CHEMILUMINESCENCE'S EMISSIONS AND ACOUSTIC CORRELATION MEASUREMENTS OF STABLE TRANSITION-UNSTABLE SWIRL PROPANE/AIR FLAMES IN AN INDUSTRIAL COMBUSTOR

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الملخص

شهدت بحوث الاحتراق الغير مستقر نضجاً على مدى العقد الماضي، إلا أنه هناك حاجة إلى تشخيص أكثر تفصيلا لهذا الموضوع. أحد أهم أدوات التشخيص تتمثل في الحصول على مقياس كمي للانتقال من الاحتراق المستقر إلى الاحتراق الغير مستقر في غرف الاحتراق. في محاولة للبحث في هذا المجال، طبقت طريقتان على دراسة ديناميكيه التحول من أسلوب الاحتراق المستقر إلى الاحتراق الغير مستقر للهب مخلوط مسبقا في غرفة احتراق تربين غازي صناعي، يمكن الوصول إليه بصريا بواسطة نافذة بصرية مثبتة على ماسورة العادم. وقد تبين أن التكامل البصري للانبعاث الضوئي الكيميائي (CHEMILUMINESCENCE) للهب بأساليب مختلفة، والمعالجة الرقمية للإشارات تشكل مجموعة فعّالة لتفحص الديناميكية المعقدة للهب.

أنواع الانبعاثات الضوئية الكيميائية الرئيسية المقترحة في هذه الدراسة هي C2* و CH* وOH*، وقد أظهرت النتائج أنه لأجل أن يكون الاحتراق مستقر فان تذبذب تلك الأصناف الكيميائية يكون منخفضا. قبل بداية الاحتراق الغير مستقر، يزداد نطاق التذبذب زيادة سريعة ومفاجئة ويصل إلى حد جديد. أما في الاحتراق الغير مستقر، فيزداد متوسط الجذر التربيعي للإشارات كما ويزداد متوسط شدة الانبعاثات الضوئية. استخدمت في هذه الدراسة المفصلة كل التحاليل الطيفية والسمعية للإشارات ومن أجل تصنيف الأطوار المختلفة لعملية الاحتراق وتمييز أفضل آلية انتقال تؤدى إلى عدم استقرار الاحتراق، تم عرض وتحليل مخططات الطور البيانية بين إشارتين. أدى قياس الإشارات المتعددة وتحليلها الي الحصول على معلومات مفيدة وقيمة عن الشدة السمعية والانبعاثات الضوئية الكيميائية C2* و CH* و OH* لديناميكية الاحتراق داخل غرفة الاحتراق بالتربينات الغازية الصناعية.

ABSTRACT

Combustion instabilities research has matured over the last decade, and with it the need for more detailed diagnostics has increased. One main gap in diagnostics is the ability to obtain a quantitative measure of transition of stable to unstable combustion in combustors. In an effort to move in this direction, two methods have been applied simultaneously to study the dynamic of the transition from stable to unstable combustion mode of premixed flame optically accessible in an industrial combustor. It has been demonstrated that the optical integration of chemiluminescence emission of the flame at different modes and digital acquisition processing is a powerful combination in the investigation the complex flame dynamics.

The main chemiluminescent emitters considered in this study are OH*, CH* and C_2* species. The results show that, for stable combustion, the fluctuations of chemical species are low. Prior to onset of unstable combustion, the amplitude of oscillation increased rapidly and suddenly to a new margin. In unstable combustion the mean and RMS (root mean square) of the signals are increased. This study makes available very detailed power spectra of each radical and the acoustic signal. Also, in order to classify different phase of combustion process and better recognize the transition mechanisms leading to combustion instability, phase space diagrams between two signals have been presented and analysed. For farther information about the acoustic pressure and chemiluminescence emissions of CH*, OH* and C_2*, the cross-correlations of these signals have been calculated. The multiple signal measurement and analysis have provided valuable physical insights into the complex combustion dynamics inside a gas turbine combustor.

KEYWORDS: Transition of stable to unstable combustion; Acoustic pressure; Chemiluminescence emissions

INTRODUCTION

The term combustion instability refers to a wide variety of oscillatory phenomena observed in combustion systems. Unstable combustion is not desirable and it can reduce efficiency and increase pollution, or even structural damage of the combustor. In several applications such as propulsion, power generation and heating processes that involve continuous combustion, instabilities are encountered. One of the main characteristics of these processes is the dynamic behaviour denoted as thermoacoustic instability.

In this paper is an industrial gas turbine combustor, in which a range of combustion modes could be induced. From Rayleigh's criterion [1], the thermo-acoustic instability can only occur if the magnitude of the phase between the heat release oscillations and the pressure oscillations at the flame is less than ninety degrees. It should be reiterated that this discussion has primarily concerned itself with the phasing, or timing, aspects of combustion instability initiation. These timing aspects are necessary. The unsteady heat release processes must not only be phased in such a way that they add energy to the acoustic field, but they must be also adding it at a rate that exceeds the rate of damping. Thus, while the associated characteristic times of various combustor processes are important, both the magnitude and phase of the heat release response to pressure perturbations are important issues that determine the stability behaviour of a combustion system. One main gap in the diagnostics is the ability to obtain a reliable quantitative measure of unsteady heat-release rate. In an effort to move in this direction using chemiluminescence as the measured quantity, multiple signal measurements have been measured simultaneously and investigated.

During the combustion of hydrocarbon, the fuel reacts with the oxygen in the air to form CO_2 and H_2O. However, this reaction does not occur in one step. Instead, a number of intermediate chemical species are formed that have very short lifetimes before being destroyed in the next steps of the reaction process to produce CO_2 and H_2O. Some of these intermediates are OH*, CH*, and C_2* radicals. Most of the radical emissions from the reaction zone are produced through a chemical reaction that leaves them in an exited energy state. This energy state tends to decay to a lower equilibrium energy state through molecular collisions and, to a lesser extent, by emission of radiation (light). This process, chemical creation in an exited state followed by emission of photons, is called chemiluminescence. While the light can, in principle, be emitted in the ultraviolet, visible or infrared region, those emitting visible light are the most common. They are also the most interesting and useful. The wavelength of radiation which is emitted is characteristic of the particular molecule and the particular transition the molecule undergoes. The more complex the molecule, the more complex the characteristic radiation spectrum observed. For some simple (diatomic) molecules, the spectrum exhibits one major peak and relatively few, weak secondary peaks. For complicated molecules, the radiation spectrum observed appears continuous. OH*, CH* and C_2* are examples of molecules exhibiting a simple spectrum with major peaks at 308, 431 and 513 nm respectively.

Chemiluminescence measurement is not a novel idea. Early researchers; Clark, [2] measured chemiluminescence from flames and attempted to find correlations between the measured chemiluminescence and experimental variables. The study laid the groundwork for a lot of the chemiluminescence research to follow. Three types of chemiluminescence were measured: OH*, CH*, and C_2*. Today, these three species are still the most commonly measured chemiluminescent species. The idea of using chemiluminescence in dynamic measurements was explored early on by Price et. al. [3] who related the noise from turbulent flames to oscillations in the strength of the chemiluminescence signal. They used premixed ethylene-air and ethylene diffusion flames in the experiments and found excellent correlation between the time derivative of the chemiluminescent light signal strength and the root mean square pressure as measured by a microphone some distance away from the flame. Chomaik, [4] and Beyler et. al. [5] used the chemiluminescence measurements to identify flame structures and flame stabilization mechanisms in gas turbine type combustors.

A quantitative measurement of dynamic heat-release rate is important in combustion instability research. For measurements of the heat release rate oscillation, OH*, CH* and C_2* radiations were studied, and they are assumed to be proportional to the heat release rate. Many investigators have attempted to obtain the time dependent heat release in unsteady combustion. Early research (Price et. al. 1968 [3]) claimed that chemiluminescence is proportional to the heat-release rate because of the linear behaviour of chemiluminescence with fuel flow rate. Langhorne [6], assumed C_2* chemiluminescence to be proportional to heat-release rate in his study. The research was conducted using C_2* and CH* chemiluminescence. The relation derived in their work relied on the chemiluminescence strength being proportional to heat-release rate. Hurle et. al. [7] have shown that the light emissions from C_2* and CH* radicals in the flame are linearly proportional to the heat release rate; their deductions have subsequently been used as a measure of heat release rate. It should be pointed out that Price et. al. [3] and Hurle et. al. [7] their studied were for premixed flame only, in which the equivalence ratio was kept constant. For diffusion flame these species may not be linked to the heat release rate. Haber [8] used the optical system for chemiluminescence measurements to collect the OH* and CH* emissions of a laminar methane Bunsen flame with co-flow of air. The study provides an important link between OH* chemiluminescence and HCO which is a major hydrocarbon oxidation intermediate previously shown to be a good indicator of heat release. Although CH* chemiluminescence is not an adequate indicator of heat release for methane combustion, the measurement of CH* chemiluminescence can provide important insights into local and global burning conditions. Lawn [9] described the instantaneous heat release from a localized region of a flame, which is then correlated with the fluctuating pressure. The technique is based on the chemiluminescence of the OH* radical at 307 nm, which is closely associated with the combustion reactions in gaseous hydrocarbon flames. Najm et. al. [10] performed an extensive study of experimental observables that are considered indicators of heat-release rate. They found that CH* chemiluminescence is not a good indicator of heat-release rate in all flame environments. CH* chemiluminescence fails to capture a decrease in the sensible enthalpy change of the gases through the flame, and they explained that OH* chemiluminescence is a good indictor of heat-release rate based on HCO. Haber et al (2001) confirm the results of Najm et. al. [10] that the OH* chemiluminescence is a good indicator of heat-release rate, their study is based on the formyl radical (HCO) for the heat release rate indictor. Ikeda et. al. [11] devolved measurement system to measure the local equivalence ratio at the flame-front of turbulent premixed flames. They showed that the fast response local equivalence ratio measurement was demonstrated by local chemiluminescence emissions (OH*, CH* and C_2*) to study the local flame front structure of turbulent premixed flames.

Combustion oscillations may easily control by simply introducing an energy source out of phase with heat-release rate. However, it has been demonstrated that successful control strategies used to suppress the pressure oscillations in combustors by using active control of combustion instability [12-16]. A number of studies have been conducted to understand the mechanisms of the combustion instabilities and control strategies of combustion oscillations by using active instability control (AIC). Several experimental studies have been conducted for thermoacoustic interaction in unstable combustors by using the conventional active control. It is necessary to have an effective and robust control of combustion. One of several aspects in an active control loop is the sensing technique such as the use of a microphone to pick up the acoustic pressure, and then to an actuator by using feedback close system. For combustion case, monitoring and measurement techniques are difficult to develop, because of the harsh environment inside the combustor and the measurements are heavily influenced by the combustion system which prevents the use of such sensors in large scale combustors. However, combustion involves heat-release and chemical reactions, and as such, it might possible to take advantage of this feature to use alternative sensing devices. Optical methods are attractive because the measurements are non-intrusive and optical materials can survive the high temperatures of combustors. Another advantage of optical methods is the generally fast time response of optical sensors. High speed monitoring devices are important in the monitoring of dynamic systems, such as modern gas turbine combustors. Zimmer and Tachibana, [17] used the chemiluminescence measurements of

CH*, OH* and background emissions at different stages for building an active control loop of combustion oscillations. They showed that for real time analysis, coupling pressure to chemiluminescence increases the reliability and dynamics of oscillating combustion detections; also they showed that the chemiluminescence measurements as input for models give a good idea of best choice for active control as for injection rate and time delays. Ng. [18] a quantitative analysis high speed imaging database had been attempted, with digital Processing techniques, it is possible to obtain quantitative information such as the frequency spectrum of the seeded mean light fluctuation recorded by each image. His results show that the frequency spectrum of the mean pixels image intensity of seeded flame is in good agreement with acoustic spectrum.

In this study, multiple signals have been measured simultaneously in a Siemens G30 combustor. Quantitative measurements of C_2*, CH* and OH* are performed and comparisons are made with the acoustic pressure of transition of stable to unstable mode of flame in an industrial gas turbine combustor. The detailed spectra of the measurement signals are compared and correlated in order to provide useful information on flame. This study makes available very detailed spectra of each radical and the acoustic pressure. Moreover, phase space diagrams between two signals had been plotted.

EXPERIMENTAL SETUP

The test rig consists of a modified Siemens G30 combustor, an exhaust system, an air compressor, and a data acquisition system. A microphone and fiber optical system are used to measure the acoustic pressure and chemiluminescent emissions of two radical species (CH*/C_2*, CH*/OH*) respectively. The overview of the experimental set up is shown in Figure (1).

Modified G30 combustor

Figure (2) illustrates the assembly of the major components of the G30 combustor. It has a pilot burner to stabilise the flame and an igniter 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.

EXHAUST SYSTEM

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. Quartz glass was used for chemiluminescent emissions measurements of two radical species (CH*/C_2*, CH*/OH*).

AIR COMPRESSOR AND AIR FLOWS

The air through the combustor was supplied by a *REAVELL* compressor. Figure (3) shows the schematic diagram of the airflow layout. 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 BS (British Standard) D-D/2 orifice plate is installed in each duct for mass flow rate measurement. It should be pointed out that the swirl air and the cooling air are designed to modulate separately. This particular setting is different from the actual G30 design so that the test condition can be varied more extensively.

ACOUSTIC PRESSURE MEASUREMENTS SYSTEM

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 mille-volts to few volts, as shown in the Figure (1).

FIBRE OPTICAL SYSTEM

To measure the chemiluminescence emission, a fibre optical system was utilized. Figure (1) shows the optical system. It consists of lenses, fiber optic cables, monochromatic filters and photomultipliers.

The optical system is used for the simultaneous measurement of two active chemical species (CH*/OH*, 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 three applied interference optic filters are given in Table 1. 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.

Table 1: Properties of the optical filters

Filter	Wavelength (nm)
C_2*	516 ± 2.5
CH*	430 ± 5
OH*	307 ± 2.5

DATA ACQUISITION SYSTEM

A data acquisition system was used to record the acoustic pressure and measured the chemiluminescence emissions of three radicals species (CH*, C_2* and OH*) signals simultaneously. The system is based on a personal computer Pentium III and a National Instrument DAQ card (model PCI-MIO-16E-1) and Labview 7 software were applied for data acquisition, monitoring and analyses.

RESULTS AND DISCUSSIONS

Quantitative measurements of C_2*, CH* and OH* are performed and comparisons are made with the acoustic pressure in the combustor at different mode of combustion. The detailed spectra of the measurement signals are compared and correlated in order to provide useful information on flame properties. This study makes available very detailed spectra of each radical and the other parameters. Moreover, phase space diagrams between two signals had been obtained.

The data of the stable-to-unstable transient of acoustic pressure and chemiluminescence emissions of CH*, OH* and C_2* are shown in Figure (4). A National Instrument DAQ card and LabVIEW 7 software have been utilized for data acquisition, monitoring and analyses. The sampling rate is 3000 samples per second and the duration of each sampling is 10 seconds (number of samples is 30000). Two test cases have been studied in this paper. The first case is C_2*-CH*, the inlet air temperature of 25^{o}C, the second case is OH*-CH* at high temperature of 300^{o}C, it can be seen that the transition from stable to unstable combustion modes at the beginning of the transition the acoustic and chemiluminescence emissions fluctuations increased gradually, and followed with a sudden and sharp burst in flame noise and chemiluminescence emissions, which indicates that the combustion process become very intense at this stage of transition. At the end of the transition, the drastic flame chemiluminescence emissions dissipated slightly and oscillated with constant amplitude and the combustion locked to the unstable combustion mode. From the Figure, it is clear that for stable combustion mode the rms of chemiluminescence emissions and acoustic signals are small. Prior to the onset of the unstable combustion, the rms increases rapidly to a new margin of fluctuation. The results show that the mean intensity of chemiluminescence emissions is also increased at the unstable mode of combustion.

Figures (5, 6, 9 and 10) present the typical combustion chemiluminescence emissions and acoustic signals for stable combustion mode as can be seen from Figures (6, 10) the acoustic signals seems to fluctuate over a wide range of frequency, that because there are other source of noise not from the combustion process, such as from vanes, air flow inlet and lab noise,……ect, but some of the modes coincide with optical signals. On the other hand, for unstable mode of combustion the instantaneous chemiluminescence emissions and acoustic signals have the same dominant frequency for two cases and also strong correlation between them.

Figures (5, 6, 7 and 8) show the spectra of CH*, C_2* and acoustic pressure measurements both mode of combustion (stable and unstable modes). It can be seen that the dominant peak frequencies (marked) of each signal are virtually the same. The power spectra of CH*/OH*, and acoustic pressure measurements are shown in Figures (9, 10, 11 and 12).

At stable mode of combustion, the power spectrum of OH* has a different dominant peak frequency at the same operating condition. This suggests a weak link between the OH* signals and the other signals, but strong link is observed in unstable mode of combustion. It can be seen from the results that the dominant frequency of OH* is sensitive to the flame mode. It is clear from the Figures that the acoustic power spectrum shows a lot of peaks compared with the power spectra of the species. This is because the microphone also captures all the non combustion related noise. For this reason the optical method is probably more suitable for feedback control system. It is worth noting however, that the peak frequency of the CH*/OH* case is higher than that of CH*/C_2* at approximately the same equivalence ratios. This may be a consequence of the effects of different temperature at the swirler inlet, which is higher in the case of CH*/OH* due to different air heating conditions.

In order to obtain more information about the acoustic pressure and chemiluminescence emissions of CH*, OH* and C_2*, Cross-correlation method has been used to compare the two time series signals and determine the strength of the relationship between them. The cross-correlations of these signals have been shown in Figures (5 - 12). It can be seen that the acoustic signal has a strong correlation with combustion chemiluminescence emissions at unstable mode.

According to Raleigh criterion for thermoacoustic instability, the phase difference between the heat-release fluctuation and acoustic pressure is very important. The simplest way to illustrate phase difference is to use phase-space diagram. The phase-space diagram between two species has been presented in Figures (13 - 14). The signal is normalised by the maximum value of each signal series. It can be seen that the phase-space diagrams between CH* and C_2* under all operating conditions have a near linear relationship and at a positive angle of 45^o with the horizontal axis, which indicates that the two signals are in-phase. The phase-space diagram has a shape of a circle, which would imply that the two signals have a phase difference of around 90^o. This trend can be seen in the CH*-OH* phase-space diagram at the stable mode of combustion as shown in the left sub-figure of Figure (14). The phase-space diagram of CH* and OH* at the unstable mode shows that the signals are out of phase, but both signals have the same dominant frequency of 168 Hz as shown in the lower sub-figure of Figure (11).

CONCLUSION

The combination of optical, and acoustic pressure signals are very useful in gathering important information about the amplitude-phase correlations of stable to unstable flame mode and the transition. Propane/air swirling flames in a G30 combustion chamber at atmospheric pressure has been extensively investigated. It has been found that the link between the power spectra of CH* and C_2* chemiluminescence with the acoustic pressure are quite strong. On the other hand there is a weak link with acoustic pressures for OH* chemiluminescence at stable mode of flames, but there is a strong link in unstable mode of combustion. Only at the unstable mode does the OH* signal have the same dominant frequency with acoustic pressure. Care has to be taken in using the chemiluminescent emission of CH* and OH* as indicators for unsteady heat release. The investigation also demonstrates that the dominant noise is generated by the combustion process.

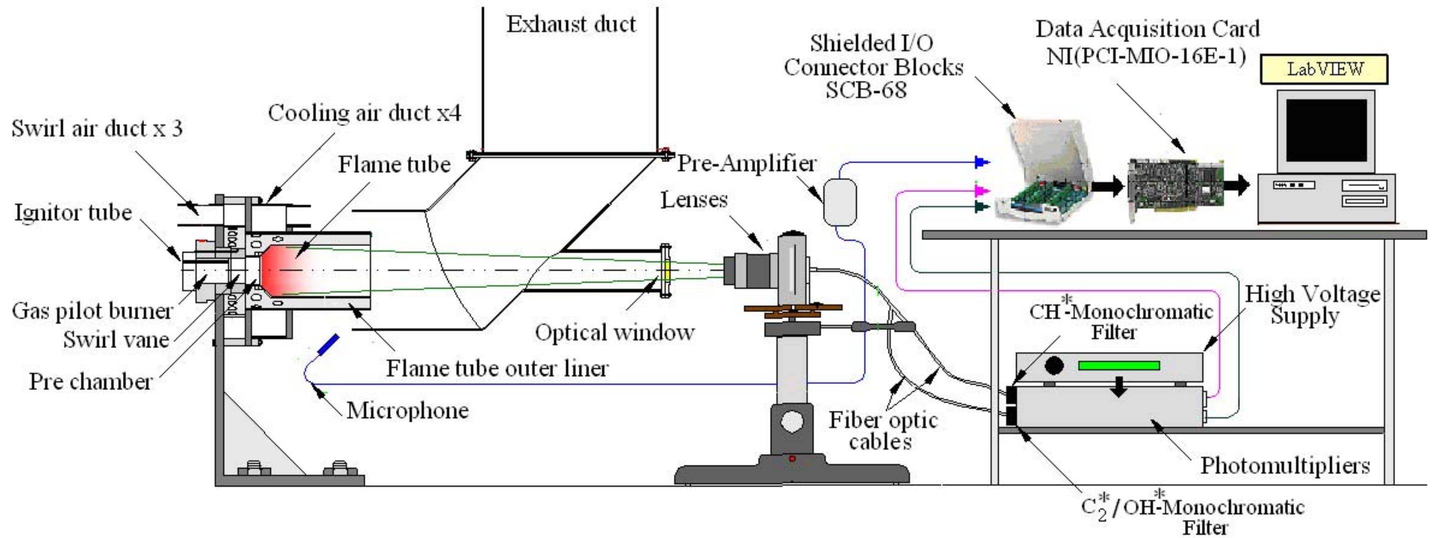

Figure 1: Overall experimental setup of the TG 30 combustor

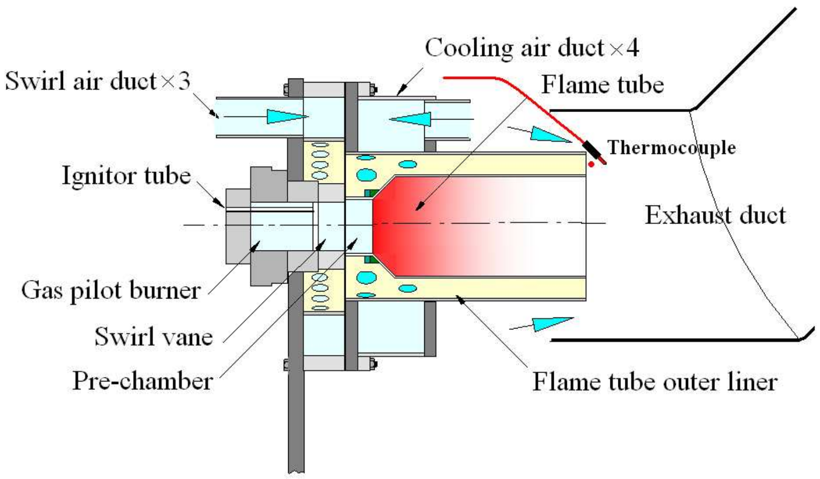

Figure 2: Cutaway view of G30 combustor.

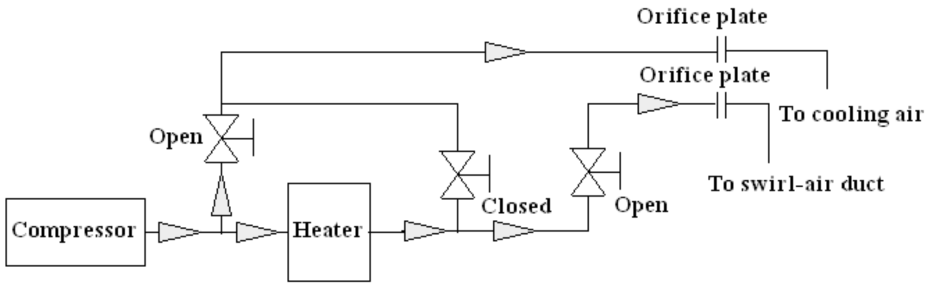

Figure 3: Schematic diagram of airflow layout.

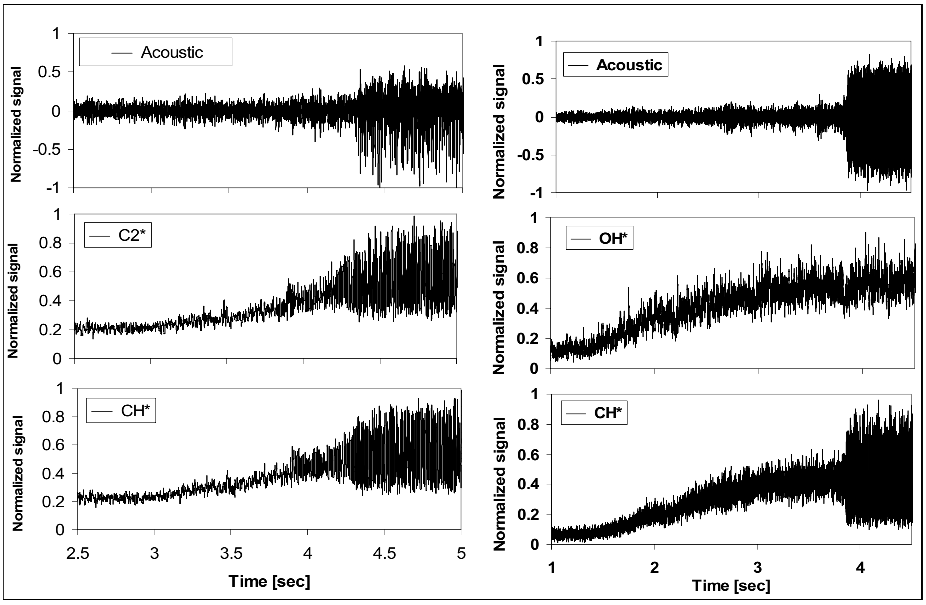

Figure 4: stable-to-unstable transient of acoustic pressure and chemiluminescence emissions of CH*, OH* and C_2*.

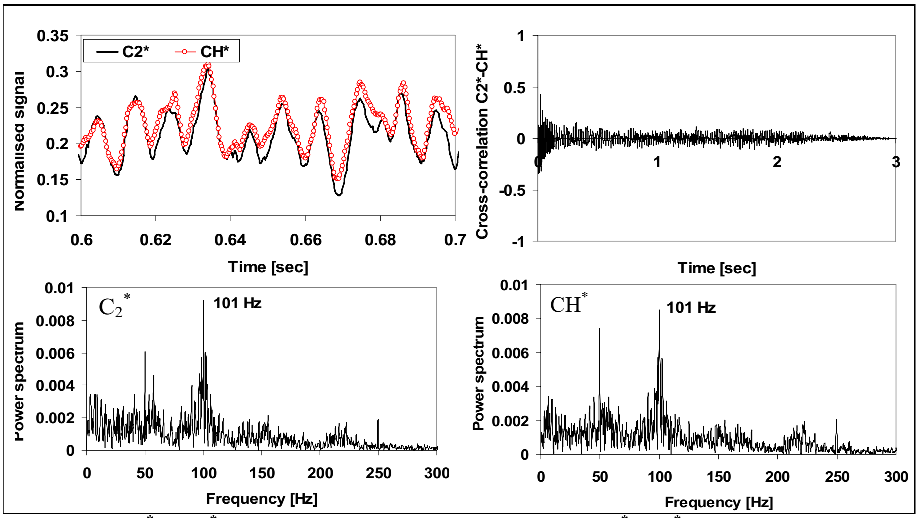

Figure 5: C_2^*, CH^* signals, Cross-correlation of the C_2^*-CH^*, and the corresponding spectra for the stable combustion mode at room temperature inlet air.

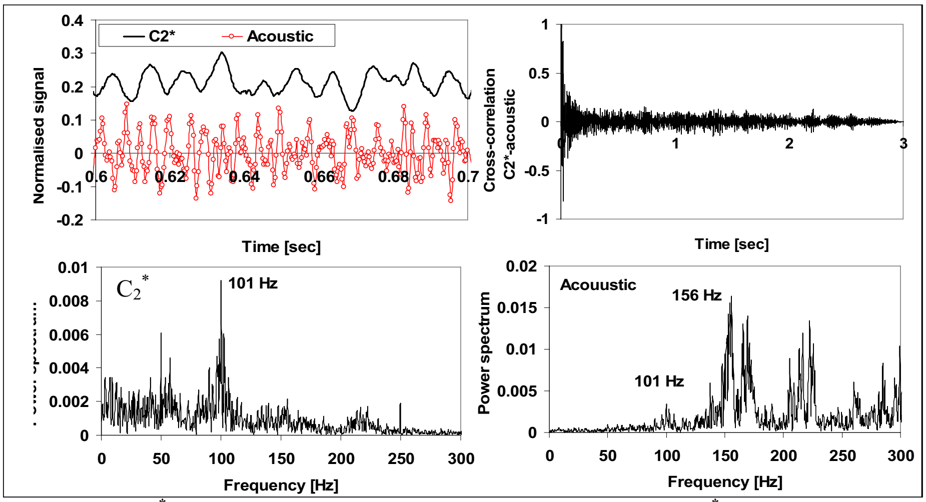

Figure 6: C_2^*, Acoustic signals, Cross-correlation of the C_2^*- Acoustic, and the corresponding spectra for the stable combustion mode at room temperature inlet air.

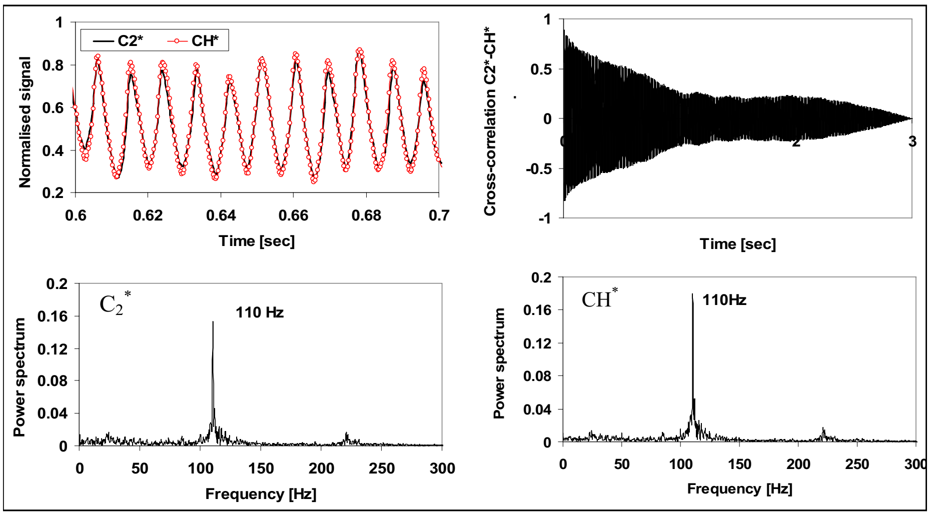

Figure 7: C_2^*, CH^* signals, Cross-correlation of the C_2^*-CH^*, and the corresponding spectra for the unstable combustion mode at room temperature inlet air.

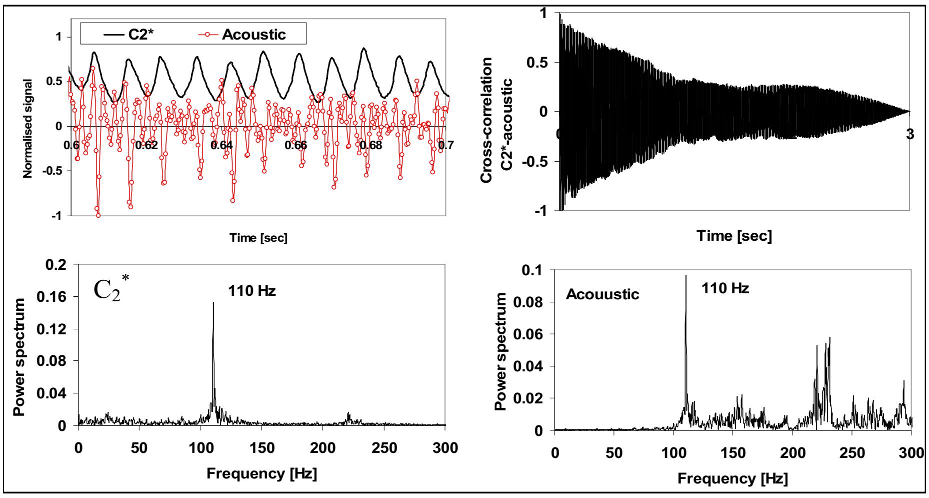

Figure 8: C_2^*, Acoustic signals, Cross-correlation of the C_2^*-Acoustic and the corresponding spectra for the unstable combustion mode at room temperature inlet air.

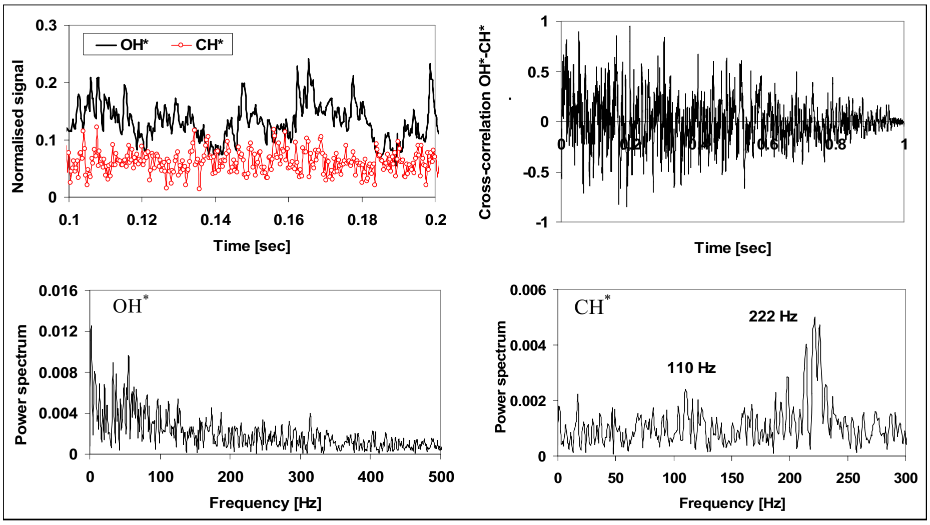

Figure 9: OH^*, CH^* signals, Cross-correlation of the OH^*-CH^*, and the corresponding spectra for the stable combustion mode at inlet air temperature of 300 ^oC.

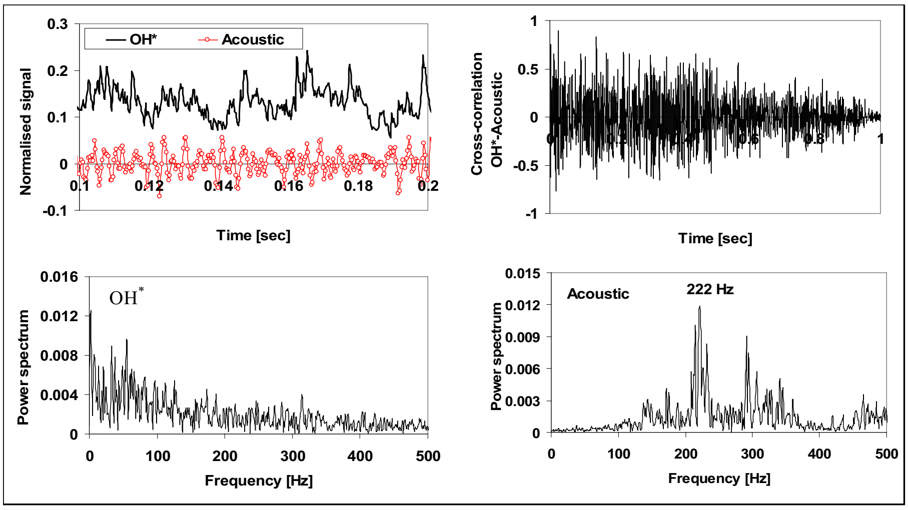

Figure 10: OH*, Acoustic signals, Cross-correlation of the OH*-Acoustic, and the corresponding spectra for the stable combustion mode at inlet air temperature of 300 °C.

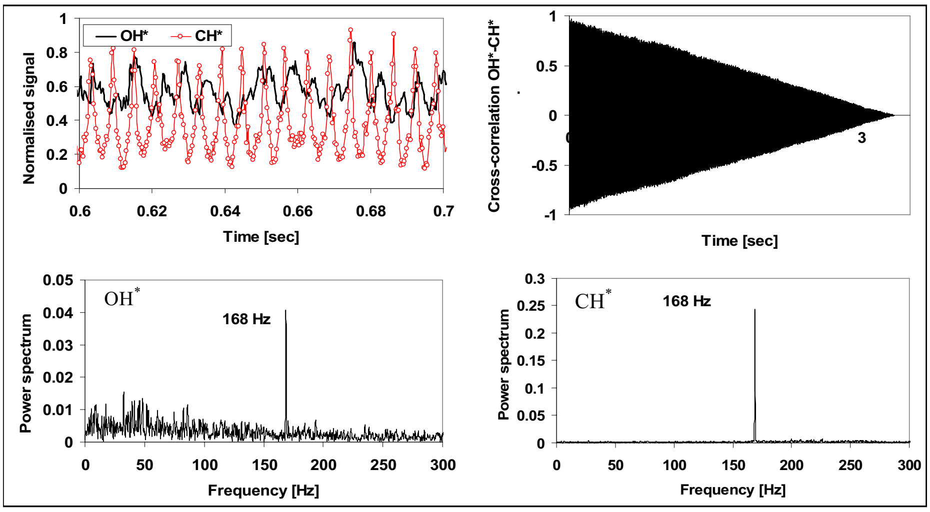

Figure 11: OH*, CH* signals, Cross-correlation of the OH*-CH*, and the corresponding spectra for the unstable combustion mode at inlet air temperature of 300 °C.

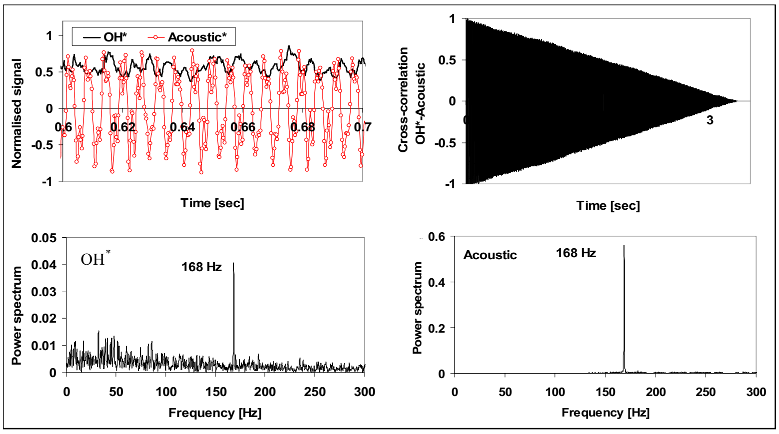

Figure 12: OH*, Acoustic signals, Cross-correlation of the OH*-Acoustic and the corresponding spectra for the unstable combustion mode at inlet air temperature of 300 °C.

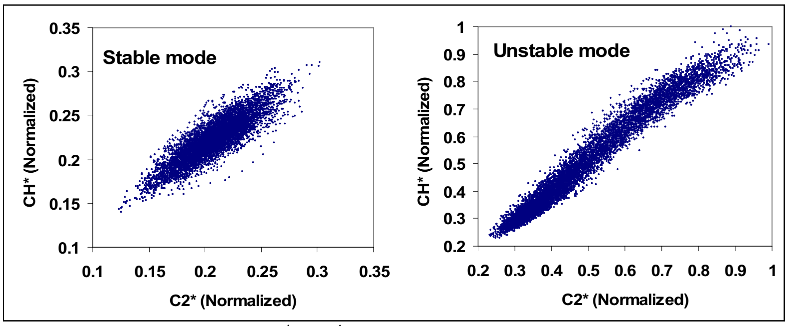

Figure 13: Phase space diagram of C2*, CH* signals, for stable and unstable modes of combustion.

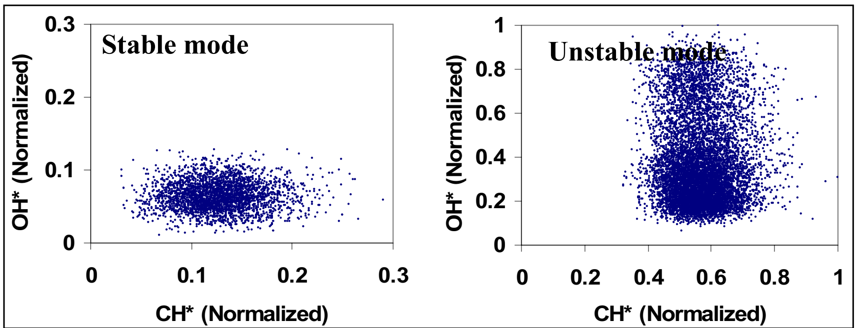

Figure 14: Phase space diagram of OH*, CH* signals, for stable and unstable modes of combustion.

REFERENCES

[1] Rayleigh, Lord. “The explanation of certain acoustic phenomena” Natural, Vol. (18): (1878). 319-321.

[2] Clark, T. “Studies of OH, CO, CH and C2 Radiation from Laminar and Turbulent Propane-Air and Ethylene-Air Flames”. NACA Technical Note, (1958). 4266.

[3] Price, R., Hurle, I. and Sugden, T. "Optical Studies of the Generation of Noise in Turbulent Flames," 12th International Symposium on Combustion, (1968). 1093-1102.
[4] Chomiak, J. "Application of chemiluminescence measurement to the study of turbulent flame structure," Combustion and Flame, 18: (1972) 429-433.
[5] Beyler, C. and Gouldin, F. "Flame structure in a swirl stabilized combustor inferred by radiant emission measurements" 18th International Symposium on Combustion, (1981) 1011-1019
[6] Langhorne, P. J. "Reheat Buzz: An Acoustically Coupled Combustion Instability. Part 1. Experiment," The Journal of Fluid Mechanics, 193: (1988). 417-443.
[7] Hurle, I., Price, R., Sugden, T. and Thomas, A. "Sound Emission from Open Turbulent Premixed Flames," Proceedings of the Royal Society Series, A(303): (1968). 409-427.
[8] Haber, L. C. "An investigation into the origin, measurement and application of chemiluminescent light emissions from premixed flames," PhD thesis, Blacksburg, Virginia. (2000)
[9] Lawn, C. J. "Distributions of Instantaneous Heat Release by the Cross-correlation of Chemiluminescent Emissions," Combustion and flame, 23: (2000). 227–240.
[10] Najm, H. N., Paul, P. H., Mueller, C. J. and Wyckoff, P. S. "On the adequacy of certain experimental observables as measurements of flame burning rate," Combustion and flame, 113: (1998). 312–332.
[11] Ikeda, Y., Kojima, J. and Nakajima, T. "Fast Response Local Equivalence Ratio Measurement I Premixed Turbulent Flame," Kobe University, Japan. (2001)
[12] Billoud, G., Galland, M. A., Huynh Huu, C. and Candel, S. "Adaptive Active Control of Combustion Instabilities," Combustion Science and Technology, 81: (1992). 257–283.
[13] Bloxsidge, G. J., Dowling, A. P., Hooper, N. and Langhorne, P. J. "Active Control of an Acoustically Driven Combustion Instability," Journal of Theoretical and Applied Mechanics, (1987). vol. 6.
[14] Gulti, A. and Mani R. "Active Control of Unsteady Combustion-induced Oscillations," Journal of Propulsion and Power, 8(5): (1992). 1109–1115.
[15] Heckl, M. A. "Active Control of the Noise from a Rijk tube," Journal of Sound and Vibration, 124(1): (1988). 117-133.
[16] Lang, W., Poinsot, T. and Candel, S. "Active Control of Combustion Instability," Combustion and Flame, 70: (1987). 281–289.
[17] Zimmer, L. and Tachibana, S. "Utility of chemiluminescence monitoring for active control of combustion," Aerospace Exploration Agency (JAXA). (2003)
[18] W.B. Ng , K.J Syed, Y. Zhang "The study of flame dynamics and structures in an industrial-scale gas turbine combustor using digital data processing and computer vision techniques"Experimental Thermal and Fluid Science, volume 29: (2005) 715-723.