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Full Length Article

Influence of chamber pressure on CNG jet characteristics of a multi-hole high pressure injector

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ABSTRACT

Natural Gas Direct Injection (NGDI) engines have attracted attention of engine manufacturers because of low pollutant emissions and high efficiency. The jet structure and injector properties are control parameters for optimal mixture formation and stable combustion. Here, the jet characteristics are investigated experimentally. The natural gas jet, injected through a multi-hole injector, is visualized using Schlieren photography. The effects of injection and chamber pressures on macroscopic jet characteristics are examined. New correlations for tip speed and tip penetration are presented. Results show that reducing chamber pressure is more effective than injection pressure for increasing the jet axial penetration. Moreover, the linear relation between non-dimensional tip penetration and time is dependent on the chamber-to-injected gas density ratio.

1. Introduction

Rapidly growing environmental concerns regarding air quality degradation due to engine emissions using conventional fossil fuels motivate engine designers and manufacturers to seek new technologies. Compressed Natural Gas Direct Injection (CNG-DI) is regarded as an attractive solution allowing for low pollutant emissions [1] [2] while maintaining high brake power [3] [4]. In direct injection engines, there are three strategies for mixture formation in the cylinder: wall-guided, air-guided and spray-guided [5].

In wall and air-guided direct injection system, fuel directly impinges on piston and cylinder walls, thus preventing the mixture being well-stratified. Moreover, they need more complex design (combustion chamber, piston crown, etc.) to improve the mixture formation process and are associated with higher emissions and fuel consumption [6]. In spray-guided system, the injector is mounted near the spark plug. This system gives rise to rich-lean mixture. A rich mixture forms near the spark plug for flame propagation within the cylinder, while forming a leaner mixture far from the spark plug at low and medium loads to reduce unburned hydrocarbons. Spray-guided systems outperform wall and air-guided approaches due to better mixture formation, resulting in lower pollutant emissions and fuel consumption [7].

In spray-guided direct injection systems, the fuel is injected at the end of compression stroke and mixture formation is mainly controlled by the injector. Among existing injector types, multi-hole injectors improve air–fuel mixing during the injection process when compared to single-hole and outward opening injectors. Thus, this type of injector provides optimized stratified charge mixture, which leads to effective combustion and reduced emission [8]910. As the spray guided concept works with locally rich-lean mixture, the spray-guided mixture formation has the best potential for reduction of fuel consumption. Jet structure and injector placement play important roles in the mixture preparation. Air–fuel mixing can be improved by increasing jet diameter and having more interaction with surrounding air. Also, the jet tip penetration should be optimized to produce a rich mixture near the spark plug. The flame can efficiently propagate within the combustion chamber. Then, improved mixture formation can lead to control fuel consumption and exhaust emissions of the CNG-DI engine. Thus, the characteristics of jet, produced by the injector, should be investigated.

Many researchers have investigated the jet structure and macroscopic properties, including jet tip penetration and jet cone angle, using different optical diagnostic techniques; Schlieren and shadowgraphy [11–15], LIF [16–18], PLIF [19] and visualization

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Nomenclature

CNG	Compressed Natural Gas
CNG – DI	Compressed Natural Gas – Direct Injection
d_e	Effective nozzle diameter (m)
d_0	Diameter of the injector hole (m)
ECU	Engine Control Unit
f	Focal length of concave mirror (m)
GDI	Gasoline Direct Injection
i	Pixel number
LIF	Laser Induced Florescence
m	Mass (kg)
$\dot{m}$	Mass flow rate (kg/s)
M	Molecular mass (kg/kmol)
NG	Natural Gas
P	Pressure (Pa)
P_0	Stagnation pressure (Pa)
P_c	Chamber pressure (Pa)
P_i	Injection pressure (Pa)
PLIF	Planar Laser Induced Florescence
PR	Pressure ratio
R	Gas constant (J/kg·K)
T	Temperature (K)
t	Time (s)
U	Velocity (m/s)
U_p	Peak tip speed (m/s)
V	Volume (m^3)
y	Mole fraction
z	Non-dimensional tip penetration (m)
Z	Tip penetration (m)

Greek symbols

α	Line slope (degree)
θ	Cone angle (degree)
ρ_{ch}	Chamber density (kg/m^3)
ρ_n	Exit flow density (kg/m^3)

by injection in liquid ambient [20]. But there are a few experimental works [12,15–17] concentrated on the structure of a jet produced by multi-hole nozzles.

The tip penetration of Methane, issuing from multi-hole injector, was examined using Laser Induced Florescence (LIF). This study was conducted in CNG-DI engine, which is a modified Diesel engine, under both motoring and stationary piston conditions by Rubas et al. [16]. There was a good agreement between their measured tip penetrations and predictions from the vortex ball model [21]. Chiodi et al. [17] investigated experimentally and numerically the effect of injection strategies, injector types and piston crown geometries on the mixture formation. Also, jet characteristics of methane produced from single and multi-hole Gasoline Direct Injection (GDI) injector were examined in an optical access chamber using LIF. They showed that multi-hole injection gives higher efficiency of engine performance than single-hole injection.

The tip penetration of a nitrogen jet using Planar Laser-Induced Fluorescence (PLIF) was determined by Mohamad et al. [19]. The fuel was injected into the combustion chamber through a Spark Plug Fuel Injector (SPFI), which is a combination of a fuel injector and a spark plug. They examined the effect of chamber pressure on tip penetration. Results showed that there is a good agreement between the gas jet behavior and the vortex ball model. A detailed description of this model can be found in [21]. They also obtained the values of tip penetration and cone angle for the fully developed jet. The characteristics of high-pressure transient jet including, tip penetration and velocity, were studied under different injection conditions by Yu et al. [18]. They visualized the jet, issued from single-hole injector, for different experimental conditions by means of LIF to investigate the effects of shock waves on the flow structures and turbulent mixing. They found that the higher injection pressure and larger nozzle hole yield higher tip penetration and velocity and also help improve the fuel–air mixture distribution. Hajialimohammadi et al. [11] investigated the characteristics of a helium jet produced by a single-hole injector nozzle using a high-speed Schlieren technique. They also studied the pressure drop in the injection of helium gas and proposed an analytical formulation based on shock tube theory for pressure loss prediction during high pressure gas transient injection for single hole injector. They concluded that the real pressure ratio (injection pressure to chamber pressure) for high pressure gas injection is approximately half of the setting static pressure.

The structure of a helium jet, was examined experimentally, analytically and numerically by Chitsaz et al. [13,22]. They used semi-analytical solution to transient start of weakly underexpanded turbulent jet and Schlieren photography to visualize jets issued from a single-hole injector with different nozzle diameters. It was found that higher pressure ratios (injection to chamber) and nozzle diameters cause tip penetration to be greater. Erfan et al.'s [14] experimental study of natural gas jets from a single-hole direct injector using the Schlieren technique presented the correlations for tip penetration for near and far field of the jet. They compared tip penetration for a natural gas jet for different injectors and injected gases.

Petersen [12] investigated the structure and penetration of multi-hole nozzle spray of hydrogen and proposed a scaling for angle and penetration. Jet characteristics of multi-hole injector, injecting helium at different pressure ratios, were determined using the Schlieren technique by Hajialimohammadi et al. [15]. They presented a new scaling for nozzle diameter and tip speed and also new correlations for tip penetration and tip speed. When using this scale, it was noted that once the individual jets have merged, the downward jet behaves in many respects similarly to other free jets and those produced by single-hole injectors. The effects of chamber pressure and injected gas type on the jet characteristics were not studied in [15]. The examination of the jet structure under real working conditions can help engine designers to effectively optimize mixture formation quality and injection mounting design. Thus, jet properties have been investigated in the present work using the same injector as in [15].

This work aims to characterize the influence of the jet structure parameters of tip penetration, angle, and tip speed, which are obtained using Schlieren photography, on air–fuel mixing. The experimental conditions in the current study, which have been selected based on common operating pressures and temperatures of CNG fueled engine, have not been previously considered in the literature. In this study, tip penetration for CNG is compared to helium ones [15] for the same injector. Then, mass flow rate of multi-hole injector is determined in diverse injection and chamber pressures. New correlations of tip penetration and tip speed are proposed. The paper is organized as follows. The experiments and their methodology are presented in Section 2. Experimental results and discussions are provided in Section 3. Finally, concluding remarks are presented in Section 4.