OPTICAL AND ACOUSTIC SIGNALS PROCESSING OF FLAME BLOWOUT IN AN INDUSTRIAL GAS TURBINE COMBUSTOR

Salem. A. Farhat*, Mohamed. S. Oun* and Y. Zhang**
*Mechanical Engineering Department, Al-Fateh University
** Fluids Academic Interest Group, School of Mech., Aerospace and Civil Eng., University of Manchester, Manchester, M60 1QD, UK

الملخص

في هذه الورقة تم بنجاح تنفيذ النهج البصري والسمعي معا أثناء عملية إطفاء لهب مختلط مسبقا في غرفة احتراق G30 عند الضغط الجوي، حيث تم دراسة سلوك غرفة احتراق دوامية تعمل بالبروبان C_3H_8 ذو درجة حرارة هواء عالية في حالتين: الحالة الأولى؛ إطفاء اللهب بسدّ مصدر الوقود الرئيسي للهب المسٍتقرّ، أما الحالة الثانية؛ فبسدّ المصدر الرئيسي للوقود في حالة اللهب الغير مستقرة، كما تم أيضا عرض صور التُقطت بواسطة آلة تصوير عالية السرعة أثناء انطفاء اللهب المستقرّ والغير مستقر. وأثناء ظاهرة إطفاء اللهب، تم تطبيق تقنيتان مختلفتان؛ استخدم في التقنية الأولى نظام إشعاع بصري لقياس الانبعاث الضوئي الكيميائي لكل من C_2* و CH* بمرشحات ذات أطوال موجية بصرية 516 ± 2.5 نانومتر و430 ± 5 نانومتر على التوالي، أما في التقنية الأخرى فقد تم استخدام نظام مكبّر الصوت؛ الذي يستعمل لقياس الانبعاث السمعي من غرفة الاحتراق بشكل آني مع نظام الإشعاع البصري. أوضحت النتائج السلوك العابر للإشارتين البصرية والسمعية لانطفاء اللهب الغير مستقر والذي تميّز بقصر المدّة مقارنة بانطفاء اللهب المستقرّ، حيت تميز نهج استخدام النظام البصري بسرعة الاستجابة. وقد تم تقديم صورة نمطية آنية لبُنية اللهب في أثناء إطفاء اللهب المستقرّ والغير مستقر. ولمزيد من المعلومات عن تذبذب الضغط السمعي والانبعاث الضوئي الكيميائي C_2 *, CH* تم حساب التحليل الطيفي قبل حدوث إطفاء اللهب في ظروف مختلفة. كما تم توضيح أهمية الجمع بين المعالجة البصرية والانبعاثات السمعية لتحقيق نتائج مهمة وتقديم أفكار قيمة عن ديناميكية الاحتراق المعقدة داخل غرفة احتراق التربينات الغازية.

ABSTRACT

In this paper, both optical and acoustic approaches have been carried out successfully on flame blowout in premixed combustor G30 at atmospheric pressure. This work characterizes the behavior of a swirl stabilized propane C_3H_8 combustor, running at high temperature swirl air. Two cases have been studied in this paper, in the first case; the flame blowout limit by shutting down the main fuel supply of the stable flame, in the other case by shutting down the main supply of unstable flame. High speed camera imaging of a stable and unstable flames at and near blowout conditions are also presented. During this phenomena of flame blowout, two different techniques have been applied an optical emission system to measure the visible global chemiluminescence emissions of two different radicals of C_2* and CH* with an optic wavelength filters of 516 ± 2.5 nm and 430 ± 5 nm respectively, the other technique is the microphone system, which is used to measure the acoustic emission from the combustor simultaneously with the optical system.. A typical raw image of an instantaneous flame structure under stable-blowout and unstable-blowout conditions are also presented in

this paper. For farther information about the acoustic pressure and chemiluminescence emissions of CH* and C_2*, the power spectrum of signals just before the flame blowout has been also calculated at different condition. It has been demonstrated that optical digital acquisition and acoustic emissions processing is a powerful combination in the investigation, and have provided valuable physical insights into the complex combustion dynamics inside a gas turbine combustor.

KEYWORDS: Flame blowout limits; Gas turbine combustor, Acoustic and Chemiluminescence emissions

INTRODUCTION

Combustion instabilities occur in many practical systems for example, power plants. It is well known that the control of NO_x has become extremely important in many combustion systems, to limit the production of NO_x the flame is kept as lean as possible. However, this leads to a more unstable flame, with oscillating heat-release that couples with the pressure acoustics of the chamber.

Due to the complexity of the phenomenon, they often involve an interaction between several different physical phenomena, such as unstable flame propagation leading to unsteady flow velocities, acoustic wave propagation, and hydrodynamic instability. Instability mechanisms can not be modeled by using standard analytical techniques.

This paper describes an experimental investigation of blowout. This problem has grown in prominence as development efforts are focused on reducing NO_x, CO and other pollutant emissions, and improving engine efficiency and reliability. A primary focus has been to reduce the nitrogen oxides (NO_x) emissions. "NO_x" refers to the sum of NO (nitric oxide) and NO_2 (nitrogen dioxide), which have long been identified as harmful atmospheric pollutants, contributing to acid rain production, photochemical smog and ozone depletion. [1,2]

Most of the research efforts were focused on understanding the stabilization mechanisms and improving them, not on understanding the process of loss of stabilization. When a flame is near blowout, but statically stable, or an operating condition is changed such that the combustor moves from "stable" combustion to blowout, several studies have observed that the combustion process exhibits enhanced unsteadiness. For example, Nicholson and Field [3] observed large scale, irregular pulsations of a bluff body stabilized flame as it was blowing off. It should be emphasized that this unsteadiness was not observed "after the fact"; i.e., after the flame had blown off and was convicting out of the combustor. Rather, the flame was still observed behind the bluff body during these pulsations.

Acoustic emissions provide a useful diagnostic into transient flame holding events because they are proportional to the temporal rate of change of heat release [4]. Furthermore, many ground-based systems are already instrumented with dynamic pressure transducers. As such, implementing the developed precursor detection technique simply requires inserting a software module into the existing monitoring software. Fundamentally, combustion noise is generated by the unsteady expansion of reacting gases. It has been shown in several studies that the acoustic emissions of turbulent flames are dominated by unsteady heat release processes [5-8] (as opposed to flow noise) that excite acoustic waves over a broad range of frequencies (typically between ~10 Hz – 25 kHz). Thus, acoustic measurements can be used to detect either global changes in heat release rate or fluctuations in heat release at certain time scales in a combustor by measuring its acoustic emissions in corresponding frequency bands.[9]

Nair [10] focused on swirling combustion systems. Close to blowout his study, localized extinction/re-ignition events were observed. These events, manifested as bursts in the acoustic signal, increased in frequency and duration as the combustor approached blowout. An increase in 10-100 Hz frequency regime was observed in the combustion noise spectra which appeared to be controlled by the duration of and time interval between events. A variety of spectral, wavelet and thresholding based approaches were used to detect precursors to blowout.

The emissions of acoustic and chemiluminescence can be detected by readily available sensors and can be used to characterize the blowout process in a combustor. Numerous researchers have found such as unsteady flame dynamics in combustors prior to blowout. Using CH* chemiluminescence images, they were able to capture repeated detaching and reattaching of the flame from the center body close to blowout. De Zilwa et al. (2000) [11] similarly investigated flame dynamics close to blowout in dump stabilized combustors with and without swirl. They noticed very low frequency (around 3-12 Hz) oscillations as the blowout was approached. Chao et al (2000) [12] used acoustic excitation to stabilize a jet flame beyond its stability limit and then suddenly turned off the excitation to understand the blowout process by it self. They found that the flame base pulsated from attachment to non-attachment at the burner lip prior to blowout. They found that this regime could persist over time intervals from a few pulsation cycles to several seconds. They suggest that high strain rates, much higher than the extinction strain rates, encountered by the flame base should be a prominent factor in the blowout process.

Hedman et al (2002) [13] investigated blowout in a swirl-dump stabilized combustor using OH PLIF. They observed intense flame oscillations and temporary loss of flame near the lean blowout limit. In this paper, two types of experiments are described. In the first investigation, a stable flame at a known condition, and then the fuel velocity is subsequently decreased to cause blowout by shutdown the main supply of fuel, In the other, an unstable flame conditions and then blowout during shutdown the main supply of fuel.

EXPERIMENTAL SETUP

The data presented in this paper was acquired from a combustion test rig at UMIST. The test rig consists of a modified G30 combustor, an exhaust system, an air compressor and a data acquisition system.

Figure (1) illustrates the assembly of the major components of the G30 combustor. It has a pilot burner to stabilise the flame and an ignitor tube positioned at approximately 22 mm offset from the central axis. The main burner section is composed of the fuel manifold main inlet, the adapter plate and the swirler. During the tests, the fuel is injected through a fuel inlet in the gas burner; the main fuel-intake is conveyed to the swirler for the main combustion zone while the rest of fuel is diverted to the pilot burner via grooves and ejected gradually from twelve gas holes around the perimeter of the pilot burner’s front head. The split of the main and pilot fuels can be controlled separately. Note that the fuel used was methane unless otherwise stated. Figure (2) shows the 3D View of the combustion rig of G30 combustor. An exhaust duct is installed downstream of the combustor to discharge the combustion products, which is connected to a stack of fan assisted chimneys through a long stretch of exhaust pipe. In order to provide an optical access to the burner, an optical window is mounted on the exhaust duct and facing the combustor chamber directly, this window glass was used for chemiluminescent emissions measurements of two radical species (CH* - C_2*).

The air through the combustor was supplied by a REAVELL compressor. The supplied air is diverted to two major air ducts with diameters of 7.62 cm and 10.16 cm, which are connected to the swirl-air and the cooling-air ducts of the combustor respectively. For mixing purpose, the air supplied to the swirl vane is guided to flow tangentially and mixed with the fuel introduced through a small hole at the tip of each blade. The cooling-air is introduced to the combustor through a perforated casing with uniformly distributed holes of 5 mm in diameter.

The electrostatic (capacitor) type of microphone, Philips type SBC ME600, has been used to pick up the acoustic signal. The microphone is connected to a data acquisition system through a pre-amplifier to increase the voltage from few milli-volts to few volts, as shown in the Figure (1).

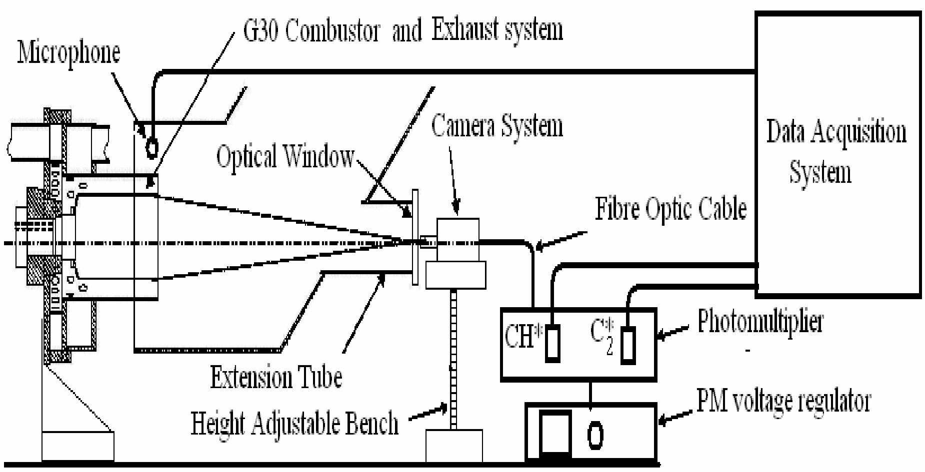


Figure 1: Schematic diagram of imaging setup and optical access

The optical system is used for the simultaneous measurement of two active chemical species CH*- C_2*. The apparatus consists of a modified camera, two photomultipliers (PMs) and a bifurcated optic fibre bundle. The camera body has been modified so that a bundle of fine optic fibres could be fixed at the back focal point to collect all the light through the front lens. The bundle of fine fibres is bifurcated randomly into two equal subdivisions to produce two channels of light signals of the same intensity from the same imaged volume. Filters then could be added to each channel to measure two interested species. The properties of the two applied interference optic wavelength filters are 516 ± 2.5 nm and 430 ± 5 nm for C_2* and CH* respectively. The subdivided fibre optic bundles are guided to two photomultipliers (ORIEL model 70704). The intensity of the light is converted into voltage signals. Outputs from the photomultipliers were displayed and stored in a PC. Care was taken to make sure that the PMs were working in the linear region of signal inputs versus the applied high voltage.

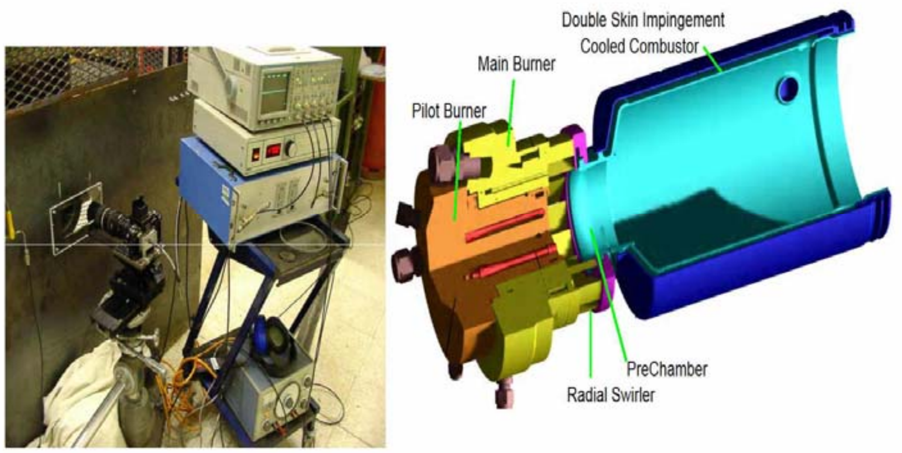


Figure 2: 3D View of the combustion rig of G30 combustor and data acquisition system [UMIST].

A data acquisition system was used to record the acoustic pressure and measured the chemiluminescence emissions of three radicals species (CH* and C_2*) signals simultaneously. The system is based on a personal computer and a National Instrument DAQ card (model PCI-MIO-16E-1). A Labview software were applied for data acquisition, monitoring and analyses.

RESULTS AND DISCUSSIONS

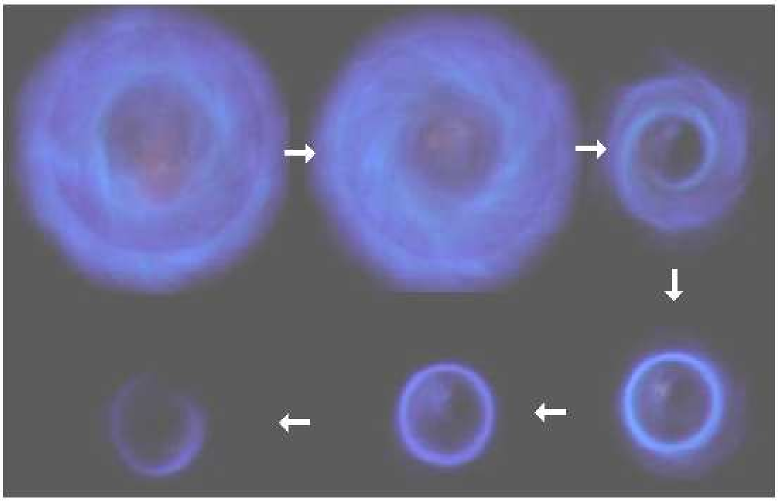
Detail spectrum of the flame blowout limit using the PMs global measurements of two radicals and acoustic pressure were made with the gas turbine combustor. In these experiments, two chemiluminescent radicals, CH*, and C_2*, were detected using optical filters and a PM tube. The selection of the optical filters (optic wavelength filters are 516 ± 2.5 nm and 430 ± 5 nm for C_2* and CH* respectively) was based on the measured detailed spectrum of a C_3 H_8 swirl premixed flame, and two radicals were measured simultaneously. The recorded emissions are principally from CH* and C_2* are very good indicators of the reaction zone. The results of high speed camera imaging of a stable and unstable propane-air premixed flame at near blowout conditions are also presented. By shutting the main supply of fuel the flame became leaner and leaner and then blowout. In this paper two cases have been studied experimentally, in the first case; the flame blowout limit by shutting down the main fuel supply of the stable flame, the other case by shutting down the main supply of unstable flame. Figure (3) shows sequence of images captured by the high speed camera. Since the images were obtained without optical filtering, they represent the total emission of the light from the flame in all spectra wavelength. Figure (3 **Case I**) shows the characteristic flame behavior from stable to blowout limit, while figure (3 **Case II**) shows the characteristic flame behavior from an unstable to blowout limit, It can be seen from this figure that, at stable condition to blowout, the flame became thinner and the flame takes a ring shape during the blowout, and has long time duration to blowout. At the unstable condition; the flame sudden to blowout, the flame became yellow at the centre of the combustor, because of the soot production during the blowout, which indicates that the combustion process was becoming very weak at this stage of transition.

Power spectrum is applied to extract the frequency information from the time domain signals from optical and acoustic sensors at stable and unstable Close to blowout limit. Figure (4) shows the sensors output signals at both cases during the blowout. Overall, the acoustic signal decreases due to the decreased heat release as the fuel is reduced (by shutdown the main supply of fuel). The CH*, and C_2* emissions behaves similarly.

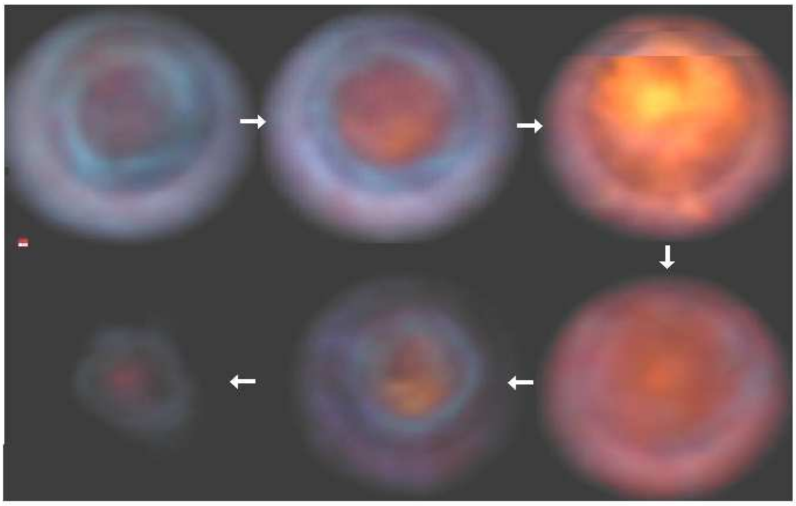
At the flame blowout; the CH*, and C_2* emission signals drops towards zero at the same time that the acoustic signal decreases to the certain level. The acoustic signals has a non zero amplitude of pressure fluctuation after the blowout limit, because the noise of the air flow in the combustor. The lift hand side of the figure (4) shows time variation of three simultaneous signals of CH*, and C_2* radicals and acoustic over a time of 10 seconds during stable and flame blowout limit, the sampling rate was 2000 samples per second. In right hand side shows the stable, unstable and then blowout limit over a time of 20 seconds, the sampling rate was 1000 samples per second.

The above analysis was based on interpretation of the signals in the time domain. Frequency analysis is also commonly employed to study time-varying data. To illustrate this behavior better, just a portion of these time traces are shown in Figure (5), from the optical emission signals and acoustic signal for both cases. In the case 1 (stable to blowout limit). Figure (5) shows the analysis of some of sensors samples of the total signals at close to flame blowout limit. The right hand side of the figure (5) shows the power spectrum of the optical and acoustic signals for stable mode of combustor close to the flame blowout limit. The figure shows the spectra of CH*, C_2*, and acoustic pressure measurements, It can be seen that the dominant peak frequencies (marked) of each signal are virtually the same. The power spectrum shows that the peak frequencies of 233 Hz for all signals. The match of the acoustic peak frequencies with the chemiluminescence demonstrates that the dominant noise is generated by the combustion process.

In order to obtain more information about the chemiluminescence emissions of CH*, and C_2* signals, the cross-correlations of these signals have been shown in Figure (5). It can be seen that the CH* signal has a weak correlation in this case of combustion mode with C_2* signal. The sound pressure level in this case is found to be 109 dB. In the case II (unstable to blowout limit) Figure (6) shows in the right hand side, the power spectrum of three simultaneous signals of CH*, and C_2* radicals and acoustic for unstable mode of combustion close to the blowout limit. It can be seen that the dominant peak frequencies (marked) of each signal are virtually the same. The power spectrum shows that the peak frequencies of 122 Hz for all signals and the sound pressure level is found to be 120 dB. It can be seen from Figure (6) that sub-harmonic frequencies are observable for the test cases II with high amplitudes of power spectra which indicates that higher amplitude acoustic modes would have more observable sub-harmonics. At unstable mode, the cross-correlation shows very strong correlation between the optical signals of CH*, and C_2*. The above mentioned observations were quite repeatable for several combustor operations e.g., combustion with different fuel and different inlet air temperature to the combustor.



Case I – stable to blowout limit



Case II – unstable to blowout limit
Figure 3: High speed camera images for case I and II

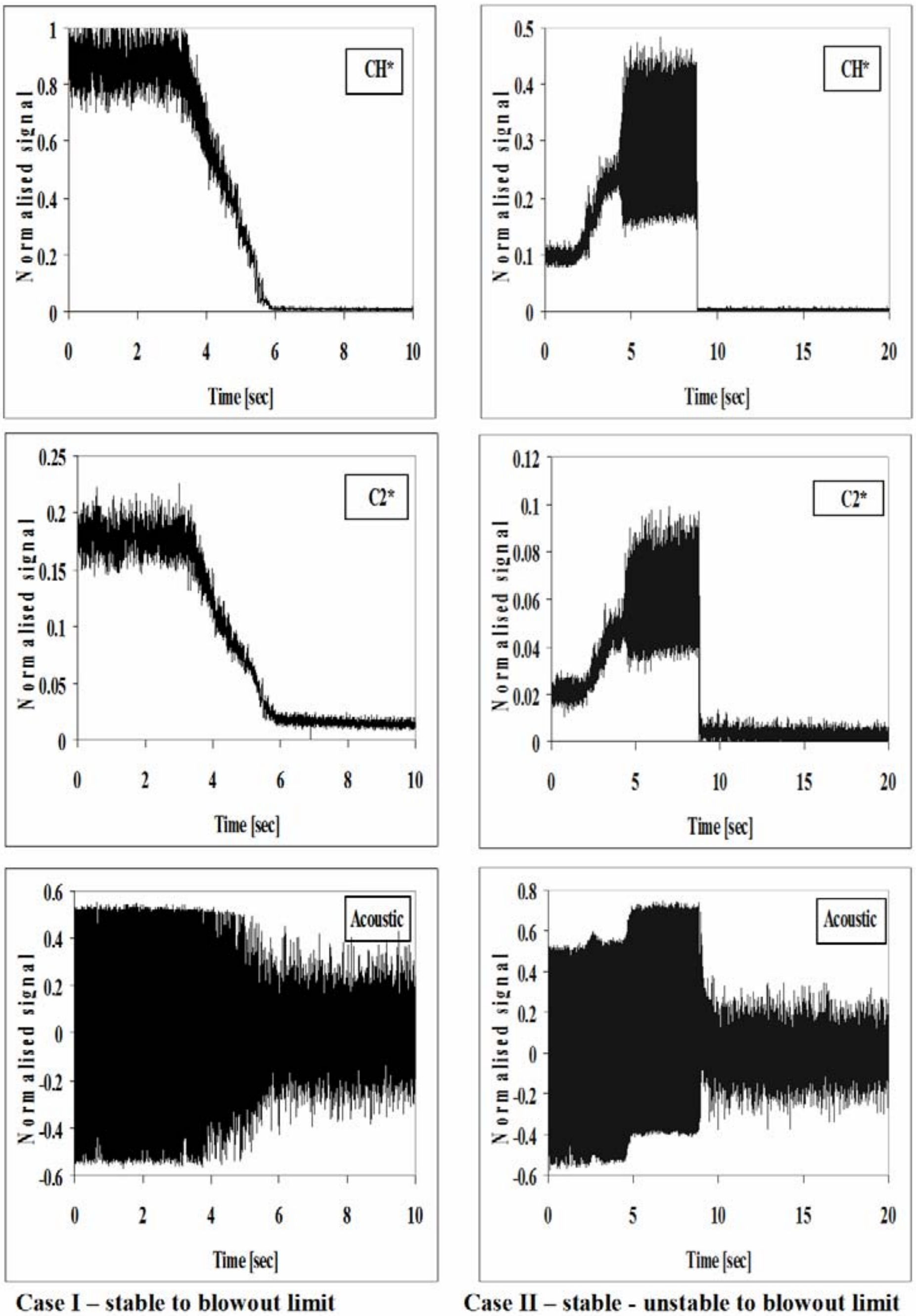


Figure 4: Time series data of three simultaneous signals of CH*, and C_2* radicals and acoustic signals.

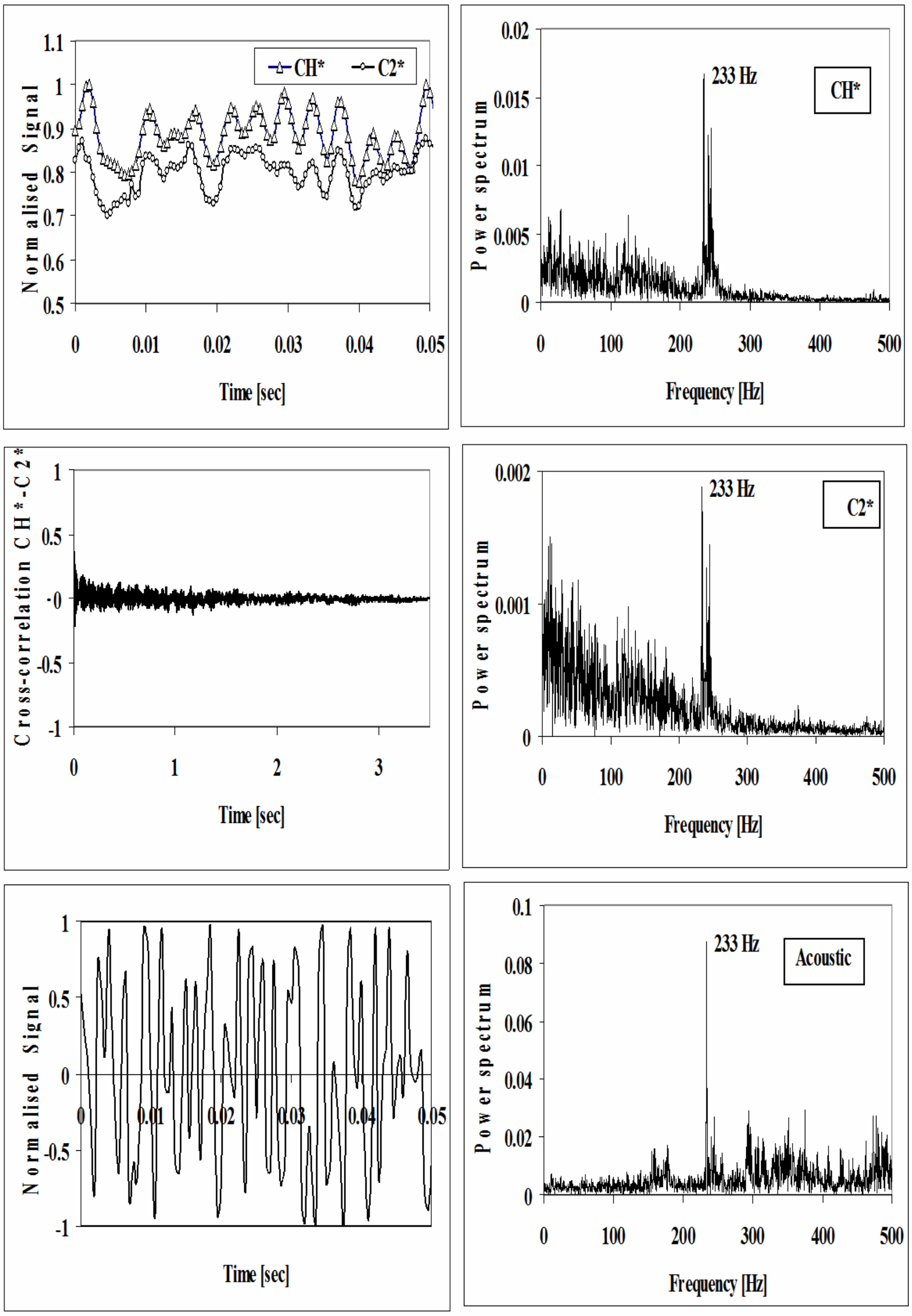


Figure 5: Power spectrum of the CH* and C_2* radicals and acoustic signals and the cross-correlation of CH*- C_2* at stable mode of combustion close to blowout limit. (SPL = 109 dB)

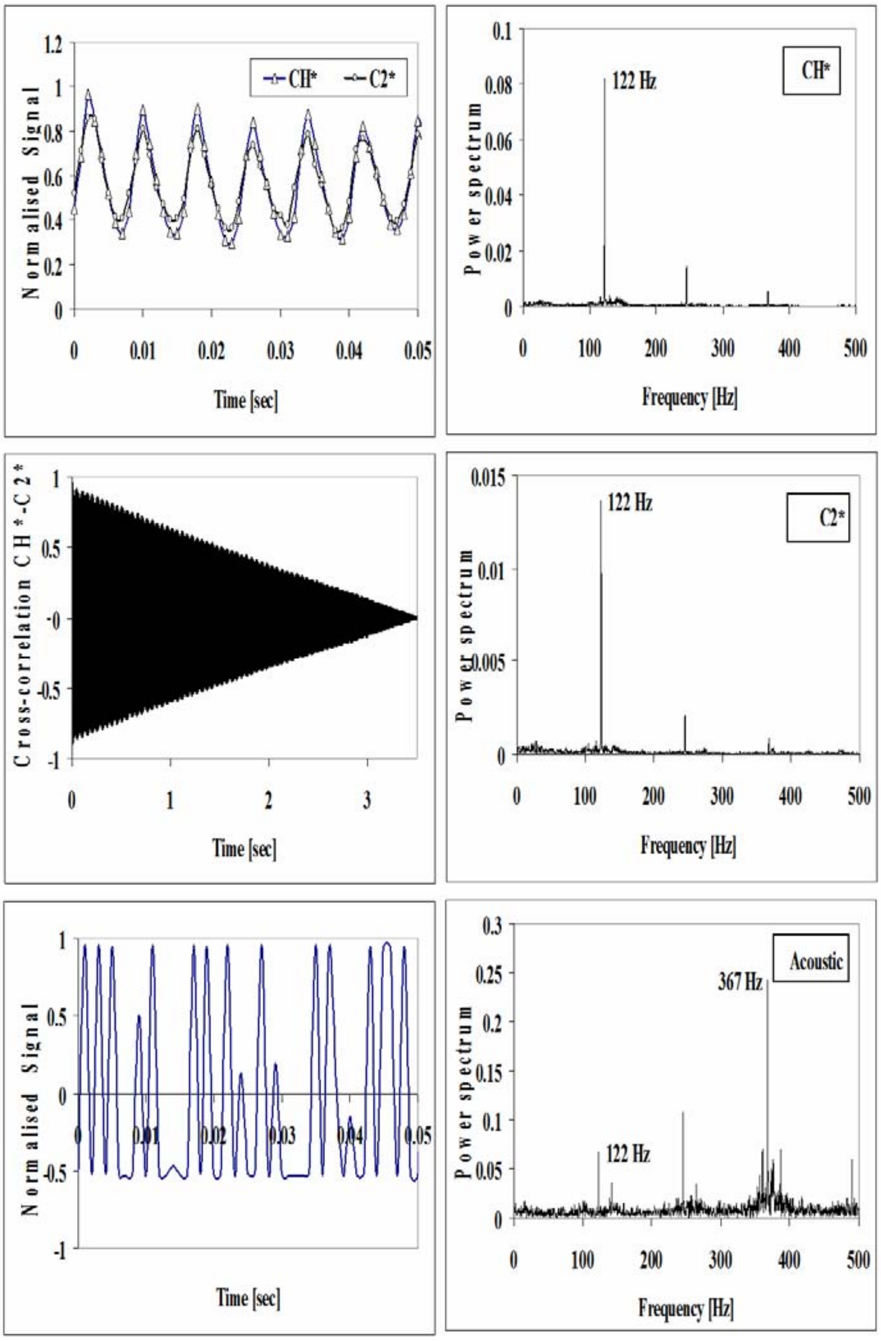


Figure 6: Power spectrum of the CH* and C_2* radicals and acoustic signals and the cross-correlation of CH*- C_2* at unstable mode of combustion close to blowout limit. (SPL = 120 dB)

CONCLUSIONS

The combination of optical and acoustic pressure signals is very useful in gathering important information about the flame blow-out limit correlations. The optical emissions from a swirling, premixed, Propane G30 at atmospheric pressure combustor were measured using simultaneous measurements of the visible global chemiluminescence emission of, C_2* and CH*with optic wavelength filters, and the acoustic pressure has been extensively investigated during this phenomena of flame blowout. Two cases have been studied: in the first case; the flame blowout limit by shutting down the main fuel supply of the stable flame, in the other case by shutting down the main supply of unstable flame. The high speed camera imaging of a stable and unstable flame at and near blowout conditions are also presented. Several interesting results were obtained that can be used to provide useful information on the combustor.

The time series measurements of three simultaneous signals measurements of global chemilimence and acoustic pressure were obtained to elucidate the flame blowout limit. At the flame blowout; the C_2* and CH* emission signals drops towards zero at the same time that the acoustic signal decreases to the certain level. The acoustic signals has a non zero amplitude of pressure fluctuation after the blowout limit because the noise of the air flow in the combustor. For unstable to blowout limit the flame sudden to blowout, and the flame became yellow at the centre of the combustor, because of the soot formation during the blowout, which indicates that the combustion process was becoming very weak at this stage of transition. For stable case the phenomena has long time duration to blowout.

Power spectrum is applied to extract the frequency information from the time domain signals from the optical and acoustic sensors at stable and unstable conditions before the blowout limit of the flame. From the results, it has been found that the link between the power spectra of C_2* and CH* chemiluminescence with the acoustic pressure are quite strong, the dominant peak frequencies of each signal are virtually the same for all conditions, which demonstrates that the dominant noise is generated by the combustion process. The results also show that, at unstable mode, the cross-correlation is very strong between the optical signals of C_2* and CH*, compared with stable case which shows a weak correlation.

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