

High-Pressure Hydrogen Jet and Combustion Characteristics in a Direct-Injection Hydrogen Engine.

Mithun Kanti Roy, Nobuyuki Kawahara, Eiji Tomita, Takashi Fujitani
Okayama University

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ABSTRACT

Hydrogen spark-ignition (SI) engines based on direct-injection (DI) promise significant advantages in terms of thermal efficiency and power output, as well as a means of overcoming problems related to knocking, backfiring, and pre-ignition. In a DI hydrogen engine, the fuel/air mixture is formed by injecting a jet of hydrogen into the air inside the combustion chamber. An Ar-ion laser beam was used as a light source to visualize the hydrogen jet in a constant-volume chamber. This allowed us to study the structure of the jet in addition to other physical processes resulting from hydrogen gas injection. Combustion experiments were conducted in a single-cylinder SI optical research engine equipped with a DI system to detect the early kernel growth assisted by the spark, as well as flame propagation. Various equivalence ratios and fuel injection timings were analyzed to identify the effects on combustion.

INTRODUCTION

Alternative fuels are strong drivers for research and development for improving energy efficiency and reducing greenhouse gas emissions. The hydrogen internal combustion engine (ICE) may be an important step on the road to cleaner and renewable propulsion systems. Advanced hydrogen engine concepts based on direct-injection (DI) fuel systems have shown that the performance potential of H₂-DI operation is approximately 17% higher than that of gasoline port injection [1]. In contrast to port-injection, DI not only avoids loss of power due to low volumetric efficiency, but can also overcome combustion problems, including knocking, backfiring, and pre-ignition [2].

The primary reason for using hydrogen-fueled ICEs is that ICE technology already exists and is comparatively inexpensive. Because hydrogen combusts fairly readily, it does not take much in the way of modifications (primarily new fuel injectors and a storage system) to be able to run an ICE on hydrogen. The combustion properties of hydrogen are very different from gasoline or diesel; specifically, it

burns much faster. This contributes to the relatively high thermal efficiency because there is a shorter combustion period at the ignition time, which can be close to top dead center [3]. Moreover, the knock-free operational window tends to narrow significantly with increasing compression ratio and intake temperature [4].

A major challenge with H₂-DI is in-cylinder hydrogen-air mixing. Hydrogen has the highest diffusion coefficient of all gasses and hence the highest driving force to adjust imbalances in concentration and inhomogeneities in the fuel/air mixture [5]. To promote proper mixing and to supply sufficient amounts of hydrogen to the cylinder, high pressure gas injectors are required. High-pressure plain-orifice injectors create turbulent jets; the jet is constantly supplied with momentum through the orifice, and the momentum is, in turn, passed between the quasi-steady jet and the head vortex [6]. Also, the effect of the injector location and nozzle design on the efficiency and emissions of a direct-injection hydrogen engine have been studied by Wallner *et al.* [7].

Several experimental studies have been carried out to investigate the macroscopic characteristics of the high-speed unsteady jet. Shadowgraph visualization was applied to natural gas and hydrogen jets to investigate the development of unsteady jets, and the effects of the injection pressure and nozzle size were discussed [5, 8]. Recently, laser-induced fluorescence (LIF) and laser-induced breakdown spectroscopy (LIBS) techniques have been developed to measure the mixture formation in a hydrogen DI system, and the reports favor increased injection pressure and careful nozzle design [7, 9, 10, 11]. Blotvogel *et al.* used a triethylamine (TEA) tracer-based LIF technique (rather than an acetone tracer) to measure mixture formation in H₂-ICE under a high-temperature and high-pressure environment, and demonstrated a very good signal-to-noise ratio [12]. There have been some studies on DI gas engines; however, better knowledge of the basic combustion characteristics is necessary. Heywood *et al.* used Schlieren images in a optical SI engine to compare the combustion flame

thickness and flame propagation speed of hydrogen and propane [13]. However, very little work has been reported on hydrogen optical engines, and there is a need for high-resolution direct combustion images to measure the fuel distribution and flame propagation under a range of operating conditions, and varying parameters, including the injector size, fuel injection timing, ignition timing, and fuel-air equivalence ratio.

There are two aspects to this work. First, hydrogen jets were investigated using high-speed direct photographs to achieve a clear representation of the effect of the injection pressure on the gas jet. Second, high-resolution direct images of spark-ignited combustion were acquired to investigate the effect of fuel injection timing on the early kernel growth and the flame propagation at different fuel-air equivalence ratios.

CONSTANT VOLUME VESSEL EXPERIMENTS

A constant volume vessel was used for the hydrogen jet visualization to eliminate the effect of air flow. The closed vessel was made from a 125-mm-long and 80-mm-diameter steel cylinder (Fig. 1). The three walls of the chamber were formed from circular quartz windows to permit full line-of-sight optical access to the chamber. The hydrogen injector was mounted at the upper end plate of the closed vessel so that the jet was directed axially into the cylinder. A pressure accumulating-type injector was used and actuated by an electromagnetic valve. The ambient gas was nitrogen, and was collected from an N₂ cylinder and introduced into the vessel by a pressure-regulated inlet valve. Hydrogen was supplied from an H₂ cylinder and a fuel accumulator (see Fig. 1) was used to maintain constant fuel feed pressure to the injector. The fuel injector was a swirl-type DI gasoline injector that is widely used in gasoline DI engines, and the H₂ was introduced through a single orifice. The injector had a nominal cone angle of 60° and an orifice diameter of 1.0 mm.

HYDROGEN JET VISUALIZATION USING A HIGH-SPEED CAMERA

A high-speed CMOS (complimentary metal-oxide semiconductor) video camera (NAC GX1) was used to visualize the hydrogen jet in the constant volume vessel. The frame resolution was 256×256 pixels and the capture rate was 25,000 frames per second. The injection signal was controlled by an electric injector driver requiring a high-voltage power source and external trigger input to control the pulse width. The onset of the high-speed camera recording was synchronized to the H₂ injection. Figure 1 shows the optical system used to image the jet flow.

The constant-volume chamber was filled with nitrogen gas and the hydrogen jet was injected into the chamber. An Argon-ion laser beam (Spectra-physics, Stabilite 2017) with an output power of 6 W was used as the light source. The thickness of the laser light-sheet was approximately 2 mm. The laser beam was focused on the hydrogen jet, and the visualization

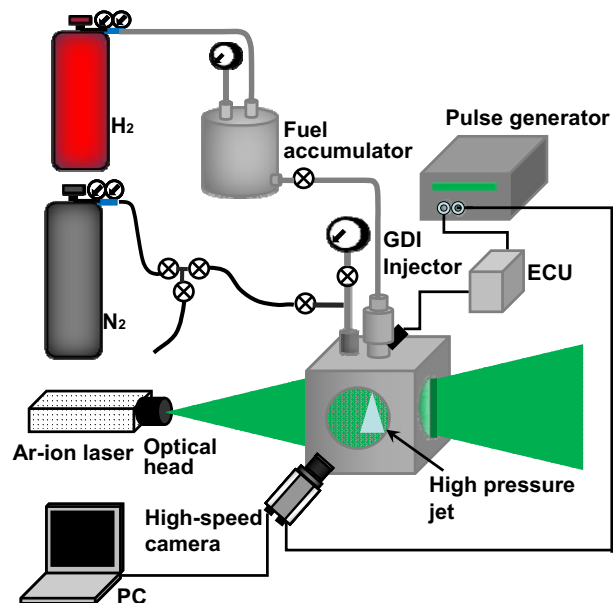


Figure 1. Experimental setup for hydrogen jet investigation.

region was approximately 20×20 mm² near the nozzle tip. A fine particle of spherical porous silica (God Ball B-6C, Suzuki Yushi Co. Ltd.) with a nominal diameter of 2.5 μm was seeded into the intake flow (choosing the appropriate size of the flow field visualization tracer was very important to accurately track the airflow). The origin of the jet image is located at the centerline of the jet exit. The Z_p and r denotes the jet axis direction and radial direction, respectively. The high-speed images provided qualitative information of the jet structure, as well as quantitative information of the jet penetration and cone angle.

OPERATING CONDITIONS

The characteristics and operating conditions of the constant-volume chamber and the injector are summarized in Table 1.

Table 1. Operating conditions for constant volume chamber experiments.

Chamber volume (cm³)		628.31			
Chamber wall temperature (K)		298			
Orifice diameter (mm)		1.0			
Injection duration (ms)		4			
Mass of H ₂ injected at 5MPa (mg)		2.07			
Fuel injection pressure with ambient condition					
Fuel	Fuel injection pressure, MPa	Ambient pressure, MPa (Ambient density, kg/m³)			
		N ₂	N ₂	N ₂	N ₂
H ₂	3	0.1 (1.15)	0.5 (5.611)	1.0 (11.22)	1.5 (16.83)
H ₂	5	0.1 (1.15)	0.5 (5.611)	1.0 (11.22)	1.5 (16.83)

This section concerns the hydrogen jet in the constant-volume vessel. In ICEs, the mixing rate of the injected fuel with air is important because it affects the combustion rate. Gas injection at high pressure can increase the momentum injected into the cylinder, the mixture turbulence level, and the overall amount of

fuel-air mixture. The penetration depth and jet cone angle are important factors. Unlike gasoline fuel, there is no droplet formation or evaporation during the injection process. Figures 2 a) - c) show the development of the hydrogen jet for an injection pressure of 3 MPa and various ambient pressures. The constant-volume chamber was filled with N_2 at different pressures. The ambient pressure was varied

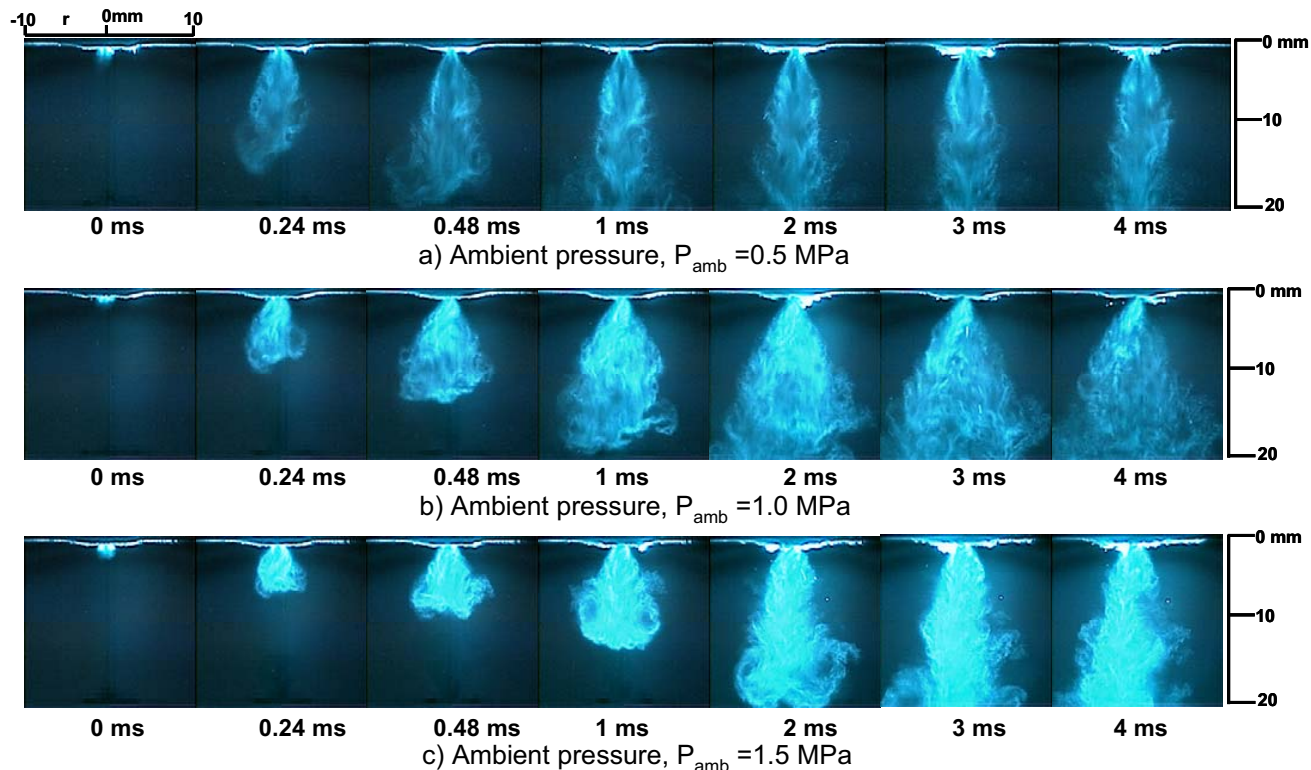


Figure 2. High-speed direct images of a 3-MPa injection pressure hydrogen jet into three different ambient pressure N_2 -filled chambers. The recording speed was 25,000 frames/s.

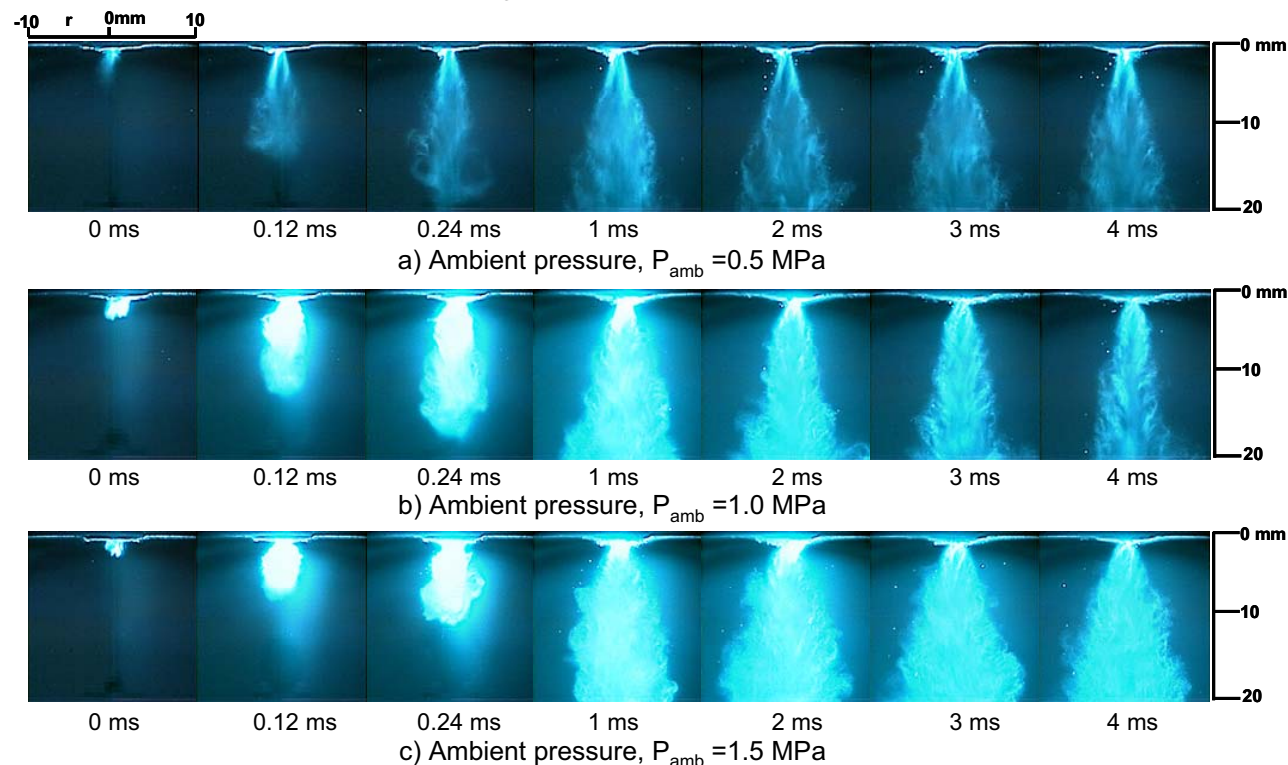


Figure 3. High-speed direct images of a 5-MPa injection pressure hydrogen jet into three different ambient pressure N_2 -filled chambers. The recording speed was 25,000 frames/s.

from atmospheric pressure to 1.5 MPa, changing the ambient density from 1.15 to 16.83 kg/m³. The image shows that the jet diameter expands rapidly just downstream from the nozzle exit. The fuel jet dispersed slightly more in low ambient density than in high ambient density. The intensities of the image can be related to the gas concentration. At low ambient pressure, the jet was conical. Figure 2 a) shows a jet plume which appears to penetrate faster than the plumes in Figures 2 b) and c). At $t = 0.24$ ms, and at the increased ambient pressure corresponding to Figure 2 c), a vortex ring formed around the jet tip and this vortex, which grew upwards over time. The flow induced by the vortex was squeezed out the fuel from the jet tip, which is thought to cause the entrainment of the fuel to the surrounding nitrogen. The symmetry of the vortex may account for the slower spreading of the jet.

Figures 3 a) - c) along with Figures 2 a) - c) show sequential images of the 5-MPa injection pressure jet injected into environments of high and low ambient density. The higher injection pressure in Figures 3 a) - c) resulted in faster growth of the hydrogen plume than for the lower injection pressure. Comparison of Figures 2 and 3 shows that increasing the injection pressure resulted in a significant difference in the jet structure in the initial part of the injection for all the different ambient pressures.

Figures 4 a) - b) show the jet penetration as a function of time for a range of injection and ambient pressures. The graph shows the hydrogen penetration depth, Z_p , as a function of time, t , in from the onset of injection. The penetration of the jets was determined from the axial distance from the nozzle tip to 20 mm from the tip of the jet. The penetration lengths indicate that sufficient distance would be traveled by the gas jet for satisfactory air-fuel mixing in the combustion chamber of an ICE. Figure 4 a) shows the jet penetration rate into different ambient pressure levels with an injection pressure of 3 MPa. Different penetration rates were obtained depending on the ambient pressure in the chamber. Figure 4 b) shows that, at an injection pressure $P_{inj} = 5$ MPa, the jet penetration increased with increasing injection pressure; however, it also decreased due to the higher ambient pressure. In all cases, the tip penetration rate increased in the near-nozzle region and then decreased downstream, which may be due to N₂ entrainment. Similar trends were observed in diesel engine spray patterns, where, at constant injection pressure, an increase in the ambient pressure caused a reduction in the penetration rate, which is equivalent to a reduction of the jet exit momentum [14].

Figures 5 a) - b) show the effect of the injection pressure on the jet angle as a function of time after the onset of injection. The cone angle was characterized by measuring the angle generated by a triangle connecting the center of the nozzle tip and the widest horizontal span of the gas jet. The jet cone angle was measured 20-mm from the nozzle tip. The jet cone angle is the parameter which is most commonly used to describe spray distribution, and is important because it affects the axial and radial distribution of

the fuel. At $t = 1$ ms, Figure 5 a) shows that an increase in the ambient pressure results in a maximum jet angle. An increase in the jet angle results in slower penetration of the fuel jet in the downstream region. Slower penetration occurs because the larger cone angle reflects greater N₂ entrainment, and also because the density of

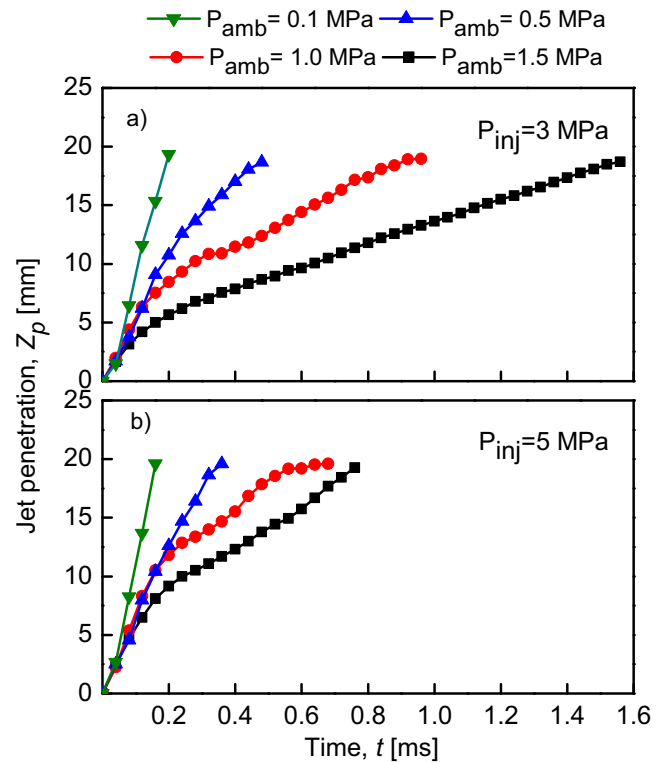


Figure 4. Jet tip penetration for a) an injection pressure of 3 MPa and b) 5 MPa.

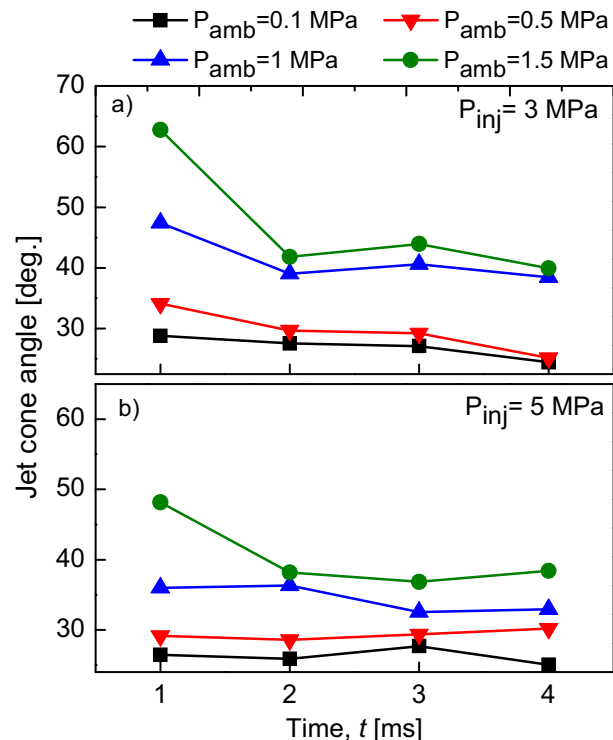


Figure 5. Jet cone angle for a) an injection pressure of 3 MPa and b) 5 MPa.