Zero Carbon Fuel Operation of a Piston Engine with Transient Pulse Enhanced NH_3/H_2 Combustion

Boxin Zhang, Mariano Rubio, Joseph Abello, Kaitlyn Cambero, Esteban Mace-Carrillo, Fokion Egolfopoulos, and Stephen B. Cronin

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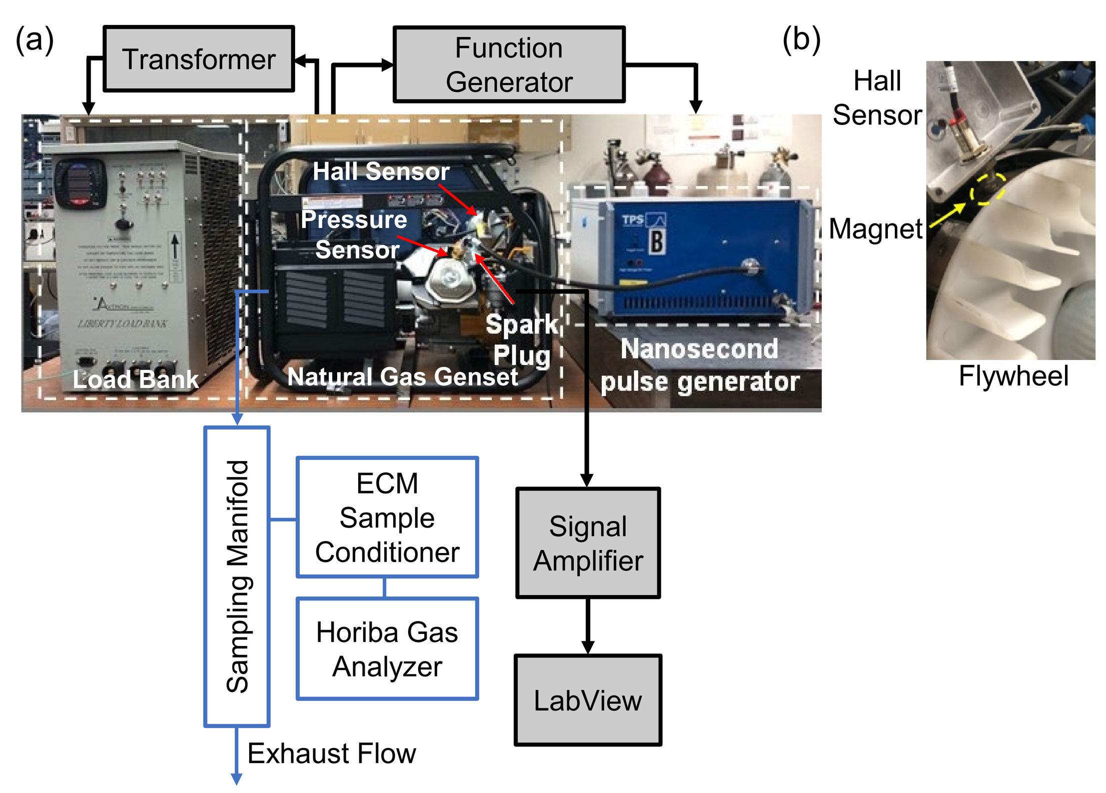
Introduction

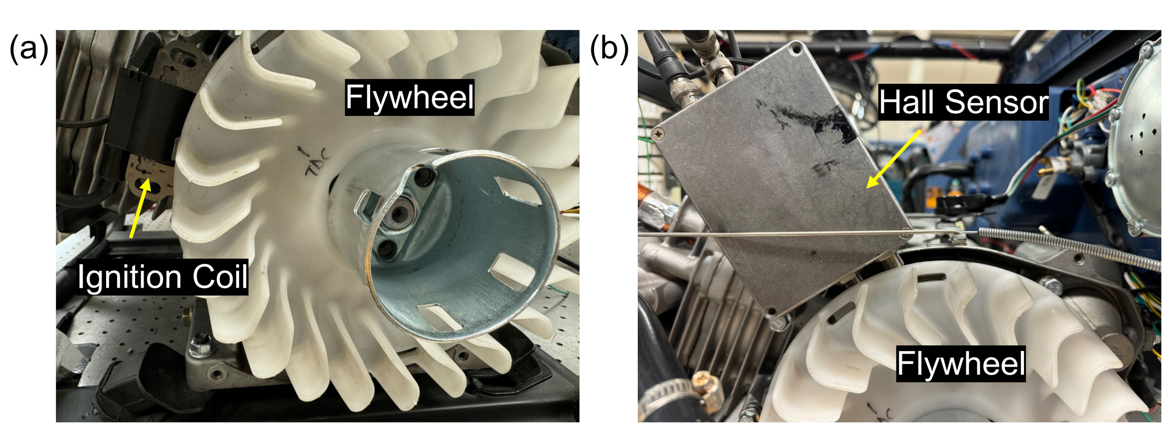
The potential for ammonia combustion piston engines operating to produce zero-carbon emissions are often hindered by the limited energy output capability of traditional spark ignition systems and their single arc discharge characteristics. Enhanced operation of single fuel ammonia (NH_3) engines and dual fuel ammonia and hydrogen (H_2) engines can be realized using transient plasma ignition (i.e. TPI) which supports stable engine operation while at the same time increasing the power output of the engine. An increase in engine output of 28% was realized using TPI with the dual fuel of NH_3 and H_2. The transient plasma-based enhancement arises from hydrodynamic effects, (i.e., ionic winds), which gives rise to turbulence and multi-scale mixing. This is supported by Schlieren imaging, which shows an augmented flame surface area and reduced ignition delays with TPI compared to that of conventional spark ignition (i.e., CSI) while combusting a 30% H_2 and 70% NH_3 fuel mixture. It was also found that CSI was unable sustain stable engine operation when operating with only NH_3 which relates to the inability of CSI to generate radicals prior to ignition occurring. By delaying the ignition timing to compensate for the change in flame speed, the engine power output during NH_3 combustion using TPI was found to increase based on the NH_3 flow rate amount.

Experimental Setup

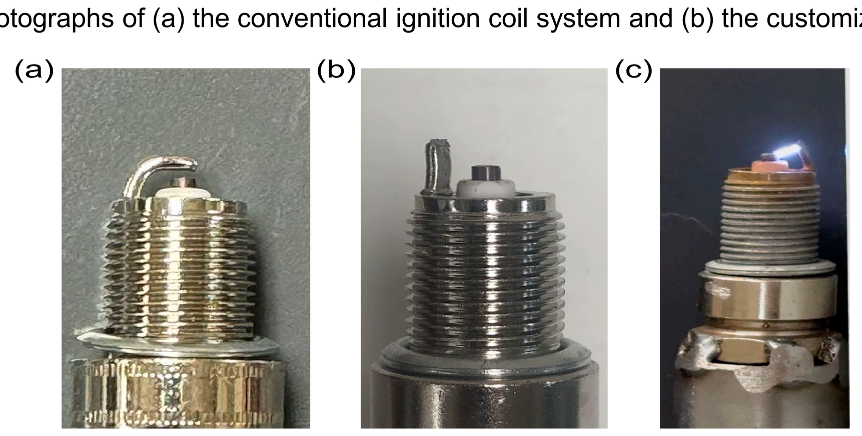


(a) Photograph and schematic diagram of the multi-gas engine test platform with modified nanosecond pulse transient plasma ignition (TPI) system and exhaust gas characterization configuration. (b) Photograph of the customized TPI trigger system.

Customization Details



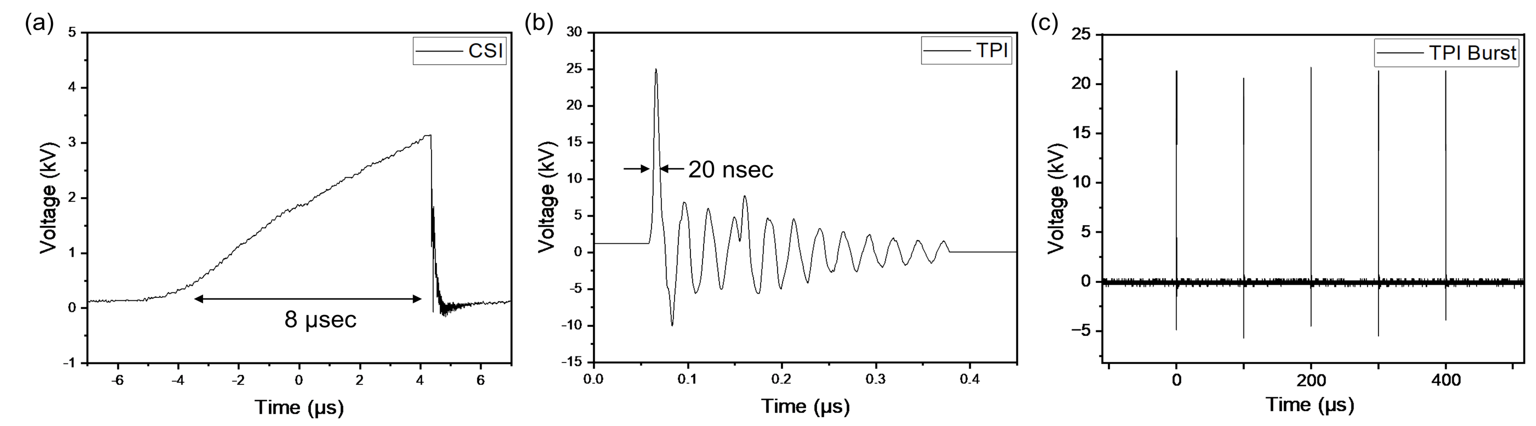
Photographs of (a) the conventional ignition coil system and (b) the customized TPI system.



Photographs of (a) conventional spark plug, (b) customized TPI spark plug with increased spark gap distance, and (c) plasma discharge in the customized spark plug.

- A magnet is fixed on the flywheel and a Hall Sensor is installed above the flywheel to catch the signal from the magnet when the flywheel spins. The signal is used to trigger the function generator which then triggers the pulser to discharge plasma for TPI.
- The flat head of the conventional spark plug is taken off for a larger gap for TPI, which is beneficial for combustion events.

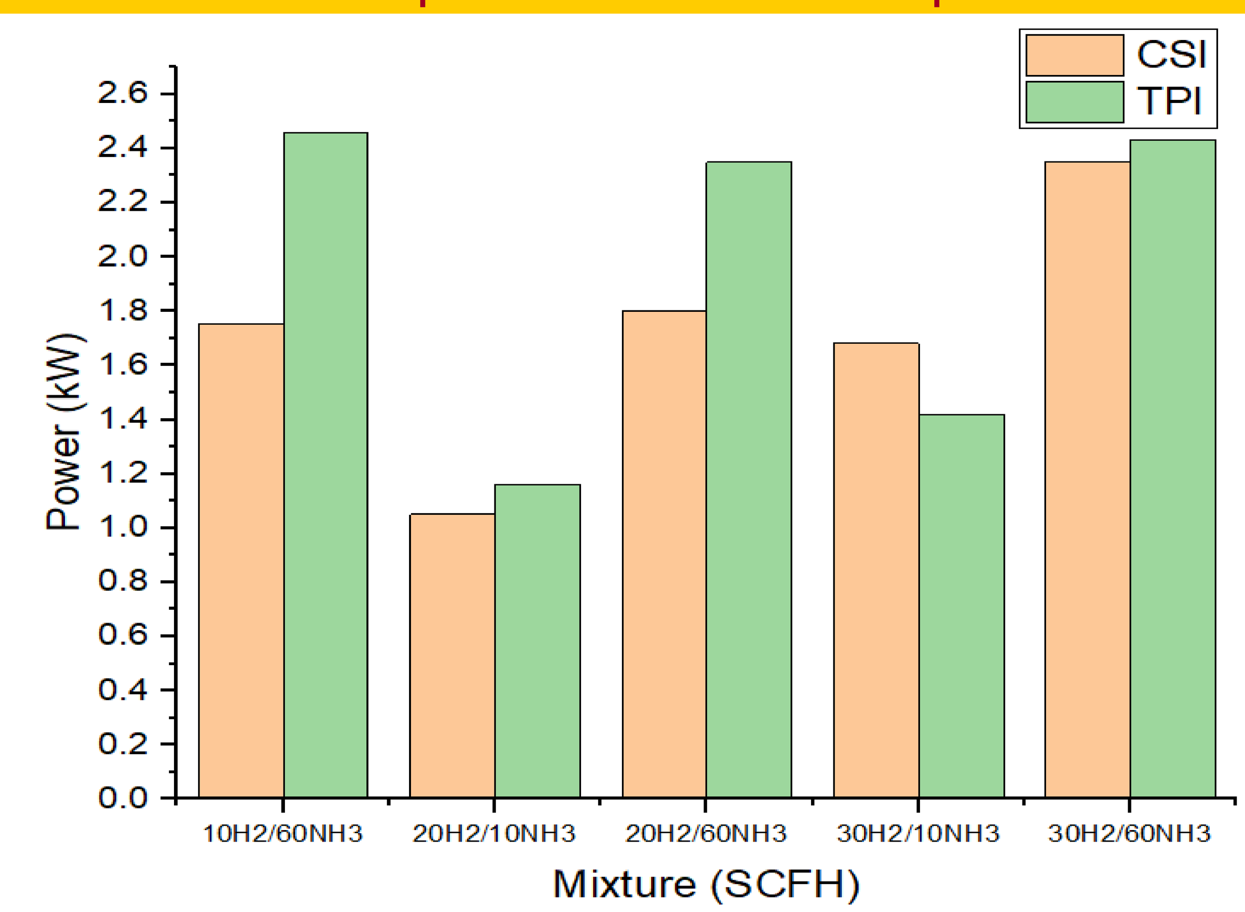
Discharge Characteristics



Voltage waveform plots for (a) conventional spark ignition (CSI) and (b) transient plasma ignition (TPI). (c) Waveform plot for a plasma burst of 5 pulses discharged at 10 kHz.

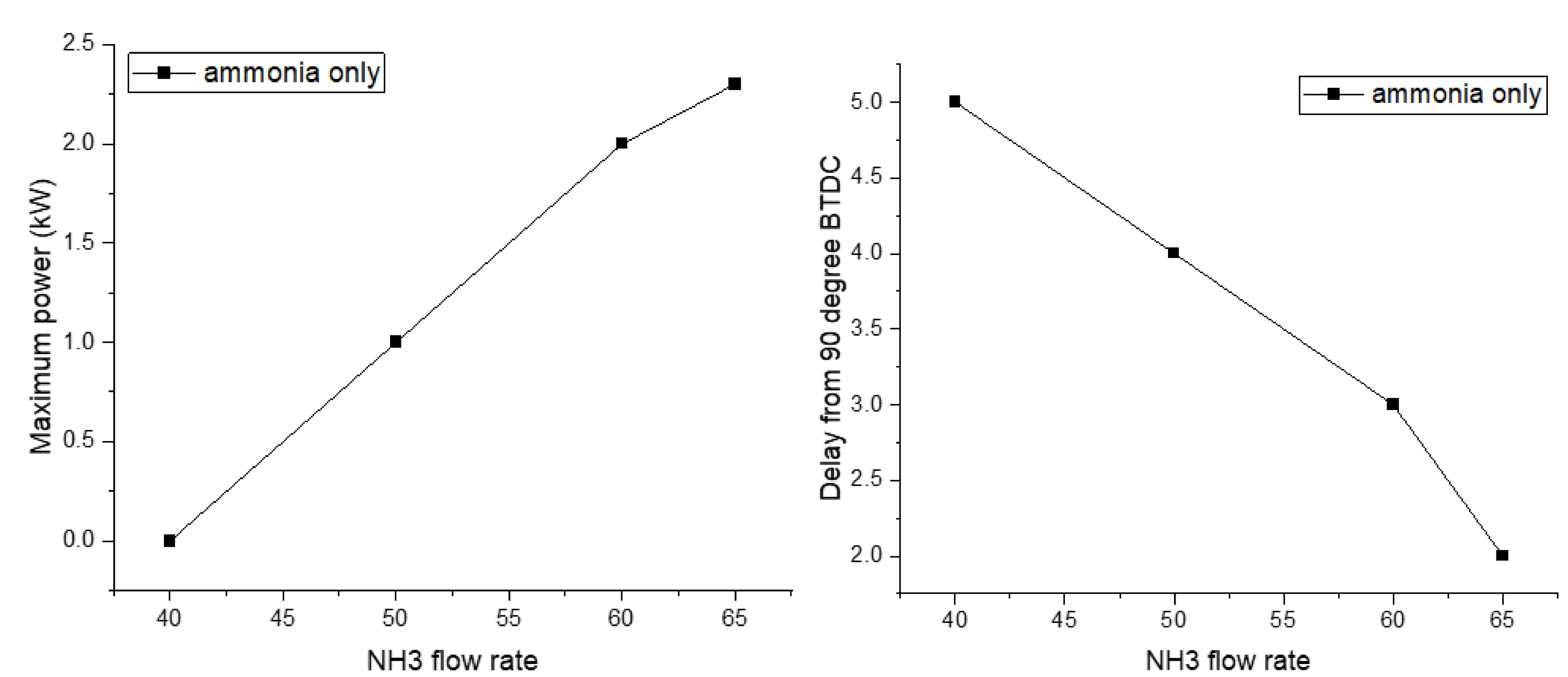
- TPI discharges a burst of 5 pulses in every revolution.
- The CSI delivers 56 mJ in 8 μsec (instantaneous power = 7kW), whereas the TPI discharges 20mJ/20nsec (instantaneous power = 1MW), which corresponds to an enhancement of 142X in instantaneous power.

Multicomponent Mixture Comparison



Power output comparison of dual fuel engine operation with CSI vs TPI at various H2 and NH3 flow rates.

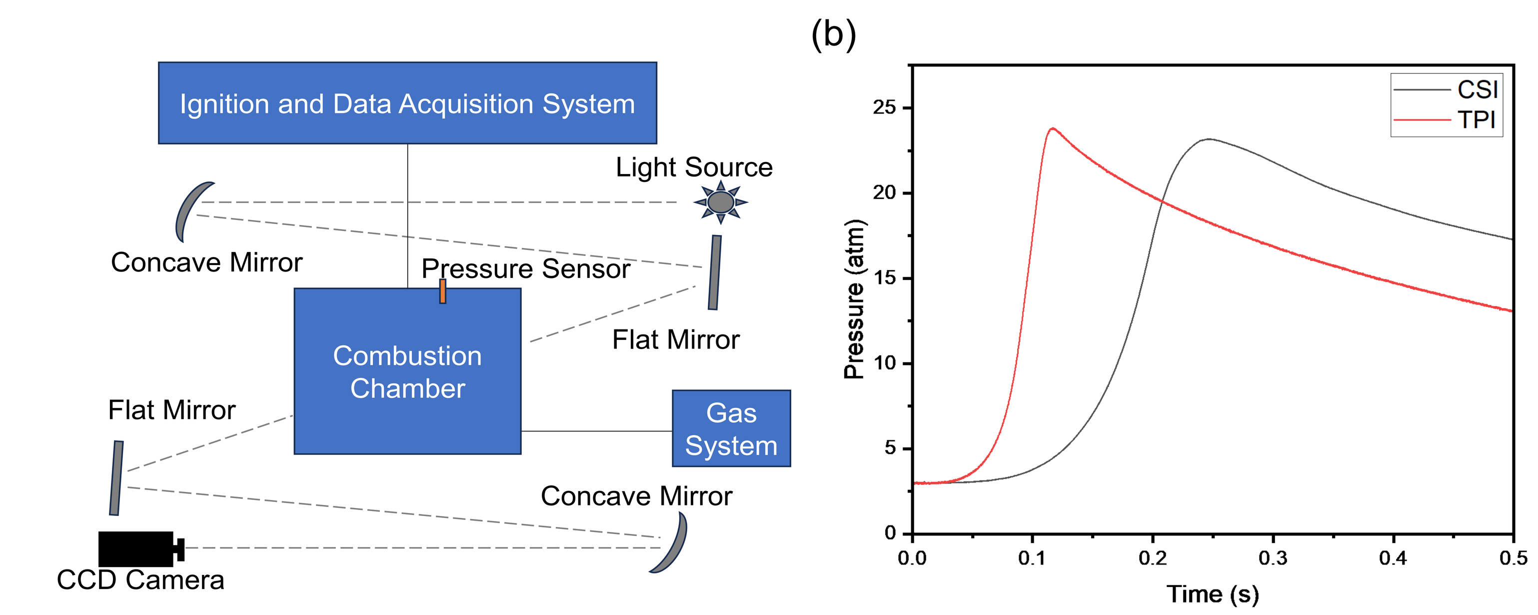
Power Output vs. NH_3 Flow Rate

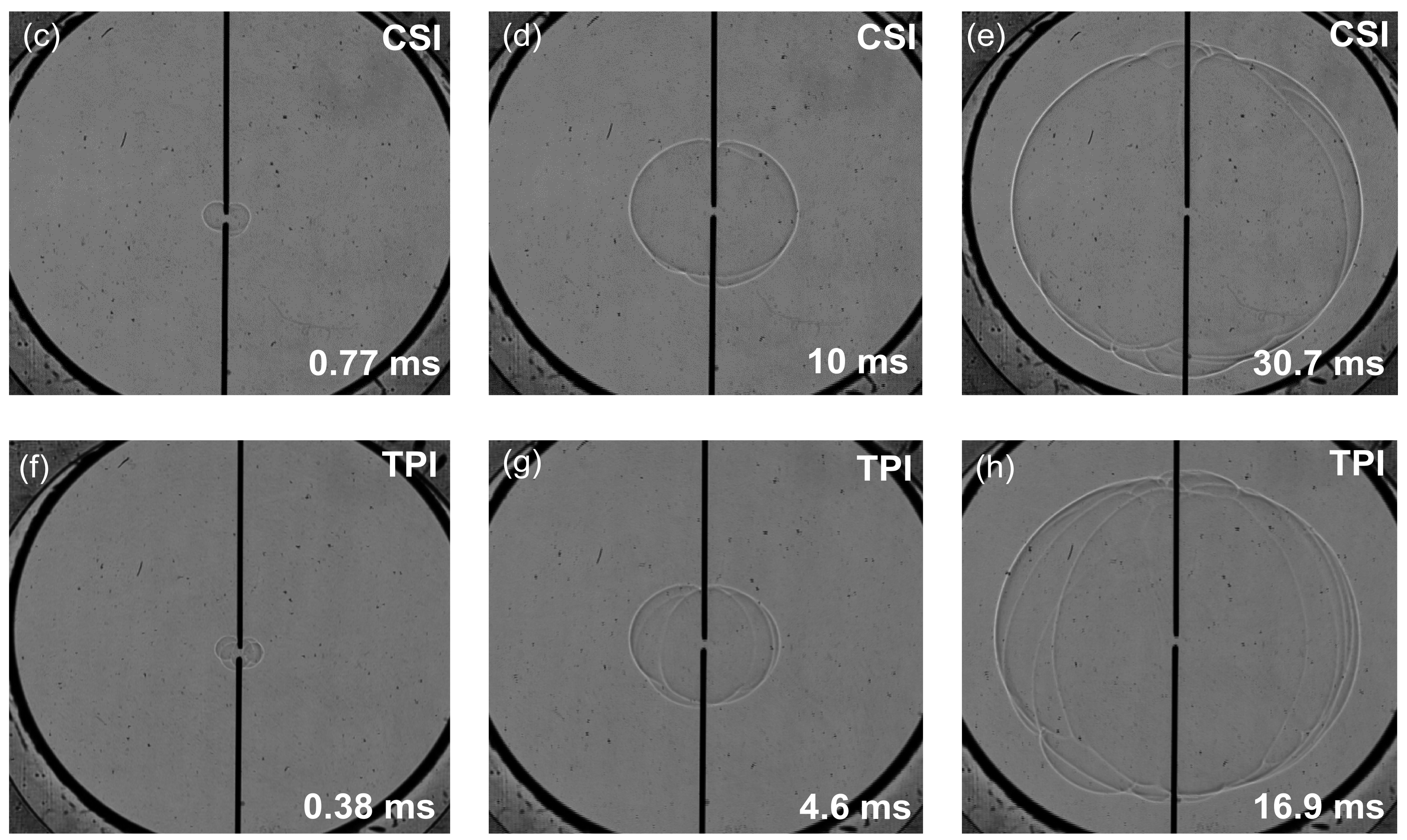


Data concerning maximum power output of the engine using single fuel NH3 single fuel and the ignition timing delay needed to maintain combustion.

- Single fuel NH3 engine operation was sustainable with TPI only with CSI not able to maintain engine output due to lack of radical formation prior to the ignition event.
- A nearly 50% reduction in NO emission was achieved with TPI for $0.5 \le \phi \le 0.6$ under both no load and load conditions.

Pressure Curves & Flame Images





(a) Schematic diagram of the constant volume combustion chamber system. (b) Chamber pressure curves of the combustion events with $\phi = 0.4$ using both CSI and TPI for a 30% hydrogen and 70% ammonia mixture. Screenshots of the high-speed videos of the combustion events at different times with (c-e) CSI and (f-h) TPI.

- The corresponding chamber pressure vs. time curves demonstrate substantially reduced ignition delays and faster pressure rise times (i.e., dP/dt) with TPI compared to that with CSI. This data shows quantitative enhancement in the flame speed and reduction in ignition delay under these ultra-lean conditions.
- The Schlieren imaging provides clear evidence of ionic winds and hydrodynamic effects, which give rise to turbulence and mixing that ultimately result in increased flame surface area and flame stability.
- Flame propagation speed is also noted to be higher with TPI and CSI and due to the cellular characteristics created by the hydrodynamic instabilities, the flame propagation would sustain more stable flames in highly turbulent scenarios, e.g., engine operating conditions.

Conclusions

In conclusion, the enhanced combustion of H_2 and NH_3 in an internal combustion engine with TPI is able to provide higher power output and more stable operation than CSI. We observed a 28% increase in the engine's peak power output during lean H_2 and NH_3 operation. We also observed the ability for TPI to combust single fuel NH_3 in an engine while CSI was unable to maintain stable engine operation. The underlying mechanism of enhancement from the transient plasma is a result of hydrodynamic effects, also referred to as ionic winds, leading to turbulence and multi-scale mixing. Schlieren imaging supports this, revealing an increased flame surface area and enhanced flame stability under ultra-lean conditions when employing TPI. Consequently, this results in significantly reduced ignition delays and faster pressure rise times (i.e., dP/dt) with TPI compared to those observed with CSI. Compensation for the flame speed variation based on NH3 flow rates was also realized utilizing ignition delay strategies at leaner fuel mixtures. These results could have important practical implications over a wide range of engines and combustion systems and can be used as the basis for in-depth fundamental studies in canonical laboratory configurations.

Acknowledgements

This research was supported by the generous donation from the Citrus College Foundation Board member Dr. Martin Gundersen (IEEE member), and the Citrus College Summer Research Experience program (SRE).

References

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