FLICKERING PPROPANE/AIR DIFFUSION FLAME MEASURMENTS USING LIGHT CELL AND HIGH SPEED CAMERA IMAGE PROCESSING TECHNIQUES.

Salem A. Farhat, and Abdul-Hafid El-Majani

Mechanical and Industrial Engineering Department,
Faculty of Engineering, University of Tripoli, Libya
E-mail: salemfarhat_t@yahoo.co.uk.

الملخص

تم في هذه الورقة تسليط الضوء على مجال تحليل الإشارات الضوئية المنبعثة من اللهب بهدف دراسة تحليل عدم استقراريه الاحتراق والوصول إلى فهم أفضل لهذا الجانب الهام جدا من عمليات الاحتراق. يعد نمط ارتعاش اللهب مؤشرا جيداً لظاهرة عدم استقراريه اللهب في عمليات الاحتراق. ولدراسة ارتعاش اللهب أو ديناميكية اللهب استخدمت العديد من التقنيات البصرية (Optical techniques). في هذه الورقة تم استخدام خلية ضوئية كتقنية بصرية بديلة لقياس الانبعاث الضوئي الكيميائي للهب حيث تم مقارنتها بكاميرا عالية السرعة كتقنية تقليدية لقياس الارتعاش الوميضي الكيميائي المنبعث من اللهب. استخدمت التقنيتين لدراسة تأثير قطر الموقد على نمط ارتعاش اللهب. الدراسة المعملية أجريت على نفث للهب انتشاري عند ظروف الضغط الجوي لوقود البروبان وبأقطار مختلفة للموقد وتم تثبيت معدل تدفق الوقود خلال الموقد. أظهرت النتائج أن نمط الارتعاش للهب الرقائقي (laminar flame) لديه تردد في نطاق من 10 هيرتز إلى أقل من 15 هيرتز، أما في المرحلة الانتقالية للهب والتي يبدأ اللهب عندها بالانتقال إلى مرحلة الاضطراب فتحدث عند تردد 15 هيرتز (Re=1200). من خلال التحليل الطيفي للتقنيتين أظهرت النتائج وجود العديد من التوافقيات الفرعية القوية والواضحة في حالة اللهب الرقائقي ومن ناحية أخرى تبدأ الترددات التوافقية الفرعية بالاختفاء عند أرقام رينولدز (Reynolds Number) العالية (أكبر من Re=1200). تبين النتائج أيضا أن وتيرة الارتعاش النموذجية للهب هي 13 هيرتز وهو ما يتفق تماما مع الابحاث المنشورة في هذا المجال. تم في هذه الورقة أيضاً عرض منحنيات معامل الارتباط لإشارات الانبعاث الضوئي الكيميائي لكل من التقنيتين عند أرقام رينولدز مختلفة. النتائج بينت أنه لا يوجد اختلاف بين منحنيات معامل الارتباط للإشارات الضوئية الكيميائية المنبعثة لكلا التقنيتين عند ظروف اللهب الرقائقي عند أرقام رينولدز مختلفة، حيث أن سلوك الإشارات متطابقة لمعامل الارتباط في الموجة الجيبية النظرية (Theoretical sine wave) وهذا يعني أن للإشارات علاقة ارتباط قوية جداً. أما في حالة المرحلة الانتقالية، فيبدأ معامل الارتباط في الانخفاض والاقتراب من الصفر وهذا يعني أن الإشارات لها معامل ارتباط منخفض وتسمى بالإشارة ضعيفة الارتباط، وتصبح الإشارات بشكل عشوائي غير مستقرة وهذا مؤشر لدخول الاشارة في مرحلة اللهب المتضطرب (Turbulent flame).

ABSTRACT

This paper will shed some light on the area of signal processing analysis, and hopefully gives rise to more work in combustion instability field, which will lead to a better understanding of this very important aspect. Flickering frequency mode could be an indication of flame instability. In this paper is a light cell as an alternative optical chemiluminescence emission technique and a high-speed camera which is considered as a conventional technique to acquire a flame flicker are used. To study the effect of burner diameter on the flame flicker mode, an experimental study on free jet propane diffusion flame with different diameters is performed, while keeping the fuel flow rate constant. The results show that the laminar flame flickering mode has a frequency in the range of 10 to less than 15 Hz, and 15 Hz occurred at transitional condition (Re=1200). The results of the power spectra of both techniques show that many of the strong sub-harmonics occurred at laminar flame mode. On the other hand, the sub-harmonic frequencies start to disappear at high Reynolds number (above the transitional value of 1200). Results also show that the typical flickering frequency is 13Hz, which agrees well with other published data. In this paper, a family of auto-correlation curves of the chemiluminescence emission at different Re number are presented. The auto-correlation curves of the Chemiluminescence emission signals of both techniques at laminar conditions are very strong correlation of laminar Re numbers conditions; their trends are similar to auto-correlation of the theoretical sine wave. In the transitional condition; auto-correlation started to drop to zero, which mean that the signal has started to become a weak correlation, and the signals became turbulent flame.

KEYWORDS: Diffusion Flame; Chemiluminescence Emission; Flame Flicker; Combustion Iinstability.

INTRODUCTION

Combustion instabilities are typically violent pressure oscillations in a combustion chamber, and long-term exposure to pressure and thermal loads reduces the life of engine components and leads to massive damage of the combustion chamber and its components. One of combustion instability occurs due to the interaction between the heat release fluctuations and high-pressure fluctuations in a combustion chamber. This phenomenon is called thermo-acoustic instability of combustion and many researches studied this phenomenon [1]. A quantitative measurement of dynamic heat-release rate is important in combustion instability research. For Rayleigh criterion integral form, the heat release rate oscillation were assumed to be proportional to the chemiluminescence emissions. Many investigators have attempted to obtain the time dependent heat release in unsteady combustion [2]. Early research (Price et al 1968) [3] claimed that chemiluminescence is proportional to the heat-release rate because of the linear behavior of chemiluminescence with fuel flow rate. To control these instabilities of combustion, two main categories of the control of thermo-acoustic instabilities exist in gas turbine combustors, active control and passive control of combustion instability [4-8]. Both active and passive control strategies have some success in controlling thermo-acoustic instabilities namely, but no strategy has completely eliminated the problem.

Passive control strategies use devices that are not time varying in order to eliminate the formation of instabilities. These devices require a thorough understanding and measurement of the system dynamics because they cannot dynamically respond to any changes that may occur during operations. Passive control techniques have been widely used in industrial burners for many years. Their application typically involves modifications to the fuel injector or combustor hardware to eliminate the source of the variation in heat release or to increase the acoustic damping in the system and thereby reduce the amplitude of any pressure oscillations. Typically, passive measures are detuning a system by modifying its burners. Many researchers have avoided passive control specifically for the reason that it cannot adapt to changes in the system. Others assert that passive control has failed in the past due to a lack understanding of the fundamental physical phenomena. If a thorough understanding of the system can be attained, then various physical components such as injector geometry, acoustic resonators, liner design, and many other smaller components can be modified or added to remove the instability. One of the passive control techniques, which has recently received many attentions, is how the fuel nozzle location affects the potential for instabilities. Many researchers including Steele [9], Straub [10], and Smith [11] have reported that the axial adjustments in the location of the fuel nozzle has a positive impact in eliminating thermo-acoustic instabilities. For passive control, the burner plays a significant role for control of combustion instabilities.

For diffusion flames, the change in the radiation intensity is associated strongly with the change in the flame shape, and the flicker is inversely proportional to the square root of the burner diameter [12-14]. A better understanding of flickering flame behavior promises to improve the current understanding of turbulent combustion systems, since a much wider range of local conditions is available to characterize the flame-flow interactions that are more dominant in turbulent flames mode.

In this paper, the burner diameter has been varied to study flickering of the flame modes in free space by using two different techniques; a light cell as an alternative technique and compared with high-speed camera as a conventional technique.

EXPERIMENTAL SETUP

Experiments are conducted using a simple test rig, schematically shown in Figure (1). The test facility consists of a burner unit, an optical system, a high-speed camera and a data acquisition system. The burner is a single copper fuel pipe of 0.7 cm inner diameter. There is a set of orifices at the end of the tube, which reduces the overall inner diameters to 0.7 mm, 1 mm, 1.7 mm 1.9 mm, and 2.1 mm, see Figure (2).

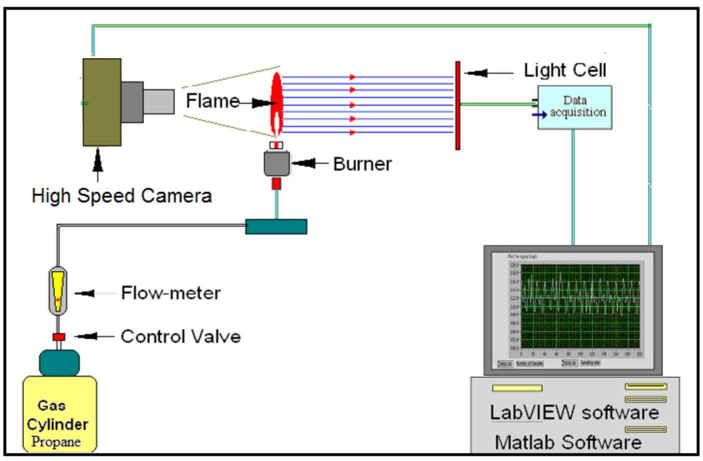

Figure 1: Schematic diagram of the flicker measurement systems.

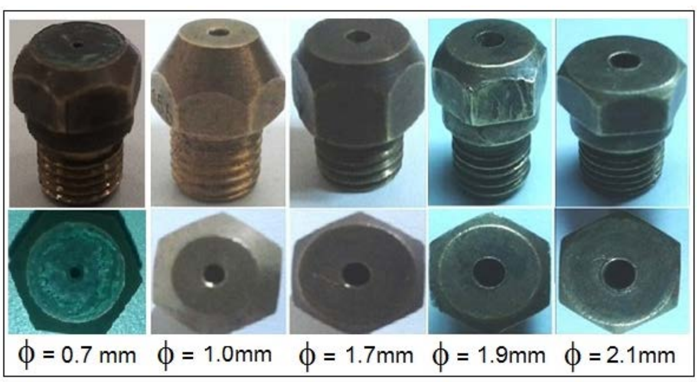

Figure 2: Burners.

The pipe is connected to a compressed propane gas cylinder. The fuel is regulated by a control valve and measured by a rotameter. The propane fuel was supplied from a propane cylinder at high pressure. Fuel Flow passes through rotameter and control valve, where the volume flow rate can be accurately adjusted and measured. The supply pressure is set on the fuel cylinder, and the flow rate is controlled before the rotameter by the valve. There are no additional control valves after the fuel rotameter, so the pressure through them is usually atmospheric. In this paper, the fuel flow rate were kept constant during the whole experiments, the fuel was released from the copper nozzle and surrounded by ambient air and hereby created a diffusion flame. To measure the flame flicker two different techniques have been used. An optical system is utilized by using the light cell, and high-speed camera for image processing. Outputs from the light cell are displayed and stored in a PC. LabVIEW software is used for data acquisition, monitoring and analyses. In order to obtain limited spatial information on the global chemiluminescence emission, a high-speed camera has been applied to obtain images of the free jet diffusion flame and MATLAP is used for imaging process.

RESULTS AND DISCUSSIONS

This paper presents the results of intensive experimental studies performed on free jet propane diffusion flame, the fuel flow rate was kept constant at 0.2 Letter/sec, and with different burner diameters (ϕ) of 0.7, 1.0, 1.7, 1.9, and 2.1 mm. The analysis and discussion of the results are presented in detail. The aim of the experimental investigation is to study the flame flicker of free jet diffusion flame with two different techniques, a light cell and a high-speed camera, both optical and digital high-speed camera approaches have been carried out successfully on different burner diameter diffusion flames configurations. The experimental investigation included a measuring of a flame dynamics mode in terms of Chemiluminescence emission of diffusion flame jet.

These two different techniques are used to obtain flame flicker frequency mode, as well as analyzing the flame dynamics. The results obtained from light cell technique measured at sampling rate of 44100 [samples/second] and duration of each sampling is 0.45 seconds. Labview software is used for data acquisition, monitoring and analyses. To acquire the second results high-speed camera is employed, which captures the flame radiation image, with sampling rate of 210 [Frame/second] and then processing the image (1000 images) by using MATLAB software. A comparison is made between results of two different techniques, in terms of power spectrum and auto correlation. The Reynolds number is calculated corresponding to the size of the burner as show in Table (1).

Table 1: Calculated the velocity and Reynolds number for propane gas at different size of the burners

ϕ [mm]	A [m^2]	V[m/sec]	Re
0.7	3.85E-07	7.096104	1208.256
1.0	7.85714E-07	3.477091	845.7789
1.7	2.27071E-06	1.203146	497.517
1.9	2.83643E-06	0.963183	445.1468
2.1	3.465E-06	0.788456	402.7518

Figure (3) illustrates a sequence of flame images captured by the camera for different burner diameters with a constant fuel flow rate obtained from experiments. The flame with these conditions are laminar, the maximum Re number was 1208 at the smallest size of the burner (in this condition just the flame entrance to the transient region), Within the region in which the flame stabilized on the rim of the burner, the height of the flame increases regularly with decreasing the burner diameters as shown in the Figure, that; because flow velocity is increased. However, under some conditions, flame flickering may appear to the eye, there appears a double flame that may correspond to the maximum and minimum positions of the flickering flame, the flicker consists of progressive necking of the flame and the laminar flame flickering has a frequency in the range of 10 to 14 Hz, for transitional flame at frequency of 15 Hz at burner diameter of 0.7mm. This range of frequency mode depends on Re number.

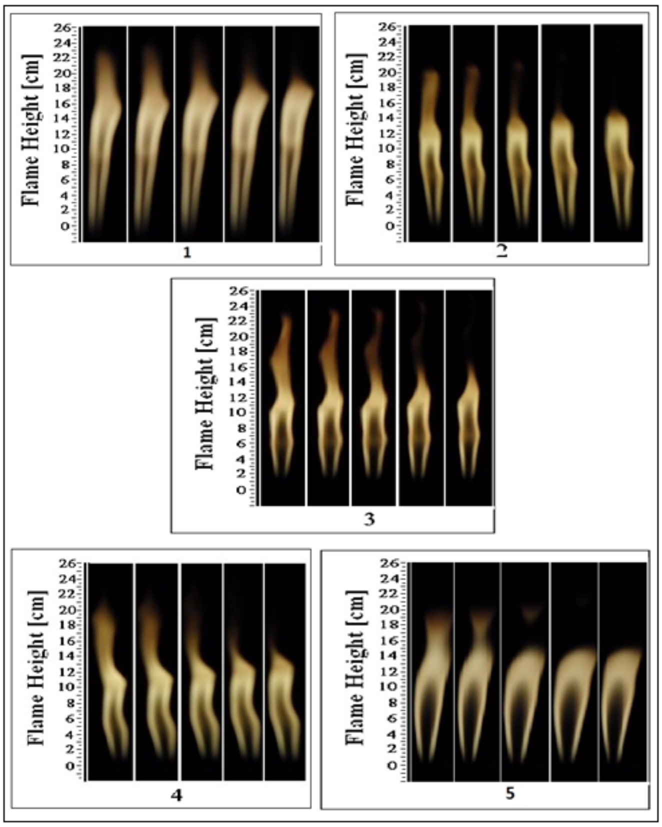

Figure 3: Sequence of flame images captured by the camera for different burner diameters (1-ϕ=0.7mm, 2- ϕ =1.0mm, 3-ϕ=1.7mm, 4- ϕ =1.9mm, and5-ϕ =2.1mm)

Figures (4-8) shows the time history, and power spectrum of the flame with different burner size, the subfigures (a) illustrate the time history of the signal received by the light cell on the right hand side and high speed camera, on the left hand side of the figures, and the subfigures (b) show the power spectrum, which basically convert the signal from time domain to frequency domain of the signals by using light cell and high speed camera.

It can be seen clearly from the power spectrum that the peak frequencies are varying from 10 to 15 Hz, depend on the Reynolds number. Sub-harmonics appeared in all burner size; Figures show that there are many strong sub-harmonics, on the other hand the sub-harmonic frequencies start to disappear at high Reynolds number (transitional Flame, Re =1200). These typical flickering frequencies of laminar diffusion flame agree well with other published data Yingpinget al. [12], in this reference high- speed CCD camera had been used.According to the literature, laminar diffusion flames are known to oscillate or flicker at a low frequency, typically ranging from 10 to 20 Hz, depending upon the operating conditions [15].

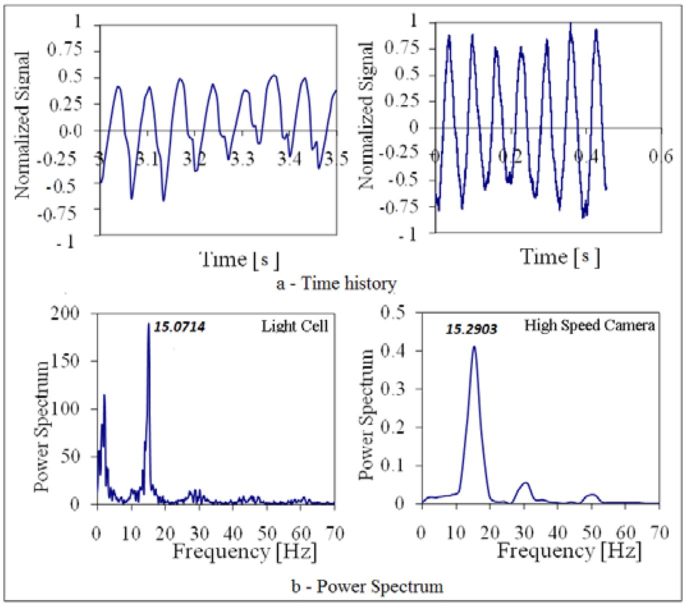

Figure 4: Time series and power spectrum of chemiluminescence signals by using both techniques with burner diameter of 0.7mm (Re =1208).

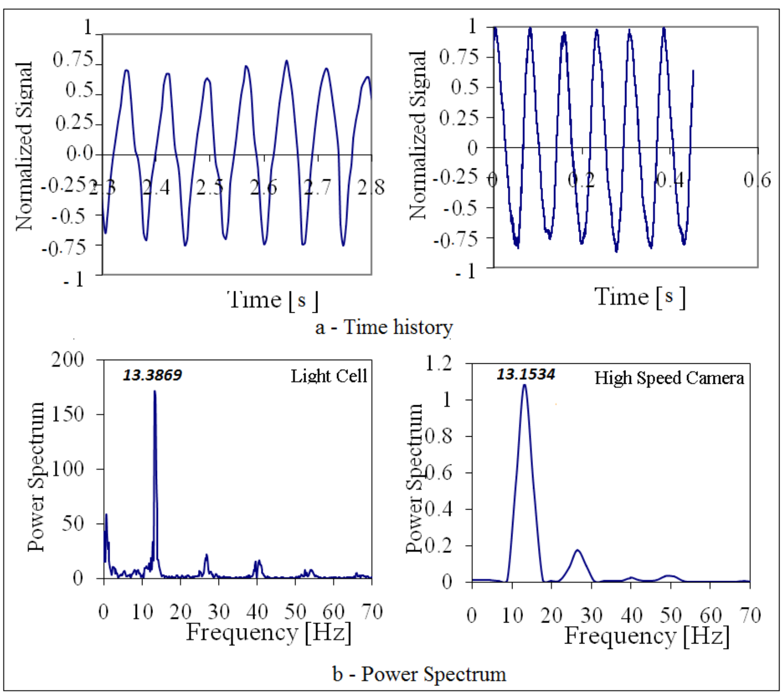

Figure 5: Time series and power spectrum of chemiluminescence signals by using both techniques with burner diameter of 1.0mm (Re = 845.8).

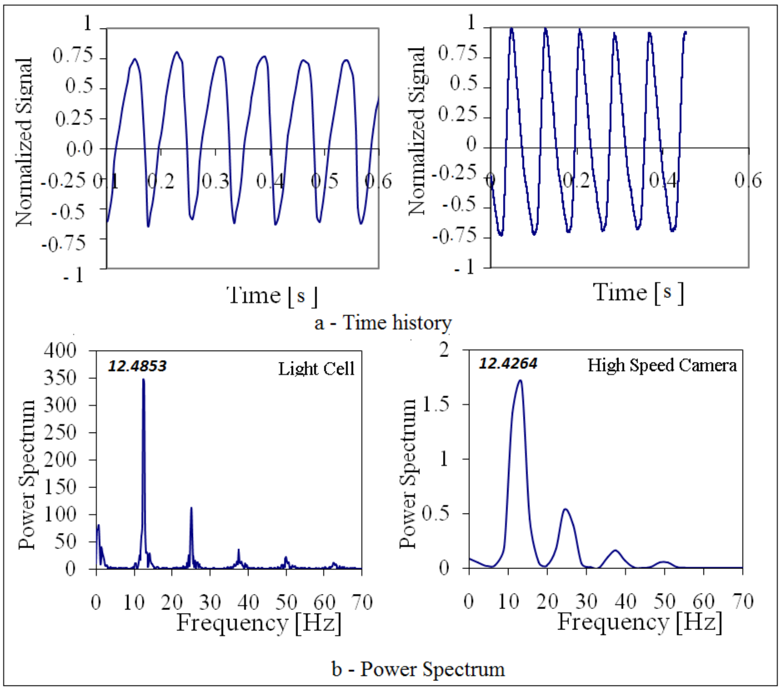

Figure 6: Time series and power spectrum of chemiluminescence signals by using both techniques with burner diameter of 1.7mm (Re = 497.5).

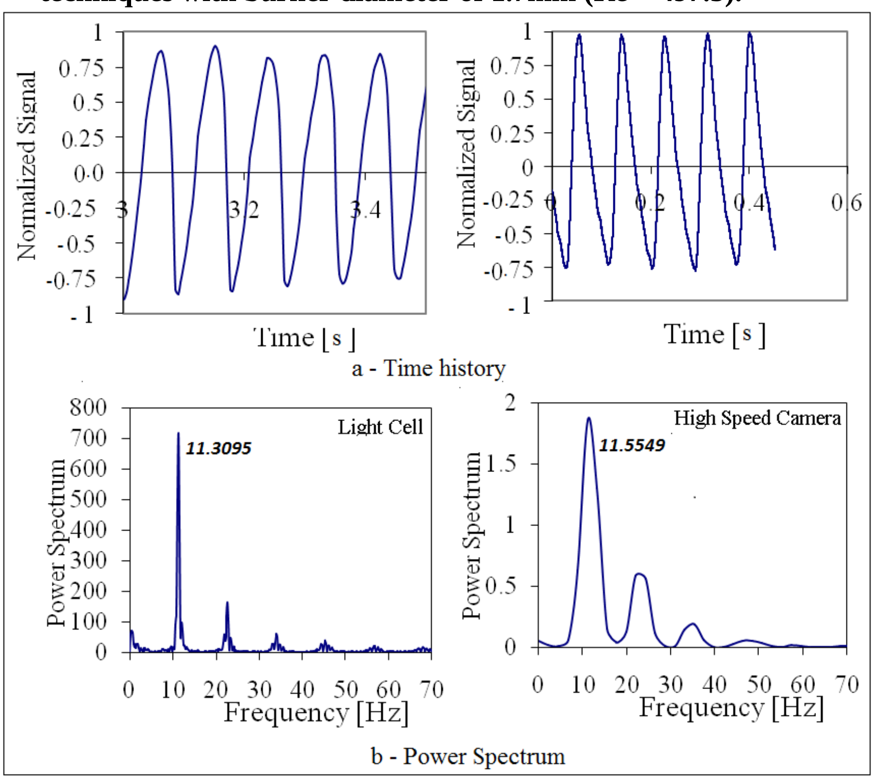

Figure 7: Time series and power spectrum of chemiluminescence signals by using both techniques with burner diameter of 1.9mm (Re =445).

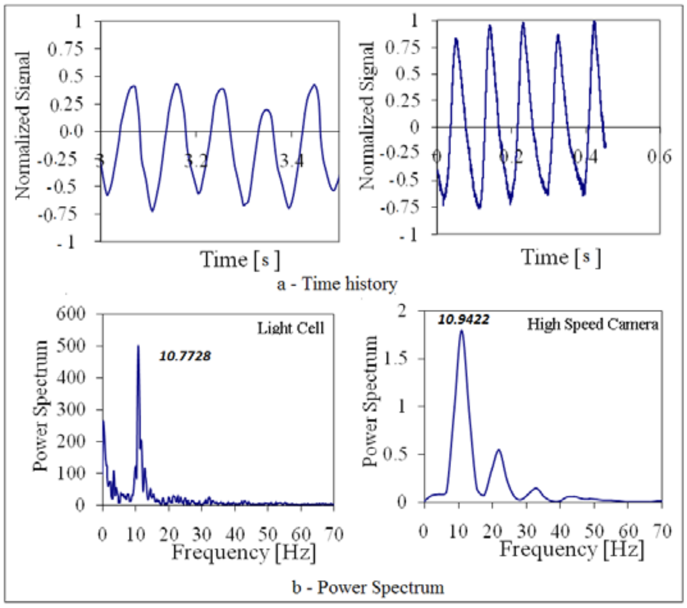

Figure 8: Time series and power spectrum of chemiluminescence signals by using both techniques with burner diameter of 2.1mm (Re =402.8).

Figure (9) shows a family of auto-correlation curves of the chemiluminescence emission at different Re number. From the Figure, it can be seen that the auto-correlation curves of the chemiluminescence emission signals do not vary for all laminar conditions; their trends are similar to auto-correlation of the sine wave. In all laminar flames, the autocorrelation curves do not drop to zero, which means that the signal has strong correlation. In the transitional condition at Re number of 1200; auto-correlation is started to drop to zero, which means that the signal started to be weakly correlated.

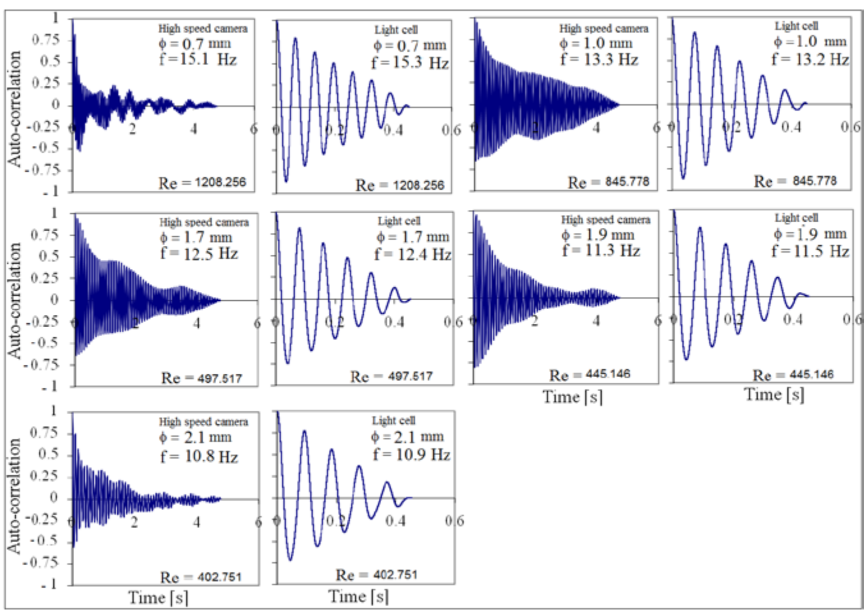

Figure 9: Autocorrelation curves of the chemiluminescence emission signals fluctuation by using both techniques at different burner diameters

Experiments were also performed for burners with diameters of 0.7, 1.0, 1.7, 1.9, and 2.1 mm (Re = 400-1200) and results show that the flicker of a diffusion flame is inversely proportional to the square root of the burner diameter. The flow rate was held constant at 0.2 liters/sec for different burners. Figure (10) is a plot of the measured flicker frequency versus the burner diameter.

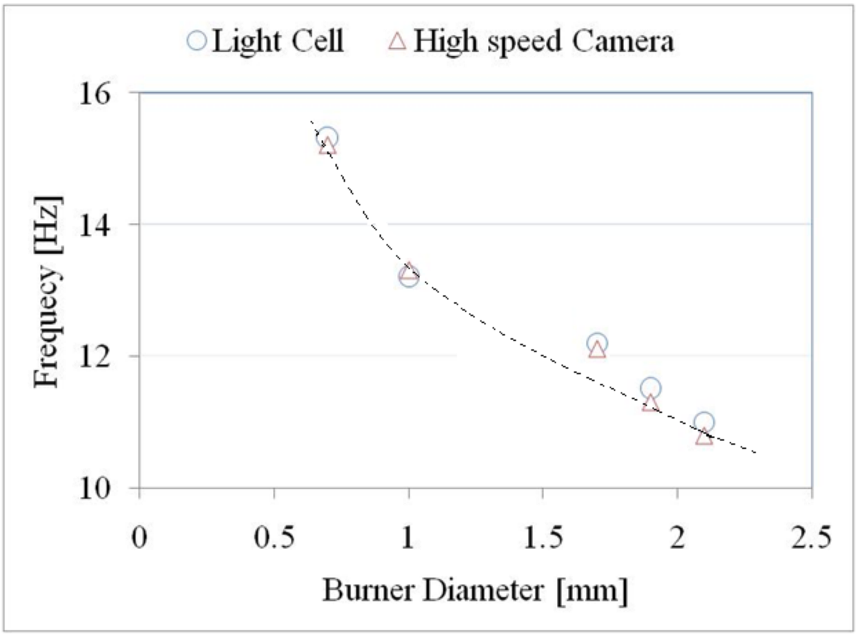

Figure 10: Measured flickers frequency versus burner diameter.

CONCLUSIONS

The flickering of a laminar diffusion flame is known to be caused by the interaction of the flame and the vortices both inside and surrounding the flame jet. Changes in Reynolds number due to the velocity of jet or different burner diameter can cause essential changes in this interaction. A quantitative explanation of the flicker has been given, which proved to be well suitable for presenting of the flickering characteristics of a diffusion flame. Reducing the burner diameter increased the Reynolds number approaching the turbulent area and the instability mode of the flame increased. The experimental results presented demonstrate that the light cell technique is capable of monitoring the flicker and analyzing the dynamic nature of the aflame. Experimental studies for propane diffusion flames have illustrated that the flame has a strong dominant frequency, depending on the Reynolds number, which is typically in the range of 10 to 15 Hz for a laminar diffusion flame. The results of the light cell technique are compared with the high-speed camera results with very strong agreement in all setup configurations, and the flicker is observed inversely proportional to the square root of the burner diameter.

ACKNOWLEDGMENTS

The authors wish to acknowledge the contributions of Engineers from University of Tripoli, Eng. Fatima M. El-lafi, Eng. Rashed. M. Alallagy, and Eng. abdelbaset. A. Altorky for their Help of this work.

REFERENCES

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

[2] L. Haber, L. C., Vandsburger, U., Saunders, W.R. and Khanna, V. K. (2001). “An Experimental Examination of the Relationship between Chemiluminescent Light Emissions and Heat-release Rate under Non-Adiabatic Conditions,” RTO/AVT Symposium, Propulsion and Power Systems, (20).

[3 Price, R., Hurle, I. and Sugden, T. (1968). “Optical Studies of the Generation of Noise in Turbulent Flames,” 12thInternational Symposium on Combustion, 1093-1102.

[4] Bloxsidge, G. J., Dowling, A. P., Hooper, N. and Langhorne, P. J. (1987). “Active Control of an Acoustically Driven Combustion Instability,” Journal of Theoretical and Applied Mechanics, vol. 6.

[5] Hathout, J. P., Fleifil, M., Annaswamy, A.M. and Ghoniem, A.F. (2002). “Active Control of Combustion Instability using Fuel-injection in the Presence of Time-delays,” Journal of Propulsion and Power, 18(2): 390-399.

[6] Hermann, J. Orthmann, A. Hoffmann, S. and Berenbrink, P. (2000). “Combination of Active Instability Control and Passive Measures to Prevent Combustion Instabilities in a 260 MW Heavy-Duty Gas Turbine,” NATO RTO/AVT Symposium on Active Control Technology for Enhanced Performance in Land, Air and Sea Vehicles: 2089-2102.

[7] Schadow, K. C. and Gutmark, E. (1992). “Combustion Instability Related to the Vortex Shedding in Dump Combustors and their Passive Control,” Progress in Energy and Combustion Science, 18: 117-132.

[8] Ben T. Zinn, Eugene Lubarsky and Yedidia Neumeier, (2007). “Overview of Different Approaches for Active Control of Combustion instabilities” 14th International congress on sound and Vibration, ICSV14, Cairns, Australia

[9] Steele, R.C. (1999). “Passive Control of Combustion Instability in Lean Premixed Combustors,” ASME (99-GT-052). Indianapolis, IN.

[10] Straub, D.L. and Richards, G.A. (1998). “Effect of Fuel Nozzle Configuration on Premix Combustion Dynamics,” ASME 98-GT-492. Stockholm, Sweden.

[11] Smith, C.E. and Cannon, S.M. (1999). “CFD Assessment of Passive and Active Control Strategies for Lean, Premixed Combustors.” AIAA 99-0714. Reno, NV.

[12] Yingping Huang, Yong Yan†, Gang Lu and Alan Reed (1999). “On-line flicker measurement of gaseous flames by image processing and spectral analysis” Meas. Sci. Technol. 10 (1999) pp 726–733. UK

[13] Rodney A. Bryant and William M. Pitts, “Particle Image Velocimetry in Flickering Methane/Air Diffusion Flames” Dantec Measurement Technology, Inc

[14] G. Papadopoulos, R. Bryant, W. Pitts, (2002). “Flow characterization of flickering methane/air diffusion flames using particle image velocimetry” Experiments in Fluids , Volume 33, Issue 3, pp 472-481

[15] Hamidreza Gohari Darabkhani and Yang Zhang, (2010).” Methane Deffusion Flame Dynamics at Elevated Pressure” Combust. Sci. and Tech., 182: 231–251.

[16] Salem A. Farhat, Samah Alghoul, Amira A. Ben Ghwaila, and Mariam A. Turkman. "Chemiluminescence Dynamics Measurements of Diffusion Flame Using Light Ce; and High Speed Camera "Journal of Engineering Research (University of Tripoli, Libya), Issue (22) September 2016: 11-20