the loudspeaker diaphragm is enclosed by a box (15cm Diameter ×10cm height), which ensures the loud-speaker is a monopole source (Closed-box Baffle loudspeaker). The burner unit consists of a fuel supply and a transparent cylindrical tube burner (combustion chamber). The burner is a single copper fuel pipe of 0.5 cm inner diameter, there is an orifice at the end of the pipe which reduces the overall inner diameter to 0.75mm. The pipe is connected to a compressed propane gas cylinder. The fuel is regulated by a control valve and measured by a rota meter. The burner fuel nozzle position in this test case placed at 30cm from the bottom of the Rijke tube. The other unit of excitation used to excite the air inside the Rijke tube at the first three modes with length of 117cm.

RESULTS AND DISCUSSIONS

In applications like power generation, heating, and propulsion, large-scale combustion encounters significant pressure fluctuations, especially under lean mixtures. Combustion dynamics often couple with acoustic fields, likening combustion chambers to resonant organ pipes. Research involves measuring diffusion flame dynamics inside a Rijke tube, analyzing flame signals' power spectra, auto-correlation and cross-correlation under varied excitation, involves exciting fuel with a signal generator in atmosphere. Monitors a jet diffusion flame in an acoustically excited Rijke tube with a simultaneous fuel excitation.

Free jet diffusion flame dynamics with fuel excitation were analyzed under the influence of excitation of the fuel feeding the flame using a loud-speaker connected to a signal generator with a known frequency. After a quick scan of the frequency applied to the excitation unit, two frequencies were chosen, the first when the frequency was very influential on the stability of the flame, and the strongest effect was 90 Hz and the type of signal was sinusoidal. Second excitation frequency, the flame was more stable, that was happened at 185 Hz. Acoustic excitation frequency has been selected with a variable voltage applied to the loudspeaker from 0 Volt (without excitation) to voltage that the flame blowout, the most commonly used type of loudspeaker is an enclosed box in which the loudspeaker is mounted, the back side of the loudspeaker is isolated from the front. The closed-box sides are as rigid as possible using a suitable material. A small air leak is provided in the box so that changes in the atmospheric pressure do not displace the natural position of the diaphragm. The fuel used in these experiments is propane, the fuel flow rate is 1 ml/min, and the burner diameter is 0.75 mm.

Figure (3) shows the effect of sound intensity on the free jet diffusion flame at applied frequency of 90Hz. The figure contains three sub-figures, which are the shows the chemiluminescence time signals emitted from the flame using the light cell, sub-figures on the right hand side shows the power spectrum of the signals and the sub-figures in the middle shows the auto-correlation of the signals. In the same manner in the arrangement of Figure (4) when excitation frequency of the fuel is 185Hz

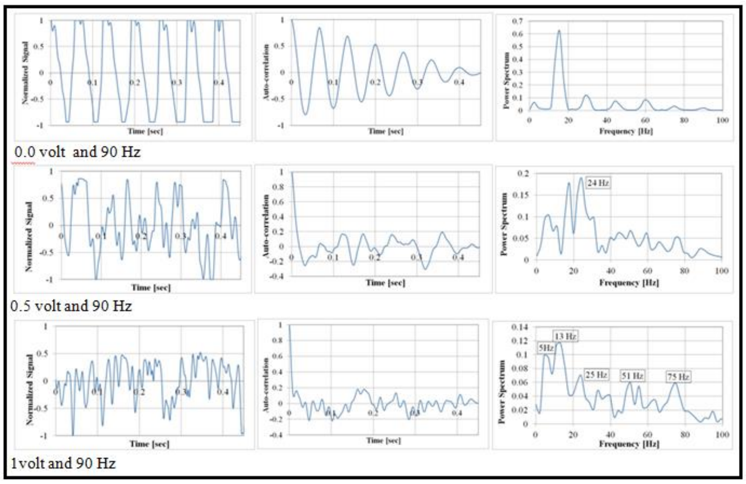


Figure3: Normalized chemiluminescence signals, auto-correlation and power spectrum of free jet diffusion flame with fuel excitation at frequency 90 Hz.

It is clear from the Figure that the excitation of the fuel has a strong effect on flame instability. In the absence of excitation, the flame was stable, laminar, and sitting on the rim of the burner, and the signal was almost like a sinusoidal signal, free of distortions that would indicate turbulence. Also, the auto-correlation was very strong, which indicates that the signal measured under these conditions has a similar to the auto-correlation of the theoretical signal of the sine wave. Spectral analysis of this signal revealed one very strong peak, which represents the dominant frequency of this signal, which is around 13Hz. Figure (4) show the comparison between previous results of spectrum analysis using a CCD camera (Yingping 1999) [13] and Farhat et. al. 2017 (14) using a light cell in this paper, the CCD camera and light cell techniques show that the power spectrum of free jet diffusion flame frequency is 13 Hz, the revised analysis flame flicker result in qualitative agreement between this research and previous studies with the same frequency of the flame dynamics. Also, the shape of the signal is almost exactly the same.

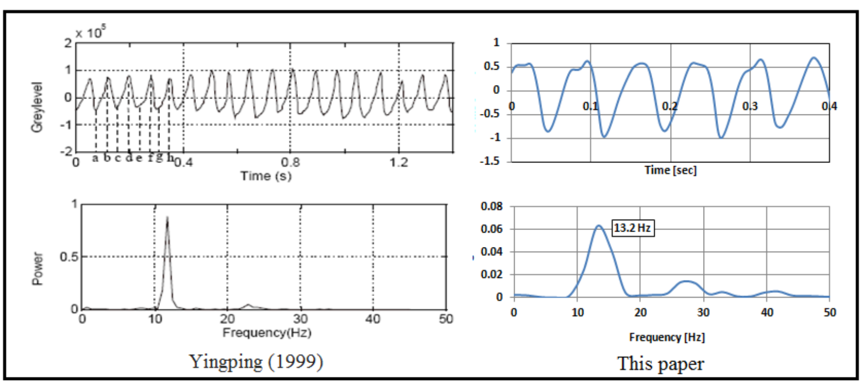


Figure 4: A comparison between previous results of spectrum analysis using a CCD camera (Yingping 1999) and using a light cell in this study

When the flame was excited at a frequency of 90 Hz and 0.5 volts, the flame began to become turbulent, changing the shape of the flame and starting to rise on the rim of the burner (flame lift-off), and the color of the base of the flame turned blue as a result of its mixture with air before the process of combustion. The flame also decreased in size and became short, which reduced the intensity of the flame's chemiluminescence emission. The disturbance was greater when the voltage was increased to 1 volt. The instability of the flame increased to the maximum extent that after this voltage the flame was extinguished. It is noted that the auto-correlation has become very weak, which means that the measured signal has become random and the number of sub-frequencies has increased, and it is considered very strong, which means that the flame has become unstable and reached the state of extinguishing at a very low voltage applied to the loud-speaker. It has been concluded from these results that the state of turbulence in the flame of this burner is strong of this burner diameter at a frequency close to 90 Hz. Therefore, it should avoid using this type of burner with a diameter of 0.75 mm in noise with a frequency closed to 90Hz. The fuel frequency excitation was also chosen at 185 Hz. It was noted that when the flame was excited at this frequency, the flame was stable under high voltage compared to the frequency of 90 Hz. Figure (5) shows the measured signal, auto-correlation, and power spectrum analysis of the flame at a frequency of 185 Hz when the applied voltage on the loud-speaker and the amplitude of the signal generator changes from 0 volts to 7 volts.

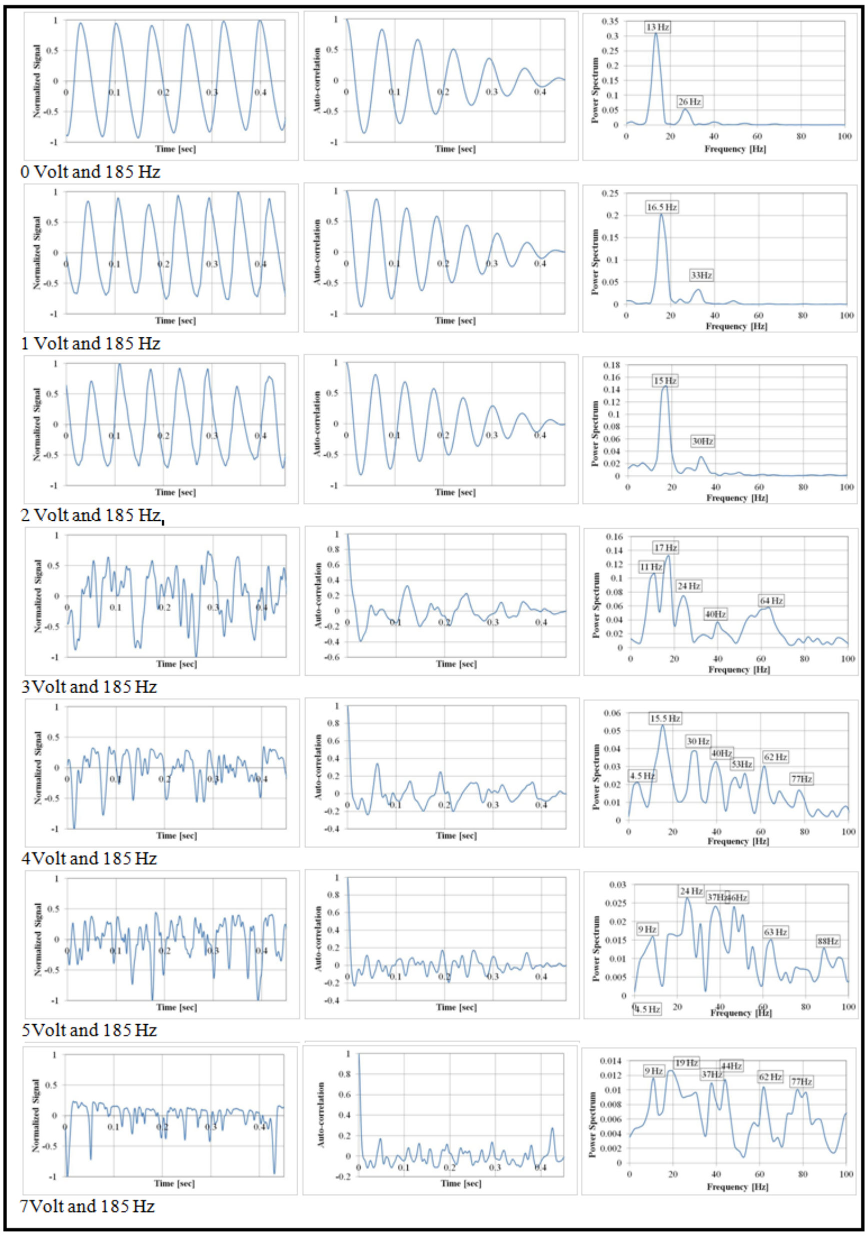


Figure 5: Normalized chemiluminescence signals, auto-correlation and power spectrum of free jet diffusion flame with fuel excitation at frequency 185 Hz.

The results obtained in Figure (5) have the same behavior compared to the results shown in Figure (3), except that when excitation at a frequency of 185 Hz, the results showed that the flame was more stable than when excitation at a frequency of 90 Hz. As shown in the figure, the flame was stable up to 7 volts and did not blowout, comparing it, when excited at a frequency of 90 Hz, the flame blowout when the applied voltage across the loud-speaker reached a little more than 1 volt. This means that, this size of the burner has the strongest flame stability when the fuel flow is fluctuated within 185 Hz.

Figure (6) shows the relationship between the applied voltage across the loud-speaker and the estimation spectrum for each of the two excitation frequencies of the fuel feeding the burner. The results are quite clear that in sub-figure A, in which the excitation frequency is 90Hz, the flame was weakly stable which the flame is blowout at 1 volt, meaning that the flame does not resist the excitation of the fuel feeding the burner when the fuel oscillates at the frequency of 90Hz. While in the high oscillation at the frequency of 185 Hz as shown in sub-figure B, at this frequency, the flame did not extinguish even if it reached 7 volts. The fuel flow rate was equal in both cases of excitations, which is 1 ml/min.

The appearance of a gaseous diffusion flame changes as the sound pressure level is increased, also the height of the flame decreases gradually. Under some conditions, the flame splits into two and forms a V-shape as shown in the Figure (7). The flame is observed to rotate around its axis forming a far more complex structure. The flame height (the height measured from the burner exit and including the flame lift-off distance) without excitation was 12 cm compared to 5 cm with excitation. The flame lifts-off with a height of approximately 2 cm above the burner exit just before it blowout. Figure (8) and Figure (9) also illustrates some typical data on lifting and the ultimate blowout of a diffusion flame under different applied voltages to the loudspeaker and applied frequency of 90 and 185 Hz. The dashed line, on which typical flames are shown, illustrates the path of the flame base as the sound pressure level is reduced and the flame is reattached to the fuel nozzle. The end point, at the applied voltage of about 1.25 volts at applied frequency 90Hz, while more than 7 volts at frequency of 185Hz, corresponds to complete blow-out (extinguish).

Diffusion flame dynamics inside acoustically Rijke tube and fuel excited is also studied. Figure (10) illustrates the first three wave modes of the measured *rms* pressure along the tube with length of 117cm. These were obtained by moving the microphone along the tube whilst keeping the loudspeaker at a constant power.

To study the flame dynamics inside the Rijke tube, the burner was placed at a distance of 30cm above the lower end of the tube (30cm above the loudspeaker), as shown in Figure (11). From the results of the tube mode, under the influence of the first three harmonic frequencies of the tube, the flame exposed on a high fluctuation of pressure at the first harmonic frequency, while at the second and third harmonic frequencies modes the flame exposed on a low fluctuation of pressure and a high velocity fluctuation. This will be studied in details in the next section.

Figure (12) shows the normalized chemiluminescence signal, power spectrum and auto-correlation of diffusion flame without excitation of fuel and air in the Rijke tube. In this experiment, the flame was placed inside a Rijke tube to study the effect of the tube on the flame dynamics without excitation. In a previous experiment, flame dynamics were analyzed under the same conditions of fuel flow rate and burner diameter, but outside the tube (Free jet flame). The comparison between them was done through power spectrum analysis and correlation of the chemiluminescence emission signal. The results show that the tube has an effect on the flame dynamics, and this is clear from the results in Figures (3) and (5) at an applied voltage of zero volts (Without excitation).

The results showed that there was a significant difference in the form of the signal and also the spectral analysis of the chemiluminescence emission from the flame, including that the frequency increased from 13 Hz in the free jet laminar flame to 19 Hz when the flame placed inside the tube. Also, there is a lot of frequencies peaks in the power spectrum of chemiluminescence emission when the flame placed inside the tube, while in the free jet flame there is only one dominant frequency, which is 13 Hz, and narrow band range. By calculating the correlation of the signals, the results showed that the flame inside the tube has a very weak correlation, while in the free jet flame it has a very strong correlation. This sums up that the flame inside the tube is unstable compared to a free jet diffusion flame. This is due to the interaction that occurs between the heat release from the flame and the tube mode represented by the fluctuating acoustic pressure inside the tube.

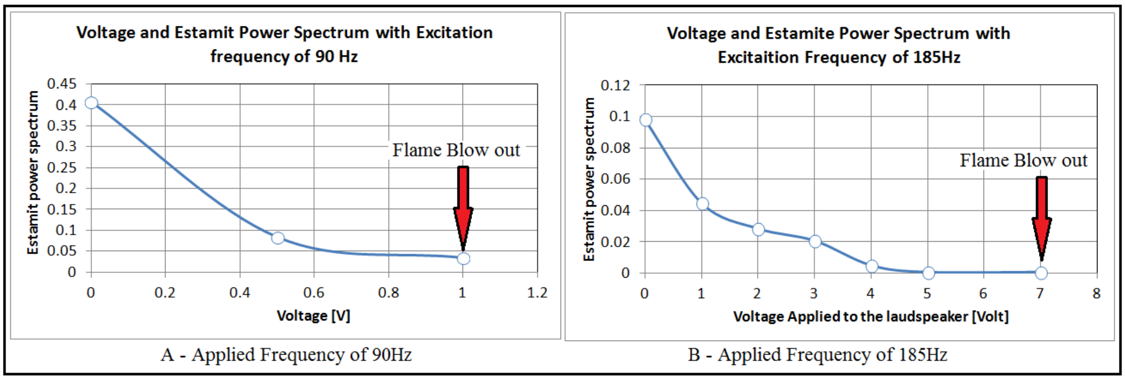


Figure 6: Voltage across the laud-speaker (sound pressure level) and the estimation spectrum for both excitation frequencies of 90Hz and 185 Hz.

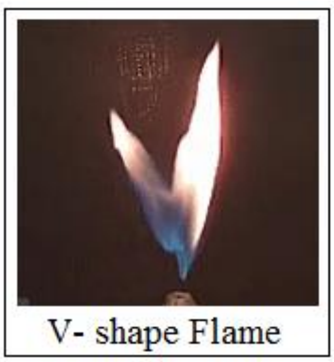


Figure 7: Flame splits into two and forms a V-shape.

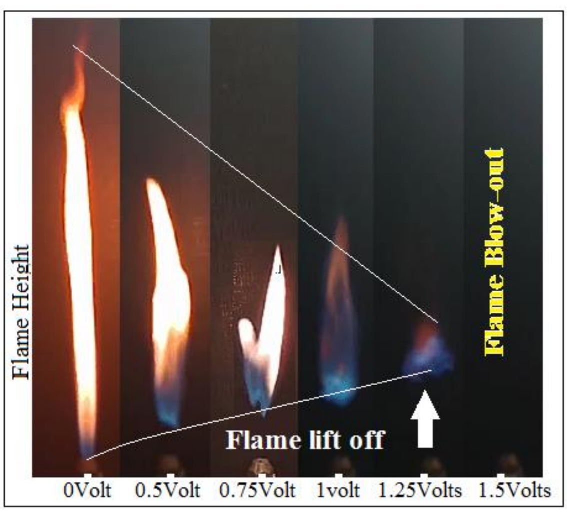


Figure 8: Effect of Voltage applied to the loud-speaker (sound pressure level (SPL)) on flame height and the flame lifting, at applied frequency of 90Hz. Propane flow rate is 1 l/min.

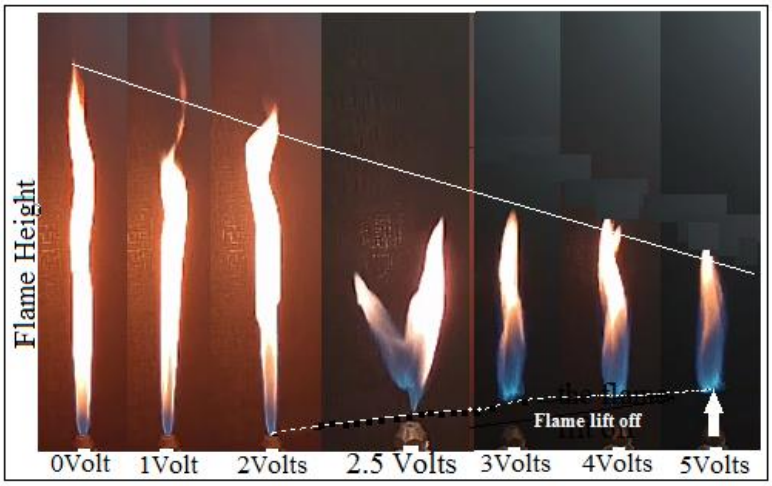
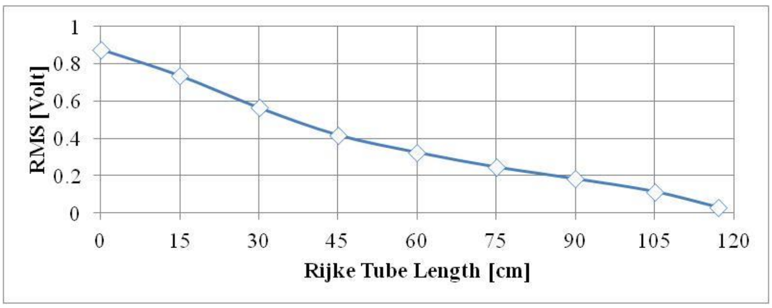
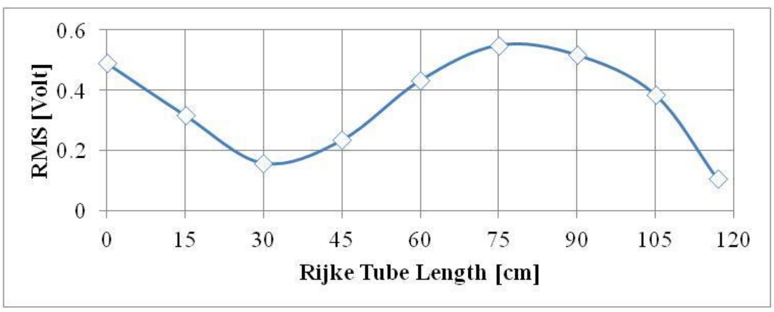


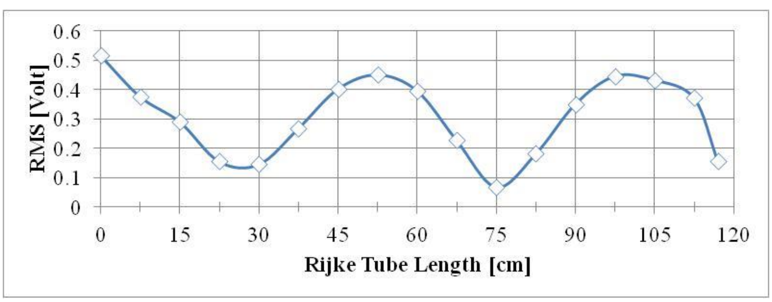
Figure 9: Effect of Voltage applied to the loud-speaker (sound pressure level (SPL)) on flame height and the flame lifting, at applied frequency of 185Hz. Propane flow rate is 1 l/min.



First mode of the tube n=1 (f=74Hz)



second mode of the tube n=2 (f=222Hz)



Third mode of the tube n=3 (f=370Hz)

Figure 10: First, second and third experimental longitudinal acoustic pressure modes of the tube. (n=1,2 and 3) (f=74, 222 and 370Hz).

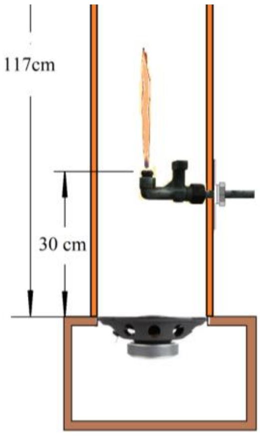


Figure 11: Burner position in the Rijke tube.

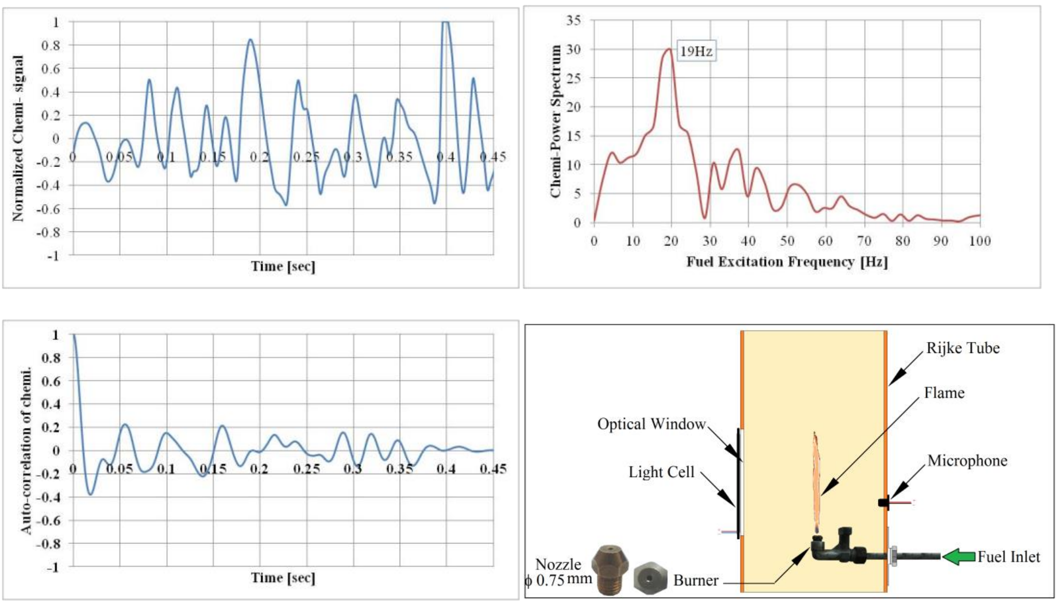


Figure 12: Normalized chemiluminescence signal, power spectrum and auto-correlation of diffusion flame inside without excitation of fuel feeding the flame and air in the Rijke tube.

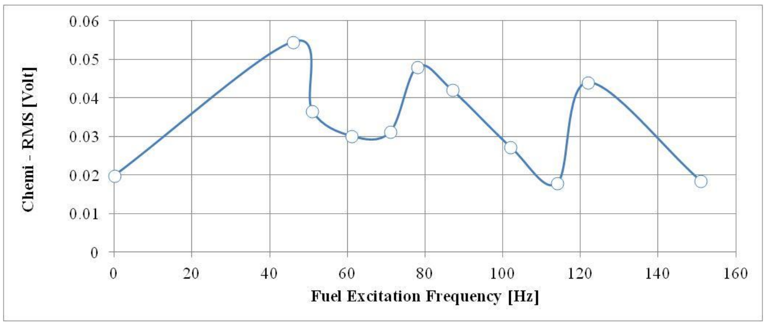
The flame inside the Rijke tube was excited by two excitation systems. The first was to excite the fuel feeding the flame using a signal generator. The excitation was with a sine wave at different frequencies. The second system was used to excite the air inside the Rijke tube at the first three harmonic frequencies modes of the Rijke tube, with 117cm long. The first three harmonic frequencies are 74, 222 and 370 Hz. The time taken for the measurement is 0.45 sec with a sample rate of 44,100 samples/sec.

Figures (13) show the relationship between the excitation frequency of the fuel feeding the flame and the RMS values of the chemiluminescence emission inside acoustically tube at the first three modes (74, 222, and 370Hz).

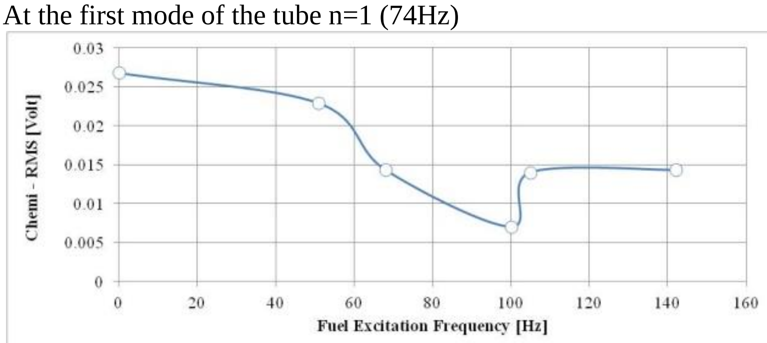
From Figure (13) there are many peaks and decays of RMS of Chemiluminescence emission. Attention must be paid to studying these peaks and decays that appeared when calculating the RMS Chemiluminescence emission. At the decays; the intensity of the chemiluminescence emission is low, and sometimes at these frequencies of the fuel excitation the flame is extinguished due to its intense disturbance, while at the peaks, the flame is stable on the burner and the flame takes the characteristics of a laminar diffusion flame, these results are consistent at all the first harmonic frequencies of the tube: 74, 222 and 370 Hz.

In the First mode of the tube; the decays occurred at the fuel excitation frequencies of 61 Hz and 114 Hz, at these frequencies, the flame is completely unstable and sometimes flame extinguishing occurs. At peaks; the flame is completely stable at the excited fuel frequencies of 46 Hz and 78 Hz, although the flame without fuel excitation, i.e., the frequency is zero, the flame was relatively turbulent compared to the frequencies 46 and 78 Hz.

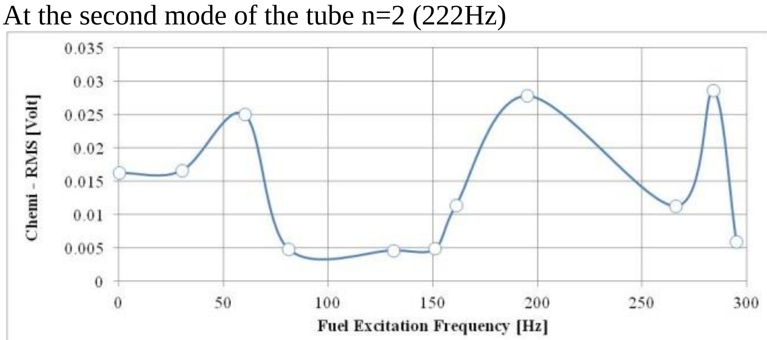
At the second harmonic frequency of the tube (f=222Hz) peaks and decays also appeared in Figure (13). The decay appeared at the fuel excitation frequency of 100 Hz. The flame was unstable, and peaks appeared in the chart at the fuel excitation frequency of 142 Hz, where the flame was stable.



At the first mode of the tube n=1 (74Hz)



At the second mode of the tube n=2 (222Hz)



At the third mode of the tube n=3 (370Hz)

Figures 13: Chemiluminescence emission RMS as a function of Fuel excitation inside an acoustically tube at first three modes (74m 222 and 370Hz).

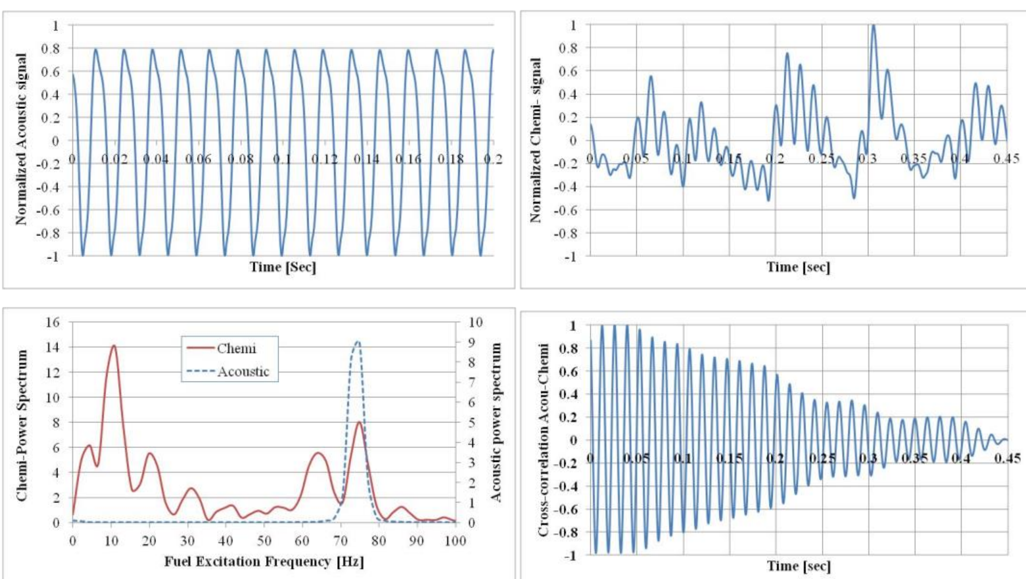
At the third harmonic frequency, peaks occur at the following frequencies of 60, 195 and 284 Hz, at these frequencies the flame is stable. Decays points in the curve at the third harmonic frequency occurred at the following fuel excitation frequencies of 151, 266 and 295Hz. Some peaks and decays were selected from the RMS of chemiluminescence emission charts for all three modes to study the dynamic signals of acoustics and chemiluminescence emission signals in terms of power spectrum as well as the cross-correlation between measured acoustic and chemiluminescence emission signals. From the results of the spectral analysis of all the peaks and decays of acoustic and chemiluminescence emissions at all the first harmonic frequencies of the tube, 74, 222 and 370 Hz, have the same behaviour, and are completely compatible, so a single excitation frequency was chosen for each harmonic frequency of the tube for a peak and a decay.

Figure (14) shows the signal processing of diffusion flame inside the Rijke tube at the first harmonic mode without fuel excitation in terms of; normalized signals of acoustic and chemiluminescence (top sub-figures), power spectrum and cross-correlation of both signals acoustic and chemiluminescence (bottom sub-figures).

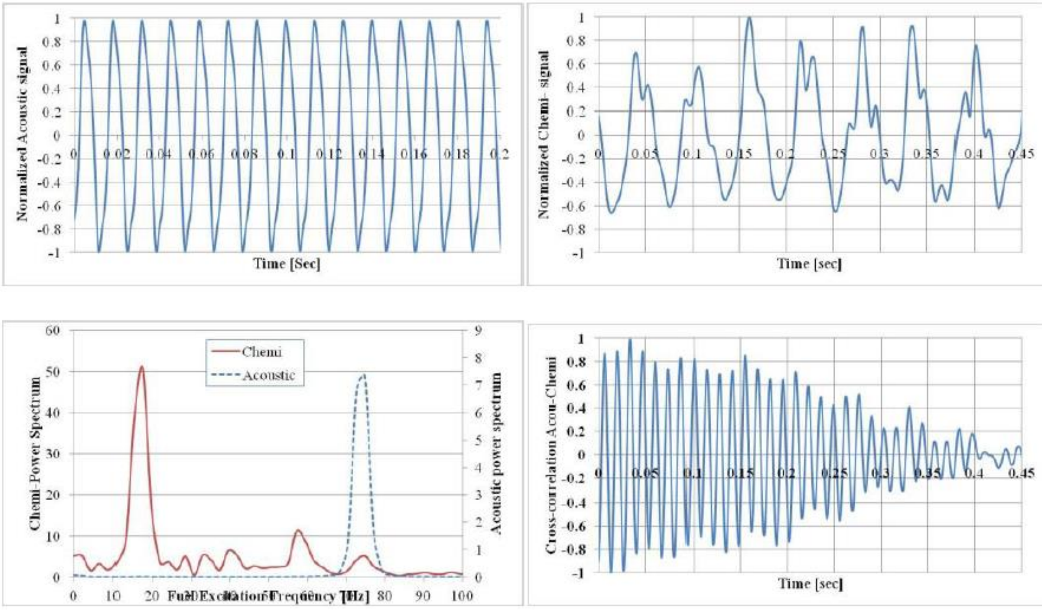
Figure (15) shows the signal processing of diffusion flame inside the Rijke tube at the first harmonic mode with fuel excitation at peak RMS of chemiluminescence emission signal, in this paper the fuel excitation frequency 46 Hz is selected. In Figure (16) the decay at fuel excitation frequency of 114 had been selected for signal processing of diffusion flame at the first harmonic frequency of the tube (74Hz).

Form the results of the first mode of the tube; through spectral analysis of the two signals, it becomes clear to us that the peaks have a different spectral behaviour from the decays. In the decays, a large group of frequencies appear and have high values at the frequency 114 Hz, while at the peak values of RMS values with fuel excitation frequency 46 Hz these strong sub-frequencies do not exist, only one dominant frequency. Strongly, that is, whenever the power spectrum analysis includes a large number of strong peaks of frequencies, it gives a strong indication of the instability of the flame, even though there is a strong correlation between the acoustic and chemiluminescence emission waves.

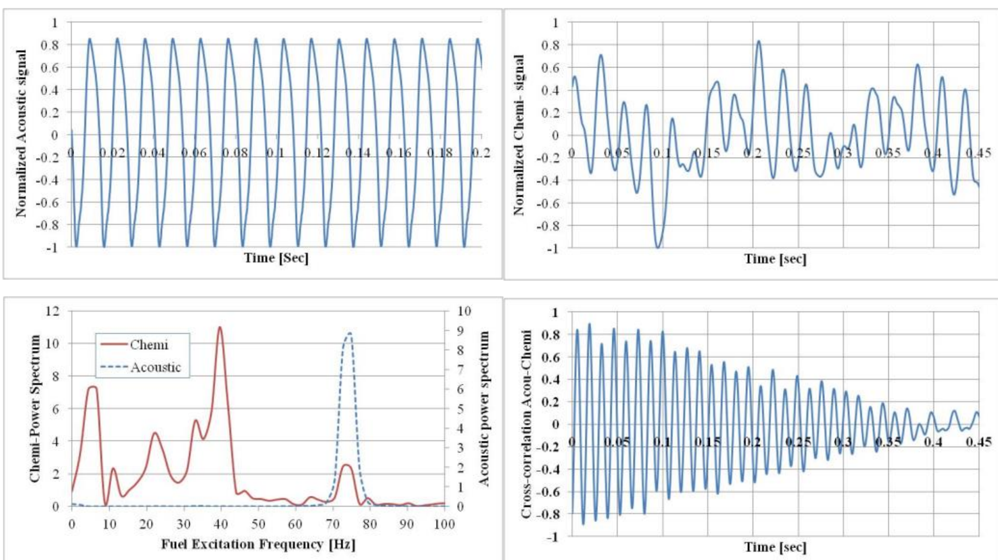
The changes that occur when the fuel excitation changes are a result of the oscillatory change of the flame with the first harmonic frequency of the tube. One of the results also is that when the tube is excited at the first harmonic frequency, the sensitivity is very high. Most often, flame extinguishing occurs, due to its instability. Therefore, in such conditions for the flame inside the tube, frequencies that cause instability must be avoided. In this experiment, the frequency 114 Hz must be avoided. These results are very important for choosing frequencies in controlling flame instability using active instability control system. This applies to the rest of the frequencies at which decays in the RMS value of chemiluminescence emission occurred.



Figures 14: Normalized acoustic and chemiluminescence emission signals, power spectrum and cross-correlation at the first mode of the tube (74Hz) without fuel excitation.



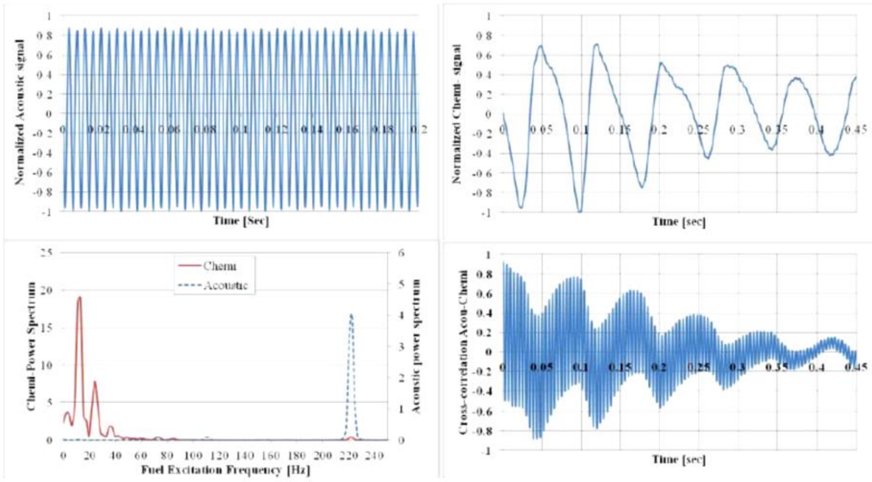
Figures 15: Normalized acoustic and chemiluminescence emission signals, power spectrum and cross-correlation at the first mode of the tube (74Hz) with fuel excitation of 46Hz.



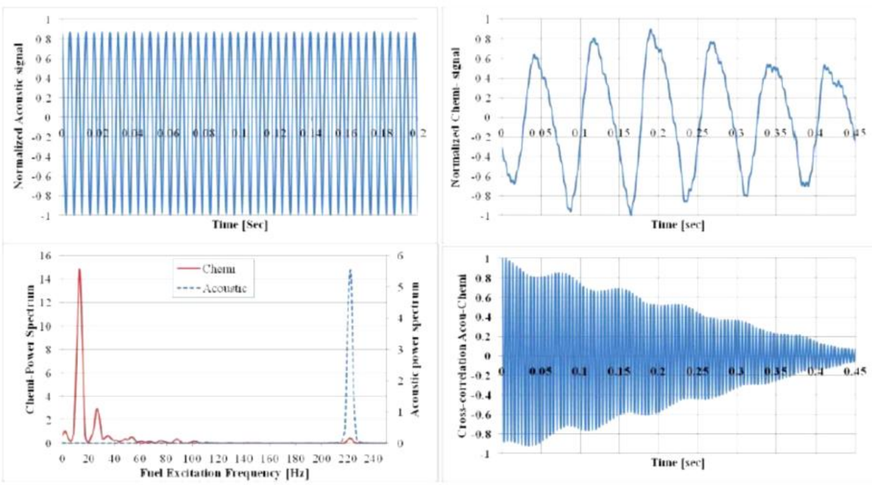
Figures 16: Normalized acoustic and chemiluminescence emission signals, power spectrum and cross-correlation at the first mode of the tube (74Hz) with fuel excitation of 114Hz.

Likewise, as in the first harmonic frequency of the tube, two frequencies were chosen to excite the fuel, one frequency at the peak and the other at the decay for the second and third harmonic mode of the tube. The spectral analysis of the acoustic and optical signals is shown in the following figures:

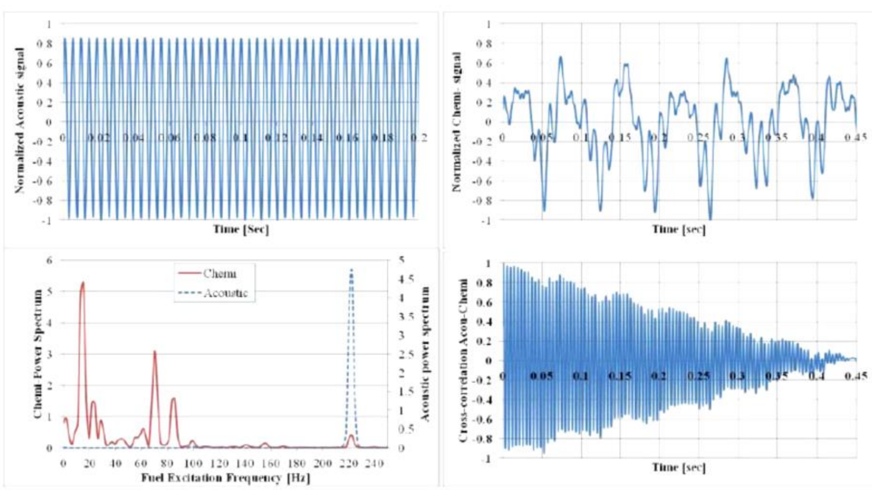
Figure (17) shows the spectral analysis of the two signals under the influence of the second harmonic frequency without excitation of the fuel, while Figure (18) shows the spectral analysis of the flame at the second harmonic frequency with the choice of the fuel excitation frequency of 142 Hz (chemiluminescence emission diagram with peak value of RMS), also, the fuel excitation frequency 100 Hz was chosen at the second harmonic frequency when the RMS value at the decay, as shown in the Figure (19).



Figures 17: Normalized acoustic and chemiluminescence emission signals, power spectrum and cross-correlation at the second mode of the tube (222Hz) without fuel excitation (f=0Hz).

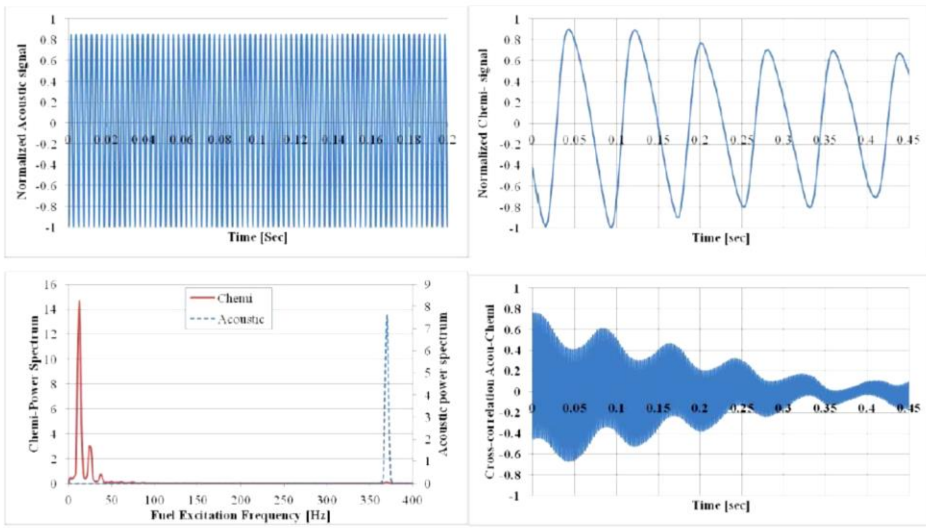


Figures 18: Normalized acoustic and chemiluminescence emission signals, power spectrum and cross-correlation at the second mode of the tube (222Hz) with fuel excitation of 142Hz

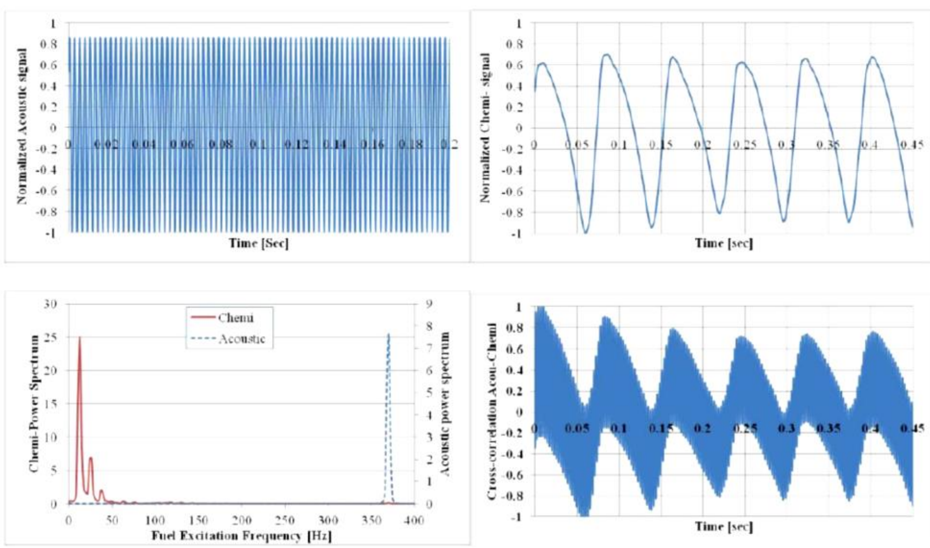


Figures 19: Normalized acoustic and chemiluminescence emission signals, power spectrum and cross-correlation at the second mode of the tube (222Hz) with fuel excitation of 100Hz

For the third mode of the tube; Figure (20) shows the spectral analysis of the acoustic and chemiluminescence emission signals in third harmonic frequency without excitation of the fuel, Figure (21) shows the spectral analysis of the flame at the third harmonic frequency with the fuel excitation frequency of 195 Hz (at peak value of RMS), the fuel excitation frequency was chosen at 295 Hz at decay of RMS value, as shown in the Figure (21).

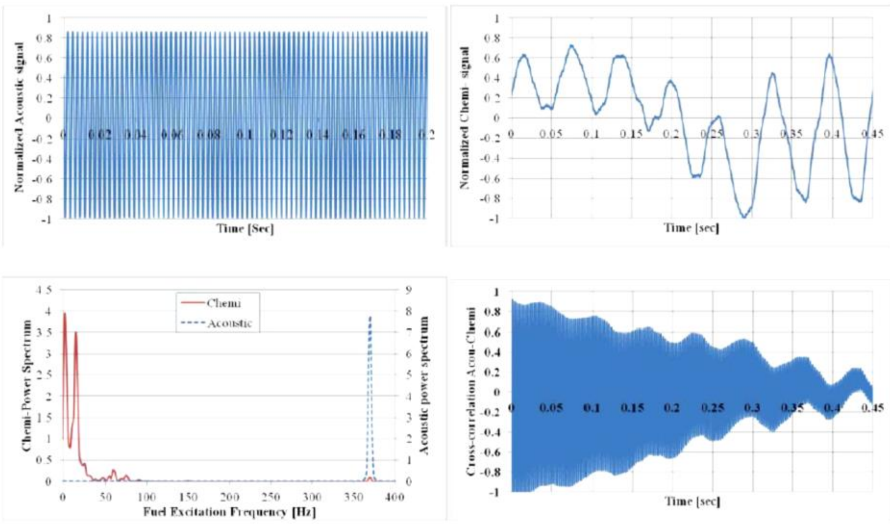


Figures 20: Normalized acoustic and chemiluminescence emission signals, power spectrum and cross-correlation at the third mode of the tube (370Hz) without fuel excitation (f=0Hz).



Figures 21: Normalized acoustic and chemiluminescence emission signals, power spectrum and cross-correlation at the third mode of the tube (370Hz) without fuel excitation (f=195Hz).

The correlation between the acoustic signal and chemiluminescence emission (cross-correlation) is relatively strong, but it has a spiral twist that is due to the large frequency difference between the two signals. Here in this correlation between the acoustic signals, which have a frequency of 222 Hz, and the frequency of chemiluminescence emission, which does not reach 30 Hz. This twisting into a form becomes stronger in its spiral form whenever the difference in frequency is very large. The main factor in this is the delay time between the two signals. The cross-correlation between acoustic and chemiluminescence emission signals increased in spiral twisting in the third mode (370Hz) due to the increase in the difference between the two frequencies for both the acoustic signal and the chemiluminescence emission signal. It is considered that the cross-correlation between the two signals is strong at all fuel excitation frequencies.



Figures 22: Normalized acoustic and chemiluminescence emission signals, power spectrum and cross-correlation at the third mode of the tube (370Hz) without fuel excitation (f=295Hz).

From Figure (23) it is clear that the flame structure is very disturbed when the flame is under the influence of excitation of the fuel and its interaction with the harmonic frequency of the Rijke tube.

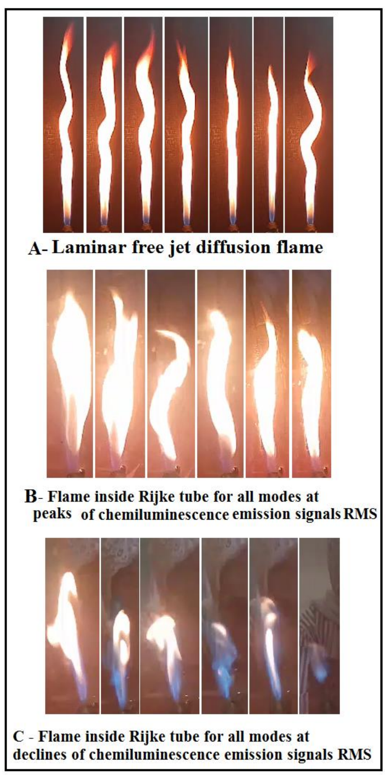


Figure 23**: Flame structure of a diffusion flame (burner located at 30 cm above the bottom end of the cylindrical tube for three modes of the tube).**

This depends primarily on the frequency of both the fuel excitation frequency and also the excitation of the air surrounding the flame inside the Rijke tube. When the harmonic frequency of the tube changes, the stability and instability frequencies of the excitation frequency of the fuel change. It is also noted that the flame shown under conditions of decays chemiluminescence emission signal indicates that the flame is very sensitive to its instability, many times causes the flame to completely extinguish under these conditions of excitation.

CONCLUSIONS

In this paper, flame characteristics in an acoustically excited vertical cylindrical tube (Rijke tube) with an open upper end and close lower end with a loud-speaker. The tube is excited at first three harmonic frequencies: 74 Hz, 222 Hz, and 370 Hz. The burner inside the Rijke tube is fuelled, and its excitation frequency ranges from 30 to 300Hz. The flame interactions with the excitation of the fuel feeding the diffusion flame have been experimentally examined to study the instability of the diffusion flame inside acoustically tube. The results can be concluded as follows:

- At a fuel excitation frequency of 90 Hz, the instability of the flame is significantly affected of free jet diffusion flame with burner diameter of 0.75mm.
- Increasing the excitation amplitude leads to changes in the flame's appearance and behaviour, such as colour change and shape transformation.
- The results show that specific excitation frequencies affect the stability of the flame inside the tube.
- There is a strong interaction observed between the oscillations caused by the excited fuel and the harmonic frequencies of the Rijke tube.
- The results indicate that certain frequencies of fuel excitation cause decays in RMS values, indicating unstable flame conditions.
- Acoustic pressure fluctuations (anti-node pressure) at the first harmonic frequency of the tube strongly influence flame instability.
- This study is crucial for developing flame stability control systems using active or passive methods of combustion instability control.

The experiment aims to understand how acoustic excitation influences flame stability inside an acoustically Rijke tube with fuel excitation, highlighting the complex interactions between acoustic waves and combustion dynamics. These findings have implications for improving combustion efficiency and stability in various applications.

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