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Injection characteristics of gaseous jet injected by a single-hole nozzle direct injector

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HIGHLIGHTS

- We provide experimental work on transient jet of natural gas.
- All nondimensional data of tip penetration are located between lines.
- The mass flow rate of injector is independent of chamber pressure.
- A port fuel injector should be utilized in a partially stratified engine.

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ABSTRACT

Engine manufacturers have focused on natural gas spark ignition engines due to the strict regulations for the reduction of emission levels. However, the characteristics of injectors play an important role in mixture formation and combustion. Two methods to identify the injection characteristics of the gaseous fuel injector which is applied in Spark Ignition Direct Injection (SIDI) engine are described. The first method studies the structure of Compressed Natural Gas (CNG) jet which is directly injected into an optical constant volume chamber for different pressure ratios. Schlieren photography is used to visualize the jet development. The correlation of tip penetration for near and far field of the jet is presented. The second experiment investigates the variations of mass flow rate due to variation of injection pressure and pressure of chamber. The results of this method indicate that mass flow rate through the injector is affected by the injection pressure linearly while it is not influenced by the pressure of chamber.
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1. Introduction

Concerns regarding air quality caused by combustion engines burning conventional fossil fuels are important current issues. Engine designers and manufacturers are required to improve these emissions. Alternative fuels, especially natural gas, are considered to be an option since there are large proven reserves and relatively low emission levels during combustion [1]. High RON [2] and hydrogen to carbon ratio [3] of CNG makes it an appropriate fuel for vehicle applications. Lower brake power of CNG compared to gasoline can be compensated by direct injection of CNG [4,5]. For direct injection NG engines, the characteristics of the NG jet, such as tip penetration and jet angle, are important to the mixing process. Hence, it is necessary to investigate the jet characteristics and fuel metering for design and optimization of CNG Spark Ignition Direct Injection (CNG-SIDI) engines. The objective of this study is to help specify the optimal position of the injector in cylinder head and the injection timing which ensures stable combustion and lower emissions.

Most works on the gas injection are limited to Diesel engines fueled with natural gas. The numerical and experimental works on the jet structure [6–10], injection system [11–13], combustion development and engine emission levels [14,15] for natural gas fueling Diesel engines were investigated in the literature.

Methane jet injection in a chamber using LIF technology was investigated in Chiodi et al. [16] and Mohamad et al. [17]. They

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Nomenclature

CNG	Compressed Natural Gas
CNG-SIDI	Compressed Natural Gas Spark Ignition Direct Injection
d	diameter
d_0	diameter of the injector hole
f	focal length of concave mirror
GDI	Gasoline Direct Injection
i	pixel number
LIF	Laser Induced Florescence
m	mass
$\dot{m}$	mass flow rate
NG	Natural Gas
RON	Research Octane Number
SI	Spark Ignition
SIDI	Spark Ignition Direct Injection
t	time
U	velocity
V_d	displacement volume
Z	tip penetration

Greek symbols

α	slope line
η	volumetric efficiency
θ	cone angle
ρ	density
ϕ	equivalence ratio

measured the axial and radial penetration length of methane issuing from a multi-hole injector and spark plug injector. The distribution of natural gas in partially a stratified charge engine using modified injector was experimentally and numerically investigated by Chan et al. [18]. The investigation of the transient injection of helium and hydrogen through multi-hole gaseous injectors using Schlieren visualization was detailed by Petersen [19], while the experimental and numerical investigation of the jet structure of helium injected through different nozzle diameters was shown by Chitsaz and Hajialimohammadi [20–22]. They also present a correlation of tip penetration for both near and far field regions of the jet. This can be compared to other works [23–27] which also report the different correlations for tip penetration of gaseous jets. Chitsaz et al. [28] also developed a semi analytical solution for transient start of underexpanded jet using Hankel and numerical Laplace transform.

Previous works have focused on natural gas injection in details for Diesel engines [6–13], but there are major differences in pressure ratios and jet structure for Diesel and SIDI engines. Injection pressure of CNG in Diesel engines is higher than twice of those CNG-DI engines [7,8]. Also, in the previous works, pressure ratios (injection and chamber pressure) are quite different with actual pressures in CNG-SIDI engines, while this work investigates jet configuration and injector performance in applicable pressure ratios for CNG-SIDI engines. It is also notable that, commercial GDI injector is used here to inject CNG. Here, penetration and angle of the natural gas jet produced by single-hole direct injector are measured at different pressure ratios. The visualization of the jet structure is done by Schlieren photography technique. And the mass flow rate of the injector is obtained. The experimental setup also characterizes the effect of injection and chamber pressure on the injector mass flow rate. A new correlation for the penetration depth of a transient natural gas jet, based on the experimental results of tip penetration is proposed.

2. Experimental apparatus

For engine designers to calibrate injection phasing and injector placement in a cylinder head, jet characteristics and the mass flow rate of direct injectors are needed. Two different experimental test rigs are used to characterize mass flow rate and jet configuration of the injector. Jet configuration and tip penetration are measured in the first experimental test rig and mass flow rate is determined using the second experimental setup. The fuel injector used is a commercial HDEV 5 Bosch single hole gasoline direct injector. The injector nozzle has a single hole of 0.68 mm diameter with a 11° angle which is shown in Fig. 1.

2.1. First experimental setup

Experimental setup One consists of a constant volume chamber, a CNG supply and an imaging system which are shown schematically in Fig. 2. Each component described in detail below.

A constant volume cylindrical chamber with transparent walls having a height and diameter of 130 mm, is filled by high pressure nitrogen at room temperature. The chamber is capable of a working pressure up to 100 bar. The Pressure and temperature of the chamber is measured and a vacuum pump is used to remove the mixture from the chamber.

A CNG tank at 110 bar pressure supplies NG through a regulator, which slops down the feed pressure as the experiment requires. In order to reduce the pressure of tank, a regulator is used. Line pressure is measured by a pressure sensor located at the high pressure vessels after the regulator. The injector is mounted at the top of the constant volume chamber to inject CNG directly. The parameters of the injection process, such as injection duration and injection timing are controlled by a Pulse Width Modulated (PWM) signal from the control unit.

The imaging system consists of concave mirrors (with focal distances $f = 2610$ mm and $f = 2570$ mm), a halogen lamp, a knife edge and a high speed camera. The halogen lamp can be considered as a point light source. The photography technique is Z-type Schlieren [29] that records shadows of the jet, when the jet is passed across the parallel light beam. In Z-type Shclieren imaging, the diverging light rays which are emitted from the halogen lamp, are converted to parallel light rays by first concave mirror. Then parallel light rays pass through the constant volume chamber. Finally, the second concave mirror converges the parallel light rays into a point at the knife edge. The Main role of the knife edge is to remove light noises from convergent light rays. For this purpose, the knife edge is placed at the focal point of second concave mirror. The final component of the imaging system is a high speed MotionBLITZ Cube/EoSens camera with the ability of capturing up to 100,000 frames per second (fps).

2.2. Second experimental setup

The second experimental setup is shown schematically in Fig. 3. This setup is comprised of a constant volume chamber, a pressure gauge, a CNG supply system and a digital scale. A pulse generator

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