Experimental Investigation of Hydrogen Jet for Direct Injection in ICE

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Abstract

Hydrogen is considered as one of the potential clean fuels because of its zero-carbon nature and it has attracted considerable attention in the automotive industry for transition toward zero-emission. Since the H_2 jet dynamics play a significant role in the fuel/air mixing process of direct injection spark ignition (DISI) engines, the current study focuses on experimental hydrogen jet characterization in terms of mass flow rate measurements and morphology investigation under a wide range of engine-like conditions by a Compressed Hydrogen Gas (CHG) injector used for typical direct injection applications. A measuring system, suitable for the gaseous fuels, was used for measuring the instantaneous flow rate as well the dynamic behavior of the injection system. High-speed z-type schlieren imaging was applied in a constant volume chamber to investigate the evolution and shockwave structures of highly under-expanded H_2 jets.

Introduction

Combustion supplies more than 80% of the global energy used in transportation, power generation, as well as industrial, commercial, and residential heat. As combustion continues to be a significant part of the world energy mix, it must be made sustainable with continued developments of technology and fuels. Advanced combustion technologies offer pathways for greatly reducing carbon emissions in all the major energy sectors. In this contest, the hydrogen (H_2) represents an attractive energy carrier for decarbonizing the transport sector, since it has the potential to address both Greenhouse gas emissions (GHG) and pollutant emission problems [1-6]. Despite the above advantages, the development of H_2-ICEs is still in the conceptual and prototype stage, due to several drawbacks mainly related to the very low density of hydrogen. More, fuel injection equipment, including injectors, high-pressure on-board pumps, cryogenic pumps, and tender couplings are key technology gaps impeding faster penetration of H_2 combustion technologies. The decrease in volumetric efficiency and the onset of abnormal combustion phenomena can be potentially solved by directly injecting H_2 into the cylinder during the compression (at high pressure) or intake (at low-medium pressure) strokes, in the so-called direct injection (DI) engines [7-9]. Due to the possibility of different injection strategies and the variation of in-cylinder back-pressure, the comprehensive knowledge of hydrogen injection spray behavior and characteristics is fundamental for improving the combustion process in DI H_2-ICE. In this contest, the present work aims to deal the hydrogen jet behavior in terms of mass flow rate measurements and morphology investigation under a wide range of engine-like conditions. The spatial and temporal evolution of the H_2 jet was studied by a z-type schlieren optical setup by injecting through a H_2 injector into a constant volume combustion vessel for a wide range of operative conditions.

Experimental Background and Method

The gas was delivered through a hydrogen pintle "outwardly opening" injector equipped with a cap on the nozzle tip. The gas supply system consists of a pressurized tank containing hydrogen connected to the injector via a line which includes the presence of a pressure regulator, a storage tank to reduce the gas pressure oscillations during the injection events, and a pressure sensor to collect the injection pressure just upstream the injector entrance. The injection rate measurements were realized through the Mexus AIR 2.0 device. This shot-to-shot device applies a variant of Zeuch's method to calculate the injection rate of a gas injector. The used device is equipped with two pressure sensors and a thermocouple to measure the pressure and the temperature inside the injection chamber. The two pressure sensors are used to get an accurate and highly resolved absolute pressure inside the chamber: a piezoresistive sensor gives the absolute pressure and the piezoelectric one gives a pressure signal with a high resolution needed for the injection rate calculation. The spatial and temporal H_2 jet characterization was studied injecting hydrogen at room temperature into an optically accessible constant volume combustion vessel (CVCV) controlled in temperature and pressure to replicate the typical thermodynamic engine conditions. Schlieren optical technique, in the classic Z-type configuration, was used to acquire the H_2 jet images for a wide range of engine-like conditions by a high-speed CMOS camera. The desired ambient pressures were realizing by delivering nitrogen inside the vessel. More details of the experimental apparatus can be found in [10]. A customized procedure developed in C# environment with the help of some image-processing libraries was implemented to process the images and ensure adequate enhancement to allow the measurement of the jet macroscopic characteristics. Further details on the adopted image processing procedure were reported in [11, 12].

Results and Discussions

The mass flow rate measurements were carried out for single injection strategies for three different injection pressures (20, 30, and 40 bar) and energizing time (1.25, 2.25, and 3.0 ms) by keeping constant ambient pressure at 3.0 bar.

In Figure 1, the mass flow rate profiles vs time are reported for three investigated injection pressures. For confidentiality reasons agreed with the industrial partner, the trends relating to the mass flow rate measurements are shown in a dimensionless way, not affecting this the complete understanding of the phenomenon with respect to the injection conditions. The area under each profile corresponds to the amount of the hydrogen injected per stroke. The profiles clearly show the injection pressure effect on the total amount of injected fuel, grater is the injection pressure more fuel flows through the nozzle exit. The rise time is function of the injection pressure indicating a prompter answer of the injecting system at highest pressures. More, the injection pressure affects the total duration of the process in the sense that higher pressures result in slightly longer durations.

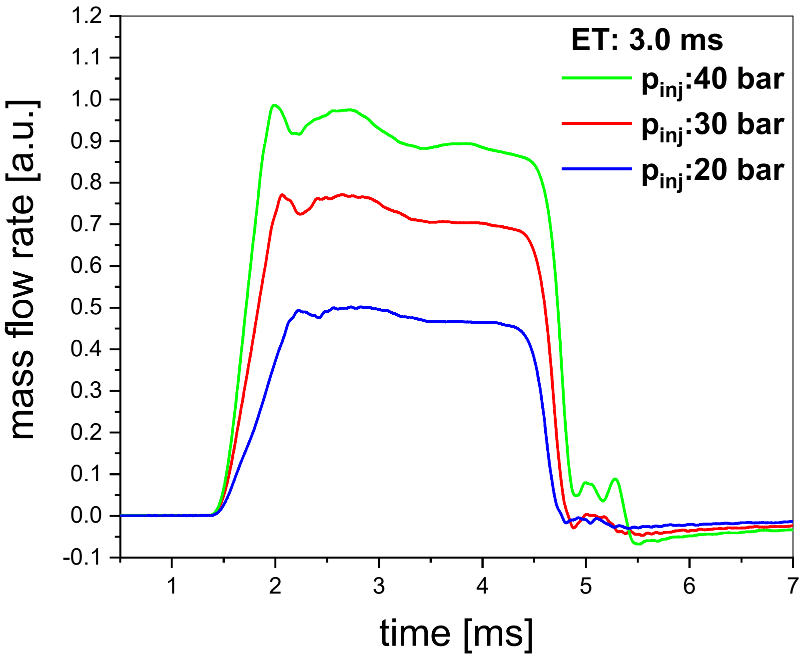

Figure 1 Effect of the injection pressure on mass flow rate profiles

Schlieren visualizations were used to determine the macroscopic jet characteristics of H_2 and its inner structure mainly in terms of gas spread, tip penetrations, and the shockwave formation inside a pressurized vessel. Left side of figure 2 depicts the volume occupied from the injected H_2 in the vessel at the explored ambient pressures of 1.5, 3.0, and 4.5 bar and injection pressures of 20, 30, and 40 bar, at 0.56 ms from the start of injections. N_2 gas was used to realize the desired ambient pressure at ambient temperature of 276 K. Schlieren characterization of hydrogen mixing revealed sensitivity to small flow change. The breaking effect of the gas density is instantly evident on jet morphology resulting in a shorter, larger, and denser jet with increasing of the N_2 pressure, at equal injection pressure. The increase of the injection pressure translates in greater quantities of delivered fuel at higher momentum. More, H_2 jet tends to disperse toward radial direction when p_{inj} is decreased. Jet penetration (right side of figure 2) was measured as the maximum distance in the axial direction between the injector nozzle and the jet tip; the limit of penetration measurements was given by the quartz windows clearance equal to 66 mm. The window optical limit was quickly reached at the lowest backpressure due to the lowest effect of the filling brake in the combustion vessel. All the curves start with a slight concavity upwards, more accentuated at low backpressures, propagating then almost linearly up to the saturation phase. It is interesting to note the drastic change of the jet tip speed by increasing the injection pressure up to 40 bar, with a quasi-linear behavior of the curves up to reaching the window limit.

When a compressible fluid is injected at high pressure into the combustion chamber, choked flow conditions can occur in the exit section of the nozzle (as well inside it), resulting in the formation of shock waves and discontinuities that influence the process mixing in the downstream area. The formation of these under-expanded structures, recognizable by the presence of “barrel shock” in the structure of the jet, depends mainly on the ratio between the pressure upstream of the injector nozzle (p_{inj}) and the pressure inside the cylinder (p_{amb}), defined "net pressure ratio" (NPR) [12, 13]. The jet undergoes an evolution of its structure passing from subsonic to moderately under-expanded up to strongly under-expanded with appearance of Mach disk. In figure 2, the Mach disks at the exit of the nozzle are well evident at the highest NPR meaning a combination of low p_{amb} and high p_{inj}. The height of the Mach disks increased during the initial phases, after that it reached a quasi-stable value with a pronounced and growing trend as the NPR ratio increases.

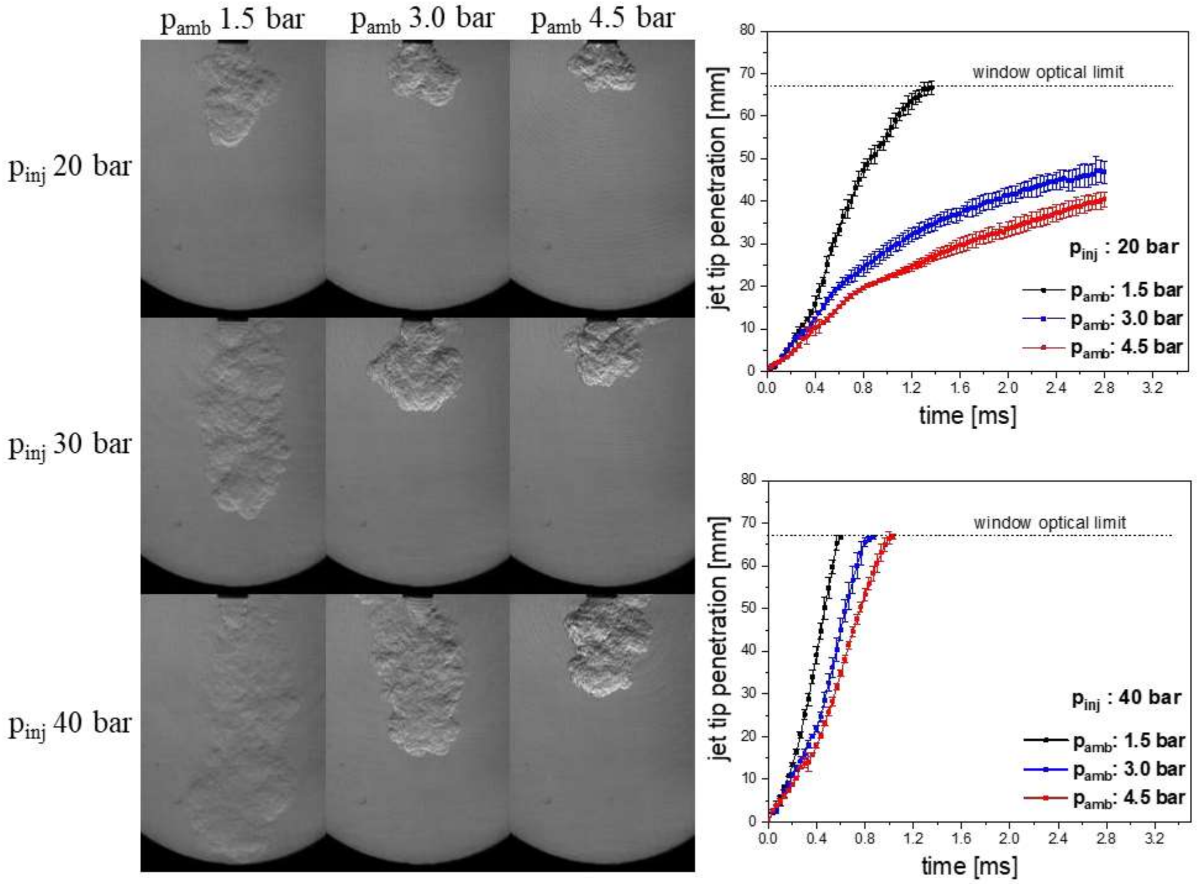

Figure 2 Effects of injection and ambient pressure on H_2 jet morphology and tip penetrations.

Conclusions

In the present study, comprehensive investigations on the hydrogen jet behavior, generated by a Compressed Hydrogen Gas (CHG) injector under different operative conditions, were performed in terms of mass flow rate measurements and morphology investigation. A measuring system, suitable for the gaseous fuels, was used for measuring the instantaneous flow rate while the jet morphology was studied in a constant volume vessel at different back pressures by the cycle-resolved schlieren imaging technique. Mass flow rate measurements showed a high repeatability with a very low RMS of the collected results for all the injection strategies demonstrating a strong stability of the entire injection system as well as accuracy of measurements obtained through the used device. Strong effects of the ambient pressure were carried out on jet evolution resulting in decreasing of both tip penetration and jet area with increasing of the ambient pressure. More, due to the compressibility of the gas, the local density inside the jet increased with increasing of ambient pressure. In conclusion, the illustrated results aim to improve the knowledge of under-expanded jets evolution under a wide range of operative conditions and could be useful to provide a robust data set to develop advanced CFD numerical models.

References

[1] Dilara P., “The future of clean cars in Europe: EU Green Deal and EURO 7”, 4th Sino-EU workshop on New Emissions Standards and Regulations for Motor Vehicles March 3-5, 2021.

[2] Stępień, Z. A Comprehensive Overview of Hydrogen-Fueled Internal Combustion Engines: Achievements and Future Challenges. Energies 2021, 14, 6504, https://doi.org/10.3390/en14206504

[3] Hosseini, S.E.; Butler, B. An overview of development and challenges in hydrogen-powered vehicles. Int. J. Green Energy 2020, 17, 13–37.

[4] Dougherty, W.; Kartha, S.; Rajan, C.; Lazarus, M.; Bailie, A.; Runkle, B.; Fencl, A. Greenhouse gas reduction benefits and costs of a large-scale transition to hydrogen in the USA. Energy Policy 2008, 37, 56–67.

[5] Yip, H.L.; Srna, A.; Chun Yin Yuen, A.; Kook, S.; Taylor, R.A.; Heng Yeoh, G.; Medwell, P.R.; Chan, Q.N. A review of hydrogen direct injection for internal combustion engines: Towards carbon-free combustion. Appl. Sci. 2019, 9, 4842.

[6] Y.H. Teoh, H.G. How, T.D. Le, H.T. Nguyen, D.L. Loo, T. Rashid, et al., “A review on production and implementation of hydrogen as a green fuel in internal combustion engines”, Fuel, 333 (2023), Article 126525.

[7] Mohammadi, A.; Shioji, M.; Nakai, Y.; Ishikura, W.; Tabo, E. Performance and combustion characteristics of a direct injection SI hydrogen engine. Int. J. Hydrogen Energy 2007, 32, 296–304.

[8] Oikawa, M.; Ogasawara, Y.; Kondo, Y.; Sekine, K.; Takagi, Y.; Sato, Y. Optimization of hydrogen jet configuration by single hole nozzle and high

speed laser shadowgraphy in high pressure direct injection hydrogen engines. Int. J. Automot. Eng. 2012, 3, 1–8.

[9] Yip, H.L.; Srna, A.; Yuen, A.C.Y.; Kook, S.; Taylor, R.A.; Yeoh, G.H.; Medwell, P.R.; Chan, Q.N. A Review of Hydrogen Direct Injection for Internal Combustion Engines: Towards Carbon-Free Combustion. Appl. Sci. 2019, 9, 4842. https://doi.org/10.3390/app9224842.

[10] Duronio, F., De Vita, A., Allocca, L., Montanaro, A., Ranieri, S., and Villante, C., “CFD Numerical Reconstruction of the Flash Boiling Gasoline Spray Morphology,” in Conference on Sustainable Mobility, SAE International, sep 2020, https://doi.org/10.4271/2020-24-0010.

[11] Montanaro, A., Allocca, L., De Vita, A., Ranieri, S. et al., "Experimental and Numerical Characterization of High-Pressure Methane Jets for Direct Injection in Internal Combustion Engines," SAE Technical Paper 2020-01-2124, 2020, https://doi.org/10.4271/2020-01-2124.

[12] Allocca, L., Montanaro, A., Meccariello, G., Duronio, F. et al., “Under-Expanded Gaseous Jets Characterization for Application in Direct Injection Engines: Experimental and Numerical Approach,” SAE Technical Paper 2020-01-0325, 2020, doi:10.4271/2020-01-0325.

[13] Pham Q., Chang M., Kalwar A., Avinash Kumar Agarwal, Park S., Choi B., Park S., Macroscopic spray characteristics and internal structure studies of natural gas injection, Energy, 263 (2023), 126055, https://doi.org/10.1016/j.energy.2022.126055.