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In-water injection of high-pressure pulsed gas jet: A simple analytical tool for direct injection of gaseous fuels in automotive engine

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ABSTRACT

Visualizing high pressure pulsed gas jet can be challenging due to its weak scattering of light which requires reliable flow tracer. Complex and costly laser source and high speed camera settings using shadowgraph, Schlieren and Laser Induced Fluorescent (LIF) techniques with seeding of flow tracers such as acetone have been used. In the spirit of simplification, this paper presents a technique to visualize high pressure pulsed gas jet in liquid ambient. It can be used as predictive tool to investigate the structure, dynamic and interaction of gas jet with the environment [1]. A gas injector with square-shaped nozzle was used. High pressure nitrogen gas at 5 and 6 MPa with 12 ms injection pulse exits the injector through a 1 mm^2 square nozzle into quiescent water. The injector tip is immersed below water surface in an optically-accessed container and placed inside an extremely low illuminated square chamber. Two small windows on opposite walls of the chamber allow image capturing with injection-flash light synchronization. Images of the gas jets formed from nozzle at various time after the start of the injection (SOI) were captured by a digital camera. During exposure, the flash light was triggered for 1 ms at some times after SOI, thus images captured correspond to the flash timing.

Results showed that the shape of the gas jet was in agreement with the vortex ball model but with difference in the magnitude of penetration with respect to previous works. Some similarities in the gas injection behavior are found in the liquid and gas ambient. The tip penetration and gas width in water environment are about half of the magnitude in the gas environment. A dimensionless gas dynamic analysis shows a good agreement in the trend of jet development between the gas environment using Planar Laser Induced Fluorescent (PLIF) imaging and in-water imaging techniques. Results indicate that both gas jet length and width are very sensitive to injection pressure.

1. Introduction

Application of high pressure gas injection can be found in many industries. In order to optimize the results of applying gas jet, a good understanding of gas jet behavior is highly necessary. One of these applications is in automotive engines. In the recent years, direct fuel injection has gain considerable interest in automotive technology and has even entered production stages, but mainly in direct injection of liquid fuels such as diesel and gasoline. Direct injection of natural gas in spark and compression ignition engines were also developed and studied extensively.

Natural gas (NG) has been extensively used in internal combustion engines powering more than 15 million vehicles worldwide [5]. The interest of using natural gas is mainly driven by low fuel cost as well as higher potential of increased thermal efficiency and significantly low exhaust emissions [6,7]. However many NG powered vehicles suffer from reduction of peak power. This is prevailing when converting mixer-type, port or manifold injection gasoline to natural gas. The main reason for it is because the density and flame speed of methane are lower than those of gasoline causing reduced volumetric efficiency and limited upper speed [8]. One way to reduce these problems is using direct fuel injection (DFI). With DFI, volumetric efficiency is increased by injecting fuel after the intake valve closes. High pressure gas jet can enhance intensity of turbulence, thus leads to improving air–fuel mixing.

Many optical diagnostic techniques for visualizing fluid flows such as Planar Laser-Induced Fluorescent (PLIF), Schlieren, shadowgraph and Particle Image Velocimetry (PIV) have been used, producing accurate performance predictions [3,4]. Phase Doppler anemometry (PDA) were used to measure near-nozzle microscopic

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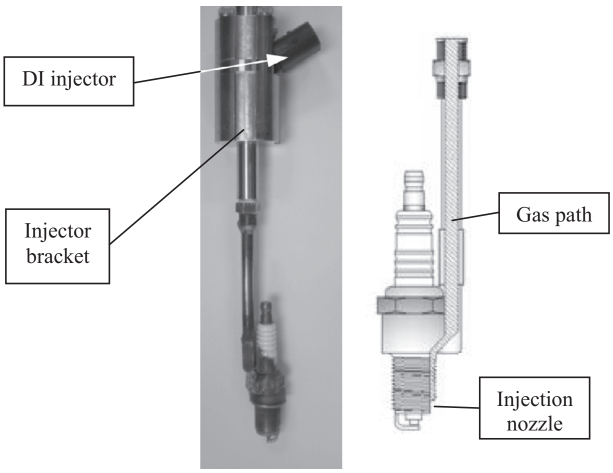

Fig. 1. Tested fuel injector.

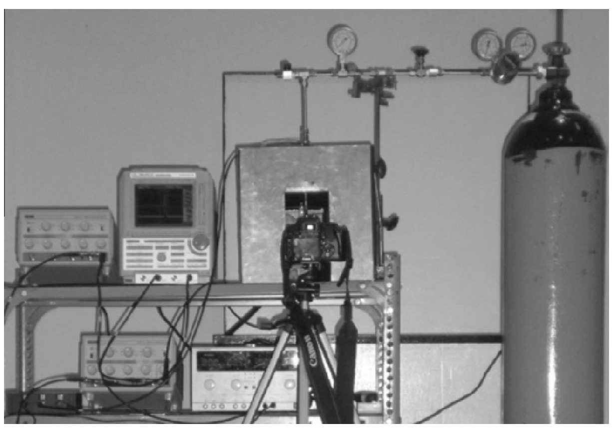

Fig. 2. In-water injection visualization set-up.

spray characteristics of Gas-To-Liquids (GTL) jet fuel and correlated with injection and ambient pressure [9]. Xue et al. investigated the gas jets and the mixing characteristics of gas–liquid using high-speed digital imaging to evaluate the effects of nozzle holes distance, injection pressure and nozzle diameter on jet expansion processes [10]. Numerical study on pulsating jet using argon gas showed significant effects on pulsation to near nozzle flow characteristics [11].

A more recent work for the concentration measurements in gas jet was done using the technique based on the Background Oriented Schlieren (BOS) method with hydrogen jet as the subject [12]. Helium jet was also used in Schlieren technique for visualization of high pressure gas jet [13]. Another approach to understanding the flow behavior is by tedious computer modeling and simulation [14]. The degree of difficulty to visualize gaseous fuel injection is considerably higher than the liquid fuel. This is because gaseous fuels are colorless in air. With laser diagnostics, flow tracer must be doped into the gas in order to gain visible effects for imaging which is very sensitive to doping concentration. Initial work on understanding and visualizing gas jet behavior was done previously but at relatively low pressure [15]. High pressure gas jet visualization studies using PLIF laser diagnostic tools was performed recently [14,16]. In-water injection of a continuous horizontal gas jet was investigated with photographic technique [17].

In this paper, a simple and cost competitive technique to visualize and quantify the behavior and the shape of high pressure vertical pulsed gas jet from a direct fuel injector in automotive engine application is presented. Photographic imaging of pulsed gas jet in liquid ambient (in-water injection) was effectively achieved. This work differs from the study in [17] where horizontal non-pulsating gas jets in water were evaluated. The images captured from this technique are compared to images obtained from PLIF imaging of the same injection process for verification.

2. Experimental set up and procedures

The experiments were carried out to visualize the formation and dynamic of gas jet exiting the injection nozzle in liquid environment. The test fuel injector is shown in Fig. 1 which has been described in previous work [16]. A Gasoline Direct Injection (GDI) injector is connected to a spark plug with a bracket and gas path in is drawn to deliver injection gas through a square nozzle (1 mm × 1 mm). Fig. 2 shows the experimental set up for in-water injection. Schematic diagram of experimental set up is shown in Fig. 3. Compressed pure nitrogen from a 23 MPa tank was used as injection gas where the injection pressure was reduced to 5 and 6 MPa using two step regulators. The pressure at the nozzle location of injection was 100.5 kPa (hydrostatic + atmospheric). The encapsulated fuel injector is actuated by a

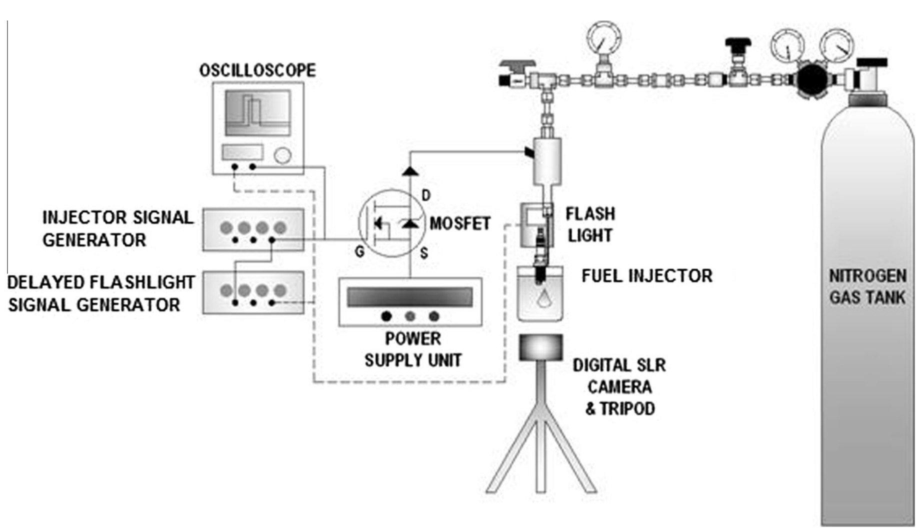

Fig. 3. Schematic of in-water injection visualization experiment.