Stability Characteristics of an Actively-valved Pulse Combustor

Xuren Zhu¹ Joel C. Lisanti², Thibault F. Guiberti³
, and William L. Roberts⁴
Clean Combustion Research Center

King Abdullah University of Science and Technology

Thuwal, 23955-6900, Saudi Arabia

This work describes the stability characteristics of an actively-valved pulse combustor through experimental methods. An ion probe detected the combustion events and a pressure sensor measured the pressure wave in the combustion chamber. By decreasing the injected fuel flow rate to approach near blow-out limit and fixing the value frequency to 270 Hz, the stability characteristics of the pulse combustor was studied systematically. The time and frequency domains of the ion and pressure data show that with decreased fuel flow rate, the ion and pressure signals amplitude decrease, time traces show some discontinuity, and low frequency oscillations appear. We then quantified the stability characteristics by introducing two indexes: the integrated power spectrum density (PSD) and PSD ratio. The indexes provide direct evidence showing that the low frequency oscillation governs the combustion dynamics when approaching blowout limit. The strong low frequency oscillation is treated as the symptom of the near blowout. The present study can be used to guide the operation of the pulse combustor and avoid low frequency oscillations.

I. Introduction

Compared to conventional steady combustion, the pulse combustion shows better performance in thermal efficiency, heat transfer intensity, and pollution emission, hence is widely used in domestic and industrial heating and holds the potential to be applied in real propulsion system [1, 2]. In addition, as one of the pressure gain combustion (PGC) devices, the pulse combustor is easier to handle compared to detonation engines with the difficulties, e.g. hard to achieve detonation initiation, extremely strong heat release and acoustics, insufficient fuel/oxidizer mixing, strong unsteadiness, and so forth [3].

A pulse combustor operates in a periodical mode. Fuel and oxidizer mix and enter the combustion chamber, which is constrained by one-way valves. The fuel/oxidizer mixture is then ignited to produce expanding combustion products. The afterburning gases are driven to the exhaust exit, meanwhile the intake valve is being shut. Due to the inertia of the combusted gases, pressure in the combustion chamber drops below atmospheric. At the same time, the intake valve opens to allow intaking fresh air and injecting fuel. Then, another cycle begins. The periodical fuel/oxidizer injection and combustion processes result in self-sustained oscillations produced from the coupling between combustion heat release and acoustic resonance [2, 4]. The stability of the combustion events and the acoustic wave propagation affect

¹ Postdoctoral Researcher, Mechanical Engineering, King Abdullah University of Science and Technology, Thuwal, 23955-6900, Saudi Arabia.

² Ph.D. Student, Mechanical Engineering, King Abdullah University of Science and Technology, Thuwal, 23955-6900, Saudi Arabia, AIAA Student Member

³ Research Scientist, Mechanical Engineering, King Abdullah University of Science and Technology, Thuwal, 23955-6900, Saudi Arabia

⁴ Director, Clean Combustion Research Center and Professor, Mechanical Engineering, King Abdullah University of Science and Technology, Thuwal, 23955-6900, Saudi Arabia, AIAA Senior Member

the performance of the pulse combustor, as well as its heat transfer efficiency [5] and noise level [2]. The pulse combustor has long been treated as a potential device for gas turbine application, stable operation is desired to guarantee efficiency, safety, and economy of the engine.

There have been numerous studies on stability issues in steady flames but few are found on pulse combustors. Among the research efforts, simple theoretical models have been developed to predict the dynamics of the gas pulsation in simplified pulse combustors [6, 7], but these models have limitations. For instance, the model developed by Ahrens et al. [6] is limited to steady state oscillations coupling with a single combustion chamber and simplified valve action. In a recent work by Li et al. [8], ion probing and a pressure sensing methods were used to investigate the near blowout characteristics of a pulse combustor. Following a similar idea used in [9], measures were implemented to predict the blowout limit of a passively-valved pulse combustor. By introducing a stability-to-instability index, which rates the energy spectra of working frequency and low frequency oscillation, the blowout can be predicted in real time. Interestingly, the economically feasible ion and pressure measurements were found to be efficient and accurate in evaluating blowout events.

Recently, the authors have developed an innovative actively-valved pulse combustor for pressure gain combustion [10-12]. By introducing a rotary ball valve, the lifetime of the pulse combustor was significantly extended compared to conventional pulse combustors using reed or flapper valves, whose movement is passively driven by the gases in the combustion chamber. Thus, this new design makes pulse combustors more applicable to real propulsion systems. In our previous studies, the general operation characteristics and performance of the actively-valved pulse combustor have been illustrated. Positive pressure gain and low emissions have been achieved. However, some important phenomena have not been well understood. Among those unelucidated observations, stability is of interest as it plays a significant role in determining the overall performance. On the other hand, unlike the reed and flapper valves, the currently used rotary ball valve opens and closes actively. As a result, the valve movement will directly affect the combustion event and pressure rise and drop in the combustion chamber. This could make the stability property of the pulse combustor significantly more complicated. Therefore, in the present work, we attempt to reveal the stability characteristics of the actively-valved pulse combustor using an ion probe and a pressure sensor.

II. Experimental Facilities and Measurement Instrumentation

In Fig. 1 (a), the experimental system includes an actively-valved pulse combustor, which features a rotary ball valve driven by a DC motor through a shaft. The dimensions of the pulse combustor are seen in Fig. 1 (b). The shaft drives the valve with a frequency in the range 200-300 Hz. Fig. 1 (c) shows the detailed structure inside the combustor head. Fuel was injected through 4 small holes (diameters of 0.35 mm) arranged on the fuel injector (diameter of 5 mm). The fuel injector points to the inlet to enhance fuel/air mixing. The fuel and air mix with each other then flow into the combustion chamber through the 10 passage holes arranged on the stagnation plane as seen in Fig. 1 (c). More details of the actively-valved pulse combustor are available in previous work [10-12].

Liquid gasoline is used as fuel. To start the pulse combustor, forced air is injected through the inlet in the front of the combustor inlet. During normal operation, which corresponds to resonant combustion events, the forced air injection can be either shut down or maintained without losing resonance. Maintaining the forced air injection simulates a pulse combustor in a propulsion device, moving through air. An absolute encoder is used to record the valve position. Two spark plugs are arranged on the combustion chamber wall. One of them is used as the ignitor and the other one as an ion probe. An absolute pressure sensor is used to measure the dynamic pressure of the combustion chamber. The sampling rate for dynamic pressure and ion signal is 30 kHz and the total samples for every case is 200k. More details on the ion and pressure sensing methods are available below.

Figure 1 (a) Schematic of the experimental setup, (b) dimensions of the pulse combustor, and (c) the combustor head

A. Ion sensing

In hydrocarbon flames, due to chemi-ionization effect, there exists charged ions in the combustor, such as CHO^+ and H_3O^+ . According to previous studies [13, 14], the following reactions are mainly responsible for the generation of ions,

By measuring the ion current, the combustion events in the combustion chamber can be detected because the ion concentration is closely related to the combustion intensity [15, 16]. Fig. 2 shows a schematic of the circuit for

measuring ion current. A DC voltage of 10-20 V powers the measurement system. Depending on the conductivity of the ionized gas between the spark plug electrode gap (seen in Fig. 2 (b)), the current flowing in the circuit changes. According to the Ohm's law, the voltage difference between point A and B is then used as a signal for determining the ion concentration change, i.e., the combustion event. A larger voltage difference indicates a reduced ion concentration and, in turn, a less intense combustion.

Figure 2 (a) Schematic of the chemi-ionization measurement system and (b) the spark plug electrode

B. Pressure measurement system

A Kistler (type 4049A) absolute pressure sensor is mounted in the same cross-sectional plan as the ion probe to measure the dynamic pressure of the acoustic waves in the combustion chamber. To prevent overheating issue, chilled water is continuously flowing through the pressure sensor. In order to maintain measurement fidelity at the elevated temperatures reached during resonant operation, electronic thermal drift compensation was applied to the dynamic pressure transducer signal. For more details, readers are referred to the previous work [10-12].

III. Results and Discussion

The pulse combustor was run with fixed valve frequency of 270 Hz, fixed forced air injection of 6 g/s, but varying fuel flow rates. The fuel flow rate was gradually decreased from 70 g/min to 42 g/min with a step of 2 g/min. The pulse combustor was very stable for 70 g/min but was very unstable for 42 g/min. Further decreasing the fuel flow rate below 42 g/min led to global extinction. Therefore, we define the fuel flow rate of 42 g/min as a near blowout. The stable/unstable behavior of the pulse combustor can be highlighted by examining time traces of the ion and pressure signals, which are now described in Sec. A.

Figure 3 Time traces of ion signal for a valve frequency of 270 Hz, a forced air flow rate of 6 g/s, and fuel flow rates of (a) 68 g/min, (b) 54 g/min, and (c) 42 g/min

A. Time trace of the ion and pressure signal

Figure 3 shows 1 s time traces of the ion signal recorded for a valve frequency of 270 Hz, a forced air flow rate of 6 g/s, and fuel flow rates of (a) 68 g/min, (b) 54 g/min, and (c) 42 g/min. Figure 3 (a) shows a shorter time period to highlight details. The signal appears periodic, indicating that combustion occurs in a pulsed mode. By decreasing the fuel flow rate from 68 g/min to 54 g/min, the amplitude of the fluctuating signal decreases dramatically. This is caused by the weakened combustion intensity as a result of reduced fuel flow rate.

However, further decreasing fuel injection from 54 g/min to 42 g/min does not yield an obvious amplitude reduction. The ion probe is located close to the combustion chamber's wall and it captures local combustion events. In the present pulse combustor, fuel/air mixture were injected into combustion chamber through the passaged holes as shown in Fig. 1. Due to sudden expansion, a strong toroidal vortex structure is produced when letting in the premixed reactants. This has been shown by Williams et al.[17, 18]. According to the simulation work for a pulse combustor by Geng et al. [19], combustion is mainly concentrated in the center of the combustion chamber due to the existing recirculating zone created by the toroidal vortex. At lean conditions, combustion is restrained in the recirculating zone and chemical reaction intensity is not strong enough to produce sufficient chemi-ions propagating to the near wall region. As a result, the ion probe signal, which is a measurement of local combustion events, does not change significantly when comparing Fig. 3 (b) to Fig. 3 (c). OH* chemiluminescence experiments or numerical simulation would provide direct evidence for this principle hence merit future work.

Figure 4 shows 1 s time traces of the pressure signal for the same operating conditions as in Fig. 3. Again, a shorter time period is shown in Fig. 4 (1a) to highlight details. Comparing Figs. 4 (a), (b) and (c) shows that the pressure signal fluctuating amplitude continuously decreases when the fuel flow rate decreases from 68 g/min to 42 g/min, and that the pressure signal becomes discontinuous when approaching blowout (42 g/min).

The pressure signal relates to the global intensity of the acoustic wave propagating in the combustion chamber. This intensity is a function of the total fuel burning rate. This differs from the ion signal, which measures local information. This explains why trends of ion probe and pressure signals with fuel flow rate differs close to blowout.

Figure 4 Time trace of pressure signal for a valve frequency of 270 Hz, a forced air flow rate of 6 g/s, and fuel flow rates of (a) 68 g/min, (b) 54 g/min, and (c) 42 g/min

B. Ion and pressure signals in the frequency domain

The time traces of ion and pressure signals were processed through fast Fourier transform (FFT) and the resulted power spectrum densities (PSD) are shown in Fig. (5) and (6), respectively. Spectra vary dramatically with fuel flow rates. For comparison purposes, PSDs were normalized with respect to their peak. Here, the analysis is restrained to the 0 – 600 Hz frequency range.

Figure 5 Power spectrum densities (PSD) of the ion probe signal for a valve frequency of 270 Hz, a forced air flow rate of 6 g/s, and fuel flow rates of (a) 68 g/min, (b) 54 g/min, and (c) 42 g/min

Figure 5 shows power spectrum densities (PSD) of the ion probe signal for different fuel flow rates, but fixed valve frequency of 270 Hz and forced air injection of 6g/s. For a sufficient fuel flow rate (68 g/min), a distinct PSD peak is found at the valve frequency. Other PSD peaks are found at 135 Hz, 405 Hz and 540 Hz, which are 1/2, 3/2 and 2 harmonics of the valve frequency. These so-called sub- and super-harmonics, which have not been observed in passively-valved pulse combustors [8], are unique features of the actively-valved pulse combustor.

By decreasing the fuel flow rate to 54 g/min, the PSD value at the valve frequency weakens dramatically relative to the harmonics. The sub-harmonic at 135 Hz dominates over all other components. The power of valve frequency component is at a level comparable to that of background noise, indicating that the resonant combustion is sustained but is weak.

At fuel flow rate of 42 g/min, which is near blowout, the low frequency components (0 – 50 Hz) feature high intensities. The valve frequency and low frequency spectrums broaden at this condition. Most harmonics become insignificant compared to the background noise, except for 135 Hz, where the PSD value is around 2/3 of that found for the valve frequency. The peak PSD value is found in the range of 0 - 50 Hz. According to previous work with steady flames [9, 20], low frequency acoustic waves are often a manifestation of combustion oscillations. In the present pulse combustor is: when blowout is approached, the flammable mixture becomes lean, and local or global extinction occur once it is too lean. Such intermittent local/global extinction events are possibly responsible for the low frequency oscillations. A further OH* chemiluminescence experiment or simulation work would help to reveal it.

Figure 6 Power spectrum densities (PSD) of the pressure signal for a valve frequency of 270 Hz, a forced air flow rate of 6 g/s, and fuel flow rates of (a) 68 g/min, (b) 54 g/min, and (c) 42 g/min

Figure 6 shows power spectrum densities (PSD) of the pressure signal for different fuel flow rates, but fixed valve frequency of 270 Hz and forced air injection of 6g/s. Similar to Fig. 5 (a), Fig. 6 (a) exhibits the distinct peak PSD at the valve frequency of 270 Hz. However, the harmonics at 135 Hz, 405 Hz and 540 Hz are very weak. When the fuel flow rate is decreased to 54 g/min, the valve frequency component still dominates over the whole spectrum map, while other spectrum components share a very weak power spectrum.

In Fig. 6 (c), significant changes are observed near blowout: the low frequency component becomes powerful and is comparable to the valve frequency component; these two components broaden; the sub-harmonic with a frequency of 135 Hz appears and its intensity is about 1/3 of that found for the valve frequency. Thus, it is argued here that the occurrence of the strong low frequency component can be used as an indication of unstable operation of the pulse combustor and proximity to blowout.

To understand the mechanism of how were the harmonic components generated, it is referred to the work for steady flames, such as the studies by Kashinath and Noiray [21, 22]. They found that the interaction between sinusoidal inflow velocity and chemical reaction produces acoustic harmonics. In the present pulse combustor, air flow was injected periodically though the rotating ball. The interaction of the periodic forced air injection and chemical reaction could result in harmonics.

The low frequency spectrum, which could be a result of global/local extinction as approaching blowout, appears and broadens in both ion signal (Fig. 5 (c)) and pressure signal (Fig. 6 (c)). The ion signal based low frequency component takes a stronger part than the pressure signal based low frequency components, as the ion method is more sensitive to the combustion extinction events.

C. Quantification of the stability characteristics

Figure 7 shows the PSD value for the valve frequency as a function of the fuel flow rate for both ion and pressure signals. The PSD value from pressure signals decreases monotonously with decreasing fuel flow rate, while the PSD value from ion signals decreases with fuel flow rate only until 56 g/min, below which no obvious change is seen. Generally, the slope of the curve is steeper for pressure than for ion. This indicates that the combustion heat release has a stronger effect on the global acoustic wave intensity than the local combustion intensity in the near wall region.

Figure 7 PSD value for the valve frequency component as a function of fuel flow rate for ion and pressure signals

In sections III-A and III-B, we observed low frequency combustion oscillation, which is a symptom of near blowout. We now introduce an integrated PSD intensity to quantify the importance of the low frequency combustion oscillation. This integrated PSD is defined as,

$$I_{low} = \int_1^{50} P_F dF \quad (1)$$

For a given frequency of F , P_F is the PSD value. Based on Figs. 5 (c) and 6 (c), the low frequency combustion oscillation in the pulse combustor is mainly in the range of 0 – 50 Hz.

Fig. 8 shows I_{low} as a function of the fuel flow rate for ion and pressure signals. In the range 60 – 70 g/min, the two I_{low} curves do not show significant change. However, I_{low} calculated from pressure signal rapidly increases when the fuel flow rate is decreased from 60 g/min to 42 g/min. This is because of the enhanced low frequency combustion oscillation when approaching blowout. However, I_{low} calculated from ion signal varies non-monotonously below 60 g/min. This suggests that more than one controlling factor is at play. Here, on the one hand, the reduced fuel flow rate results in lower total energy input hence the energy spectra of both the valve frequency component and the low frequency oscillation component decrease. On the other, with reduced fuel flow rate, the system is more likely to produce local/global extinction so that the low frequency oscillation is enhanced. The superimposed effect of these two mechanisms is responsible for the non-monotonous trend in the ion signal I_{low} curve.

Figure 8 Integrated PSD of the low frequency component as a function of fuel flow rate for ion and pressure signals

By following the previous work with passively-valved pulse combustor [8] and with steady flame [23, 24], a PSD ratio is defined to further quantify the low frequency combustion oscillation. The idea of PSD ratio is to measure the power fraction in a specific spectrum range with respect to the whole spectrum map. It is defined as,

$$PR_F = I_F / I_{total} = \int_{F-25}^{F+25} P_F dF / \int_0^{600} P_F dF \quad (2)$$

where the PR_F is a PSD ratio the frequency component in the range $[F - 25, F + 25]$. The power ratio of the low frequency oscillation PR_{low} is calculated by solving Eq. (2) with $F = 25$ Hz and the valve frequency $PR_{valve} = 270$ Hz. According to the definitions, PR_{low} measures the low frequency oscillation intensity and PR_{low} measures the combustion resonance intensity.

Figure 9 shows PR_{low} and PR_{valve} as a function of fuel flow rate for ion and pressure signals. For the ion signal, the PR_{low} increases and PR_{valve} decreases with reducing fuel flow rate. Values of PR_{low} and PR_{valve} become equal at around 58 g/min, below which PR_{low} dominates over PR_{valve} . This indicates that the low frequency combustion oscillation determines combustion dynamics if the fuel flow rate becomes small enough. In such case, the combustion resonance is weakly sustained.

However, Fig. 9 (b) shows that, for the pressure signal, the valve frequency component dominates over the low frequency component for any fuel flow rate. This proves that the combustion resonance - although very weakly - survives even near blowout.

Figure 9 PSD ratios of low frequency combustion oscillation (PR_{low}) and valve frequency (PR_{valve}) for: (a) ion signal, (b) pressure signal

D. Conclusion remarks

The present work investigated the stability characteristics of an actively-valved pulse combustor using ion and pressure probes. By gradually reducing fuel flow rate to near blow-out condition, a systematic study was performed. The study concludes that,

1. The ion probe detects local combustion events, while the pressure sensor measures global acoustic wave.

2. Harmonics, which were not seen in the passively valve pulse combustor, were found in the present actively-valved pulse combustor.
3. Similar to steady flames, the low frequency combustion oscillation appears near blowout.
4. Resonant combustion operation survives near blowout.
5. Following previous studies with steady flames and passively-valved pulse combustors, the integrated PSD ratio was introduced to evaluate the low frequency oscillation intensity.

Acknowledgments

The research reported in this publication was supported by funding from King Abdullah University of Science and Technology (KAUST), under award number BAS/1/1370-01-01.

References

- [1] A.A. Putnam, F.E. Belles, J.A.C. Kentfield, Pulse combustion, *Progress in Energy Combustion Science* 12 (1986) 43-79.
- [2] X. Meng, W. de Jong, T. Kudra, A state-of-the-art review of pulse combustion: Principles, modeling, applications and R&D issues, *Renewable Sustainable Energy Reviews* 55 (2016) 73-114.
- [3] G.D. Roy, S.M. Frolov, A.A. Borisov, D.W. Netzer, Pulse detonation propulsion: challenges, current status, and future perspective, *Progress in Energy Combustion Science* 30 (2004) 545-672.
- [4] Y. Xu, M. Zhai, L. Guo, P. Dong, J. Chen, Z. Wang, Characteristics of the pulsating flow and heat transfer in an elbow tailpipe of a self-excited Helmholtz pulse combustor, *Applied Thermal Engineering* 108 (2016) 567-580.
- [5] J.H. Lee, B. Dhar, W. Soedel, A mathematical model of low amplitude pulse combustion systems using a Helmholtz resonator-type approach, *Journal of Sound Vibration* 98 (1985) 379-401.
- [6] F.W. Ahrens, C. Kim, S.-W. Tam, Analysis of the pulse combustion burner, *ASHRAE Transactions* 84 (1978).
- [7] B. Dhar, H.C.G. Huang, J.H. Lee, W. Soedel, R.J. Schoenhals. Dynamic and thermal characteristics of a pulse-combustion gas-fired water heater. In: editor^editors. *Proc. Symposium on Pulse-Combustion Applications*; 1982. p. 4-1.
- [8] F. Li, L. Xu, M. Du, L. Yang, Z. Cao, Ion current sensing-based lean blowout detection for a pulse combustor, *Combustion and Flame* 176 (2017) 263-271.
- [9] T. Yi, E. Gutmark, Real-time prediction of incipient lean blowout in gas turbine combustors, *AIAA Journal* 45 (2007) 1734-1739.
- [10] J.C. Lisanti, W.L. Roberts. Design of an actively valved and acoustically resonant pulse combustor for pressure-gain combustion applications. In: editor^editors. *54th AIAA Aerospace Sciences Meeting*; 2016. p. 0899.
- [11] J.C. Lisanti, X. Zhu, W.L. Roberts. Improving the Performance of an Active Valve Resonant Pulse Combustor. In: editor^editors. *AIAA Propulsion and Energy 2019 Forum*; 2019. p. 3871.
- [12] X. Zhu, J.C. Lisanti, W.L. Roberts. Performance of an Actively Valved and Acoustically Resonant Pulse Combustor with Liquid Gasoline Fuel. In: editor^editors. *AIAA Scitech 2020 Forum*; 2020. p. 0922.
- [13] L.B.W. Peerlings, V.N. Kornilov, P. de Goey, Flame ion generation rate as a measure of the flame thermo-acoustic response, *Combustion and Flame* 160 (2013) 2490-2496.
- [14] A.B. Fialkov, Investigations on ions in flames, *Progress in Energy and Combustion Science* 23 (1997) 399-528.
- [15] F. Li, L. Xu, Z. Cao, M. Du. A chemi-ionization processing approach for characterizing flame flickering behavior. In: *2015 IEEE International Instrumentation and Measurement Technology Conference (I2MTC) Proceedings*; 2015: IEEE. p. 325-329.
- [16] B.F.W. Vermeltfoort, N.J. Dam, A.J.M. Pemen, L.P.H. de Goey. Experimental investigation of plasma assisted combustion using a low-swirl burner. In: *6 th International Workshop and Exhibition on Plasma Assisted Combustion (IWEPAC)*; 2010. p. 40.
- [17] T.C. Williams, G.K. Hargrave, C.P. Garner, V.I. Hanby, Inlet mixing and NO_x formation in a helmholtz pulse combustor, *Proceedings of the Combustion Institute* 28 (2020) 1289–1295.
- [18] T.C. Williams, Combustion , NO_x formation and mixing processes in Helmholtz pulse combustors, Loughborough University, 2000.

- [19] T. Geng, A. Kiker Jr., R. Ordon, A. V. Kuznetsov, T. F. Zeng, W. L. Roberts, Combined Numerical and Experimental Investigation of a Hobby-Scale Pulsejet, *Journal of Propulsion and Power* 23 (2007) 186-193.
- [20] T. Muruganandam, S. Nair, D. Scarborough, Y. Neumeier, J. Jagoda, T. Lieuwen, J. Seitzman, B. Zinn, Active control of lean blowout for turbine engine combustors, *Journal of Propulsion Power* 21 (2005) 807-814.
- [21] K. Kashinath, M.P. Juniper, S. Hemchandra. Nonlinear phenomena in thermoacoustics: a comparison between single-mode and multi-mode methods. In: editor^editors. *Proceedings of the 19th International Conference on Sound and Vibration*; 2012. p.
- [22] N. Noiray, D. Durox, T. Schuller, S. Candel, A unified framework for nonlinear combustion instability analysis based on the flame describing function, *Journal of Fluid Mechanics* 615 (2008) 139-167.
- [23] H. Li, X. Zhou, J.B. Jeffries, R.K. Hanson, Sensing and control of combustion instabilities in swirl-stabilized combustors using diode-laser absorption, *AIAA journal* 45 (2007) 390-398.
- [24] H. Li, X. Zhou, J.B. Jeffries, R.K. Hanson, Active control of lean blowout in a swirl-stabilized combustor using a tunable diode laser, *Proceedings of the Combustion Institute* 31 (2007) 3215-3223.