An Attempt for Establishing Continuous Detonation in a Linearized Combustor by Directly Injecting Liquid Jet A1

Huang Xin, Chang Po-Hsiung, Teo Zhen Wei, Li Jiun-Ming, Teo Chiang Juay,
Khoo Boo Cheong
National University of Singapore
21 Lower Kent Ridge Road, Singapore, 119077

1 Introduction, Recap and Motivation

Detonation combustion shows higher thermodynamic efficiency than conventional deflagration combustion, which attracts researchers to develop detonation-based energy conversion devices for future applications. However, the detonation combustion requires more stringent conditions to be produced and shows more complex physical phenomena, indicating that it remains to be challenging for the use of detonation combustion. There are mainly two types of detonation combustion devices, namely pulsed detonation device and continuous detonation device. Compared to the pulsed detonation device, the continuous detonation device shows advantages in compactness, power density, and operation frequency, which cause growing interest in studying continuous detonation. A plethora of studies have evidenced that continuous detonation can be established and sustained in various conventional combustor geometries, such as, annular, disk-shaped and hollow. Despite the feasibility of continuous detonation in different geometries, the continuous detonation shows complexities with regard to the multiplicity of detonation wave mode, the detonation wave dynamics differing from the Chapman–Jouguet (CJ) detonation, and the three-dimensional wave propagation structures accompanying the secondary wave. There is still a lack of understanding regarding these phenomena. Recent studies [1, 2] have evidenced that the continuous detonation can be also produced in linearized combustors, showing that waves shuttle transversely to the reactant injection direction repeatedly. Compared to the conventional geometries, the linearized combustor is a simplified geometry due to the absence of wall curvature. This makes the detonation waves propagate in a more two-dimensional environment, and hence, shows fundamental significance for the study of continuous detonation.

From an application point of view, liquid fuels are easy to store and carry, making liquid fuels superior to gaseous fuels for practical applications. However, liquid fuels are harder to burn than gaseous fuels, because a liquid fuel vaporization process is required before starting the combustion. For establishing continuous detonation by using liquid fuels, a short time scale for the liquid fuel vaporization relative to the detonation wave propagation time scale is essential. There are two general approaches for promoting the liquid fuel vaporization, which are liquid fuel pre-vaporization and liquid fuel atomization. Figure 1 shows an experiment conducted by using a mixture of Jet A1 vapour, heated air and oxygen (equivalent to oxygen mass flow rate $m_{O2} = 9.8$ g/s, equivalence ratio $\phi = 1.1$, and volume fraction $Q_{N2}/Q_{O2} = 0.73$) in the same linearized combustor as Ref. [2] (continuous detonation waves were successfully

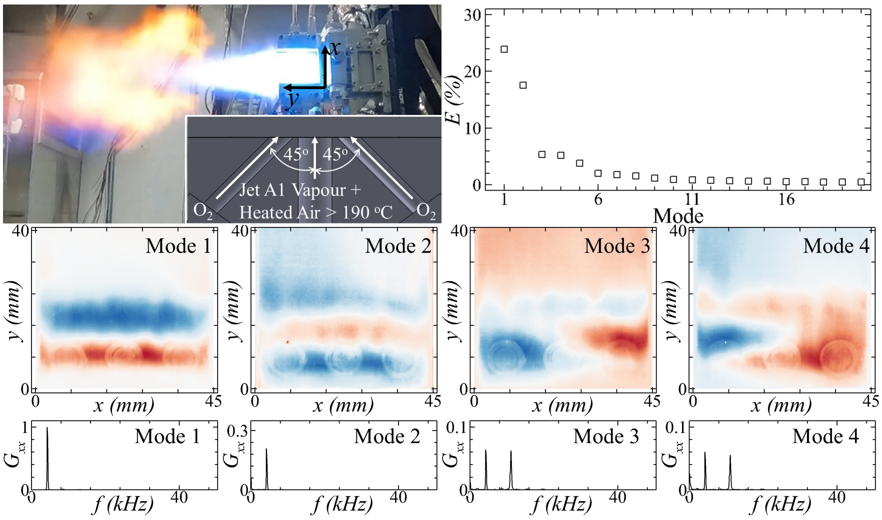

Figure 1: An experiment conducted in a linearized channel combustor with a mixture of Jet A1 vapour, heated air and oxygen. Four major modes have been found through a POD analysis of the flame luminosity images.

established by ethylene and oxygen in Ref. [2]). The linear channel width of this combustor can be varied and was changed to 11.0 mm for this experiment. The air was heated to $> 190°$C (monitored via a thermocouple on the combustor wall) through an electric air heater to fully pre-vaporize the Jet A1 before the air-Jet A1 mixture entered the combustor. A proper orthogonal decomposition (POD) analysis of the flame luminosity images (100,800 frames per second with a shutter speed of 1.25 μs) has been conducted. The first four dominant POD modes and the power spectral densities of their time coefficients are shown in Figure 1. The results indicate the coexistence of a longitudinal pulsed wave component with a characteristic frequency of 4.23 kHz and a shuttling transverse wave component with a characteristic frequency of 11.12 kHz (the wave speed was 1000.8 m/s considering that the combustor length was 45.0 mm). The emergence of the shuttling transverse wave component implies that it is feasible to establish continuous detonation in the linearized combustor by using Jet A1, which has long hydrocarbon chains relative to gaseous fuels.

If no heat source upstream of the combustor is available or there is a space requirement, the liquid fuel pre-vaporization method would not be applicable and the liquid fuel atomization would be the only approach. The liquid fuel needs to be well atomized to small droplets for accelerating the vaporization process accomplished by the combustion heat. Compared to the pre-vaporization approach, the atomization approach would bring about the benefit in compactness as no pre-heat device is required. However, it would be more challenging to establish continuous detonation, considering that a short time scale is necessary for completing the combustion process (including the liquid fuel vaporization), which supports the corresponding detonation wave propagation. In this study, a triplet impinging configuration was evaluated and used for atomizing unheated Jet A1. The Jet A1 was directly injected into a linearized combustor in an attempt to establish continuous detonation. Details about the experimental arrangements and the experimental results are presented below.

2 Water Spray Tests and Combustor Design

A triplet impinging configuration was used for injecting reactants into the linearized combustor in the current study. The atomization performance of the triplet impinging configuration was systematically evaluated through water spray tests (due to safety reason, water and air were used here, not Jet A1 and oxygen), as shown in Figure 2. Two micro-dispense nozzles with an orifice inner diameter of 0.005" (0.127 mm) were employed for injecting water. This type of nozzle had a tiny orifice, and thus, relatively low driving pressure was needed for getting small droplets compared to the commercial liquid fuel injectors. However, a 0.5 μm filter had to be assembled in the pipeline to prevent orifice blockage caused by any impurities. The air was injected through a hole with a diameter of 1.0 mm, which was in the middle of the triplet impinging configuration. The two water jets were aligned to be symmetric about the air jet during the experiments. The impinging point was 5.0 mm away from the nozzle heads for this set-up. The impinging angle, θ, could be adjusted from 20° to 70°. Mie scattering was employed for measuring the droplet size and performed by a Spraytec machine. This machine had a 632.8 nm helium-neon laser with a power of 5 mW, which emitted a laser beam with a diameter of ∼2 cm. The scattering laser light pattern was captured by a 36-element log-spaced silicon diode detector array in a laser receiver. Mie theory indicates that the scattering laser light pattern is dependent on the size of the droplets, with small/large droplets scattering laser light with low/high intensities to wide/narrow angles. By assembling a lens with a focal length of 300 mm in the laser receiver, droplets with diameters ranging from 0.1 μm to 900 μm (volume equivalent droplets) could be detected. Continuous capturing mode was used with a sampling rate of 1 Hz. The measurement duration was at least 15 seconds for each testing case. The droplets at four different locations away from the impinging point were measured, as indicated in Figure 2, and the droplet size distributions were obtained. For the case in Figure 2, it can be found that there were large droplets (>200 μm) at H4, H3 and H2, indicating that there were still large water ligaments, which did not break up into small droplets. The portion of large droplets gradually became fewer as the measurement location went away from the impinging point, and no large droplets were detected at H1.

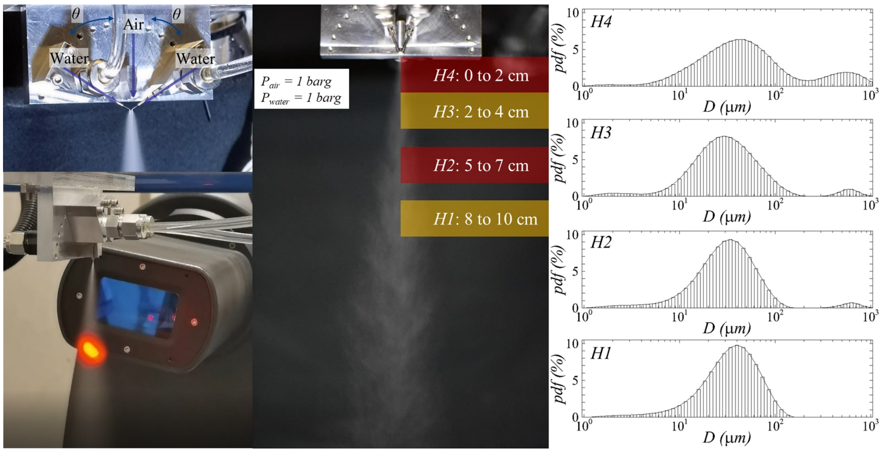

Figure 2: The experimental setup of the triplet impinging configuration for liquid atomization and the liquid droplet size measurements by using Mie scattering.

Sauter mean diameter, D_{32}, is a statistical quantity for evaluating the liquid atomization, which stands for the diameter of a sphere that has the same volume/surface area ratio as a group of droplets of interest (equienergetic, surface energy). D_{32} can be calculated from the droplet size distribution, and the D_{32} results at H3 (similar to the combustion region inside the combustor) for different testing conditions are shown in Figure 3. It can be found that there are missing results marked with 0 for six cases. The missing results were caused by the measurement failure of the Spraytec machine. This was possibly due to the water jets not breaking up into droplets, resulting in either low laser light transmittance or large volume equivalent spheres out of the measuring range. The results show that D_{32} significantly dropped when the air injection pressure, P_{air}, increased from 1 barg to 2 barg for all three impinging angles. When P_{air} was larger than 1 barg, the observed trend indicates that smaller D_{32} could be produced with

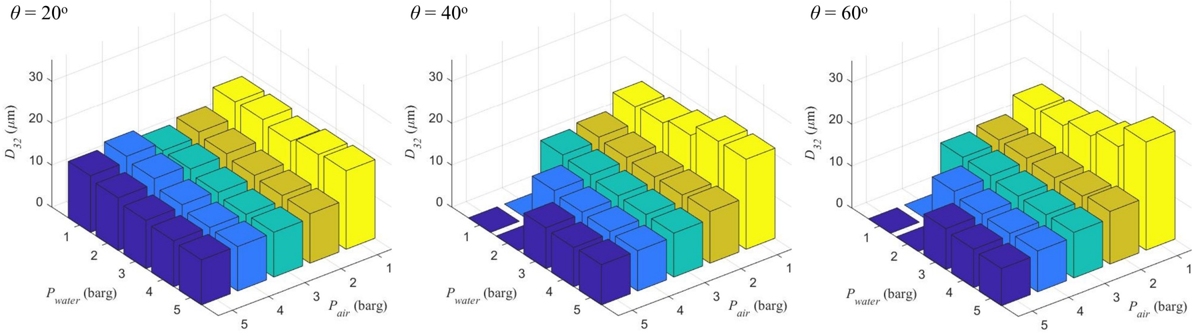

Figure 3: D_{32} measurement results of the water spray tests at H3.

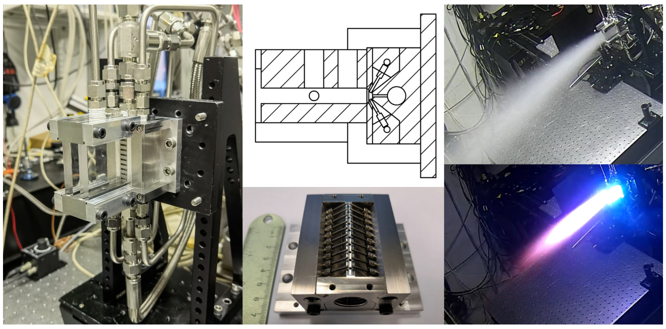

Figure 4: A linearized channel combustor with liquid fuel injected directly through dispensing nozzles, and two photos showing an oxygen-Jet A1 injection test and a combustion test, respectively.

larger θ, larger P_{air}, and larger water driving pressure, P_{water}. The smallest D_{32} of 8.88 μm in Figure 3 was produced when P_{air} = 5 barg, P_{water} = 5 barg, and θ = 60°.

The D_{32} results of water spray tests were used as a reference for the combustor design. A linearized channel combustor with an array of ten triplet impinging configurations for injecting Jet A1 and oxygen was fabricated, as shown in Figure 4. The combustor had a length of 45.0 mm, a height of 55.0 mm and a width of 8.0 mm. Ten triplet impinging configurations were arranged equidistantly along the combustor with a spacing of 4.5 mm. The impinging angle between Jet A1 jet and oxygen jet was 60° for achieving a good Jet A1 atomization performance. The diameter of the holes for injecting oxygen was slightly enlarged to 1.1 mm in comparison to the air injection holes in the water spray tests. Since the surface tension of Jet A1 (25.5 mN/m at room temperature) is significantly smaller than water (72.0 mN/m at room temperature), the D_{32} of Jet A1 in the combustor was estimated to be around or within the magnitude of 10 μm for the oxygen mass flow rate of $\sim$10.0 g/s at the stoichiometric condition based on the water spray test with similar impinging momentum. The Jet A1-oxygen mixture was ignited via an oxygen-ethylene pre-detonator. Two combustor side walls were made to be transparent. A Photron SAZ high-speed camera was employed to record the flame luminosity with 100,800 frames per second and a shutter speed of 1.00 μs. The experimental results are discussed in the next section.

3 Experimental Results and Discussions

The experiments were carried out with $m_{O2} = \sim$10 g/s from fuel-lean to fuel-rich. Similar phenomenon was observed for all these experiments. A representative case (m_{O2} = 10.3 g/s, m_f = 4.0 g/s, and ϕ = 1.4) was chosen to describe the experimental phenomenon, as shown in Figure 5. During the experiment, two pressure sensors were used to measure the Jet A1 driving pressure, ΔP_f (equivalent to

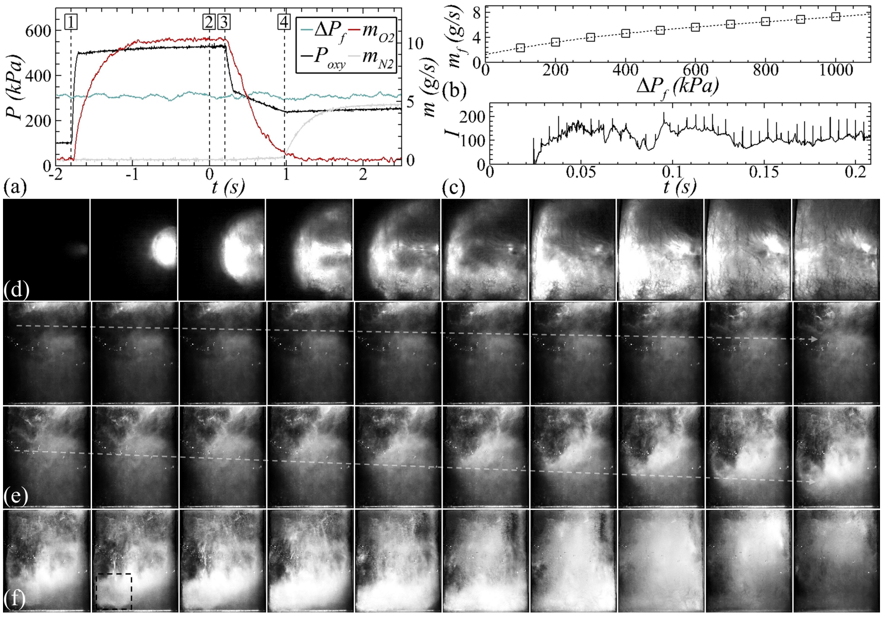

Figure 5: (a) Testing conditions. (b) The relation between the Jet A1 mass flow rate and the Jet A1 driving pressure. (c) Spatially averaged flame luminosity trace. (d) Successive frames with a time interval, Δt, of 19.8 μs showing a combustion wave coming out from the pre-detonator outlet. (e) Successive frames with Δt of 19.8 μs showing a flame structure penetrating into the combustor. (f) Successive frames with Δt of 9.9 μs showing a violent detonation.

gauge pressure, because the downstream pressure was 1 atm), and the oxygen plenum pressure, P_{oxy}, respectively. Oxygen and Jet A1 were injected (time point 1 in Figure 5(a)) 1.8 s before the spark ignition of the pre-detonator (time point 2) and the total injection time was 2.0 s. Therefore, the testing duration (between time points 2 and 3) was 0.2 s. After the experiment, nitrogen was injected (time point 4) into the oxygen plenum (combustor) to extinguish the remaining fire and ensure the safety. Two Alicat gas flow meters were used to monitor the oxygen and nitrogen mass flow rates, m_{O2} and m_{N2}, respectively. The Jet A1 mass flow rate, m_f, can be found by using ΔP_f from the data provided by the nozzle manufacturer (The Lee Company). Figure 5(b) shows the relation between m_f and ΔP_f for the 20 nozzles used in the combustor. The spatially averaged (in the region within 11.3 mm from the base plate of the combustor) flame luminosity trace shown in Figure 5(c) indicates that it took $\sim$23 ms to develop a detonation wave in the pre-detonator and send the wave to the combustor. The initial wave coming out from the pre-detonator is shown in Figure 5(d). No continuously propagating wave was established after this initial wave, but violent spontaneous detonations were frequently observed in the testing duration, which caused spikes in the flame luminosity trace in Figure 5(c). The development of the violent detonation is shown in Figures 5(e) and 5(f). The images show that a flame structure emerged near the combustor outlet and then gradually penetrated into the combustor, as indicated by the white dashed lines in Figure 5(e). When the flame structure reached the reactant injection region (black dashed box in Figure 5(f)), a violent detonation was triggered and immediately produced a transient fast propagating wave. The whole process is analogous to the deflagration to detonation transition. However, this detonation wave could not be sustained and quickly disappeared, as shown in the last frame of Figure 5(f). Interestingly, this phenomenon has also been observed in gaseous fuel experiments under fuel-ultra-rich conditions ($\phi > 1.7$). Figure 6 shows the experimental results of an ethylene-oxygen experiment ($m_{O2} = 9.8$ g/s and ϕ = 1.9) conducted in the combustor of Ref. [2] (Figure 1). The combustor channel width was also 8.0 mm for this case. Figure 6(a) shows a process of flame penetrating back and then transiting to detonation observed during this experiment. Figure 6(b) shows the wall pressure traces

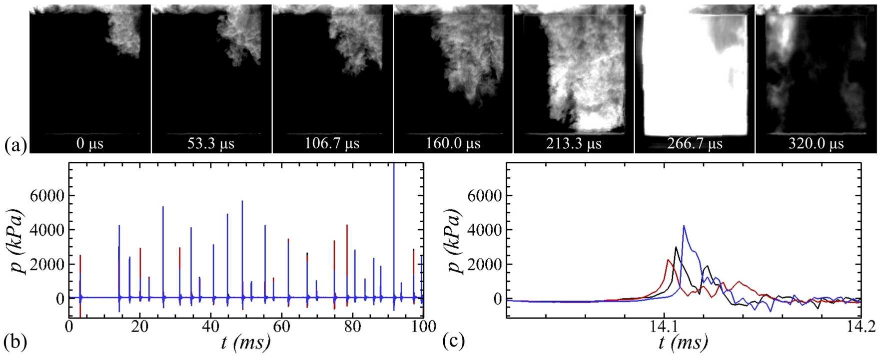

Figure 6: Experimental results for an ethylene-oxygen combustion test: (a) flame luminosity images, (b) wave pressure traces in the testing duration, and (c) wave pressure traces during a violent detonation.

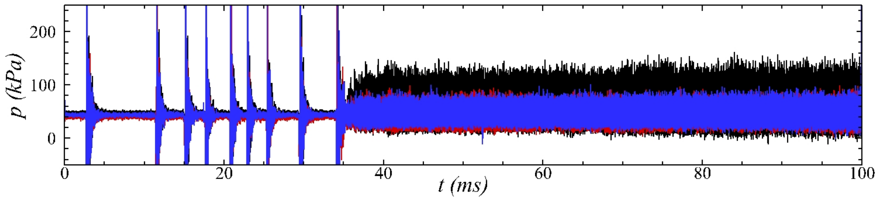

Figure 7: The establishment of double shuttling transverse wave mode after a violent detonation at ∼35 ms.

measured by three PCB 113B24 sensors, indicating that the violent detonation causing high pressure peaks frequently emerged throughout the 0.1 s testing duration. Figure 6(c) shows the pressure traces for the violent detonation happened at ∼14.1 ms, which indicates that the transient wave velocity was 3924.1 m/s (sensor spacing / time difference between pressure peaks). This is about 1.5 times of CJ detonation velocity, and hence, this transient detonation is overdriven detonation. Different from the current Jet A1-oxygen experiments, continuous shuttling transverse detonation waves sometimes could be established immediately after a violent detonation, as shown in Figure 7 ($m_{O2} = 9.6$ g/s and ϕ = 1.8). Since the frequent violent detonation phenomenon was only observed in fuel-ultra-rich ethylene-oxygen experiments, the reactant mixing quality was suspected to be poor for these experiments due to the improper equivalence ratio or the large pressure difference between the fuel and oxidizer injections. Specifically, a relatively long time scale was used for mixing the fuel and the oxidizer prior to the combustion. For the current Jet A1-oxygen experiments, the frequent violent detonation phenomenon is possibly also related to the long fuel-oxidizer mixing time scale caused by the long Jet A1 vaporization time scale. This long Jet A1 vaporization time scale would result in the failure of the establishment of the continuous detonation in the linearized combustor. The experimental results suggest that smaller Jet A1 droplets (d^2-Law) than the current study are required in future studies in order to sustain the continuously propagating detonation waves successfully.

References

[1] Taguchi, T, Yamaguchi, M, Matsuoka, K, Kawasaki, A, Watanabe, H, Itouyama, N, Kasahara, J, Matsuo, A. (2022). Investigation of reflective shuttling detonation cycle by schlieren and chemiluminescence photography. Combustion and Flame. 236: 111826.

[2] Huang, X, Chang, PH, Li, JM, Ngiam, HK, Shan, R, Teo, CJ, Khoo, BC. (2022). A continuous detonation phenomenon: shuttling transverse combustion. AIAA Paper. 2022-1457.