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Research Paper

Visualization research on injection characteristics of high-pressure gas jets for natural gas engine

Quan Dong, Yue Li, Enzhe Song *, Liyun Fan, Chong Yao, Jun Sun

Institute of Power and Energy Engineering, Harbin Engineering University, No. 145-1, Nantong Street, Nangang District, Harbin 150001, China

HIGHLIGHTS

- The evolution of high-pressure gas jet macroscopic structure is studied.
- Gas injection pressure has little effect on the development of jet tip penetration.
- Different empirical formulas of gas jet tip penetration are investigated.
- The mixing effect of gas jet is not significantly affected by gas injection pressure.

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ABSTRACT

High-pressure gas injection processes with various gas nozzle structures under different nozzle pressure ratio (NPR) were investigated experimentally. Schlieren imaging method was used to investigate macroscopic structure of gas jets. Results showed that increasing the gas injection pressure is unable to improve the jet tip penetration obviously. It is because chocking phenomenon limited gas jet velocity at nozzle exit under high gas injection pressure. The empirical formula for high-pressure gas jet tip penetration was investigated based on the experimental data under various NPRs and orifice diameters. It is found that the experimental data are in good agreement with the empirical formula proposed by Hamzehloo and Aleiferis. The increase of gas injection pressure and orifice diameter could not directly improve the air entrainment effect, nor could it increase the average equivalent ratio of gas jet due to the small gas jet kinetic energy and small density difference between gas jet and the surrounding ambient gas.

1. Introduction

With increasing concern focused on the energy crisis and environment pollution, it is necessary to exploit and utilize new alternative energy to internal combustion engine (ICE). Natural gas is regarded as one of the most promising alternative fuels due to its abundant reserves, low prices and good performance on emission [1–3]. Natural gas is mainly composed of methane (CH_4), and it also contains a small part of heavier hydrocarbons (primarily ethane and propane) and inert gases (carbon dioxide, nitrogen and carbon monoxide) [4–6]. Natural gas has the highest H/C ratio compared with other hydrocarbon fuels, so the combustion of natural gas can reduce about 25–30% CO_2 emissions compared to that of gasoline and diesel [7]. Nitrogen oxide (NO_x), sulfur oxide (SO_x) and particulate matter (PM) emissions in exhaust gases are also smaller than petroleum energy [8]. Therefore, natural gas engines are popular in recent years [9–11].

Natural gas engine can be divided into direct injection (DI) and port injection (PI) concepts according to the way of fuel injecting into cylinders [12–15]. In DI engine, natural gas is directly injected into the cylinder, which can increase charging efficiency. But it has high requirement on gas supply system and injection system. In PI engine, the gas fuel is injected into the intake manifold and mixed with air before getting into the cylinder. In China, the present situation is that most heavy-duty natural gas engine are still employing gas fuel port injection to form premixed combustible mixture in intake manifold [16–18]. However, natural gas port injection suffers from unstable combustion and high emissions of CO and unburned CH_4 due to the instability of gas quantity into the cylin-

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Abbreviations: ASOI, after the start of injection; CCV, cycle-to-cycle variations; DI, direct injection; EOI, end of injection; Fps, frames per second; ICE, internal combustion engine; LES, large eddy simulation; NO_x, nitrogen oxide; NPR, nozzle pressure ratio; PI, port injection; PIV, particle image velocimetry; PLIF, planar laser-induced fluorescent; PM, particulate matter; SO_x, sulfur oxide.

* Corresponding author.
E-mail address: sez2005@sina.com (E. Song).

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der [19]. These problems lead to the high cycle-to-cycle variations (CCV) of PI natural gas engine [20,21]. Ozdor highlighted that engine power output could increase 10% if CCV can be eliminated [22]. Therefore, many researchers have focused on the gas injection control strategies and transient injection characteristics for efficient and clean combustion [23–25].

Several articles have investigated the effect of gas injection strategies on combustion and emission characteristics in natural gas engine [17,26,27]. Yang investigated the effect of natural gas injection timing on combustion and emissions of a dual fuel engine [17]. Results showed that retarded natural gas injection timing improved engine performance. Baratta and Rapetto studied the effect of end-of injection (EOI) timing on mixture formation process. They concluded that injection timing affected the mixture formation directly [27]. Injection nozzle shape and location also have important effects on mixture formation [28]. Chiodi presented that nozzle shape affects the combustion process in DI natural gas engine [29]. Semin studied the mixing performance with single-hole and multi-hole nozzle in natural gas engine. Results showed that mixing effect is related to gas jet flow characteristics [30]. When a gaseous jet is injected through a nozzle, the gas jet flow conditions are dependent on the ratio of upstream total pressure to the ambient pressure (P_b) [31–34]. Upstream total pressure is commonly used as gas injection pressure (P_o) and the ratio is defined as nozzle pressure ratio (*NPR*). Experimental and numerical investigation of gas jet structure characteristics were analyzed in recent years [35–37]. Vuorinen measured the nitrogen and methane jet tip penetration and jet volumetric growth of single-hole nozzle under the NPR from 4.5 to 10.5 based on planar laser-induced fluorescent (PLIF). Results presented that gas injection is a transient process, the injected fuel has a large influence on mixture quality [38]. Hamzehloo and Aleiferis investigated the mixing characteristics using large eddy simulation (LES). It showed that high *NPR* leads to locally rich mixture in cylinder [39–41].

At present, there is little information about the effects of gas nozzle structure on the evolution law of gas jet macroscopic structure. Moreover, the mixing characteristics of high-pressure gas jet under different working condition need to be further studied. Based on the analysis above, this paper investigated gas injection process with single-hole nozzle by the application of Schlieren imaging. The main objectives of the current work are summarized as follows: (1) Grasp the gas jet structure parameters evolution law under different working conditions by using Schlieren method. (2) Investigate the mixing effect of high-pressure gas jet including air entrainment and average equivalent ratio with different gas injection pressure and orifice diameter.

2. Experimental setup

2.1. Schlieren system

The macroscopic structure of high-pressure gas jet was investigated by using Schlieren method. The experimental setup was shown in Fig. 1. Xenon lamp was selected as the incident light source. The light source is focused on the main light axis. The white light from the light source passes through two optical convex lenses. The diameter of the two lenses is 100 mm and the ratio of focal distance to diameter is 1.2 and 1.5 respectively. When the light passes through an aperture of 1 mm, it turns into a point light source. Through the reflect mirror whose diameter is 100 mm, the light is reflected on the spherical mirror and then forms a parallel light. Parallel light passes through the quartz windows of a constant volume vessel and transmits the information of gas jet flow characteristics to the high speed camera (Phantom V7.3) through the symmetrical arrangement of spherical mirror, reflect mirror and a knife edge at the focus.

2.2. Gas injection system and control system

High purity methane was used to investigate gas jet injection characteristics. The entire gas injection system structure was shown in Fig. 2. The diameter of the gas solenoid valve exit is 2.0 mm, and the maximum needle lift is 0.8 mm. The injector adapter was used to connect the injector and the nozzle. An orifice was processed out on forefront of the nozzle. The orifice diameter (D) covered from 0.8 mm to 1.8 mm. In this experiment, gas injection control system sent a driving signal to the gas solenoid valve and the synchronous control system sent a 5 V TTL signal to high-speed camera simultaneously. The resolution of high speed camera is 512 × 512 pixels and the frame frequency is set to 10,000 frames per second (fps) in this experiment. The pressure parameters used in this paper are gas injection pressure (P_0), orifice inlet pressure (P_i) and ambient pressure (P_b). The pressure mentioned in this paper is absolute pressure.

2.3. Constant volume vessel

The injection system injects methane into the constant volume vessel. During the measurement process, the ambient temperature is 298 K and the ambient pressure changes by filling different amount of nitrogen in the constant volume vessel. The structure of constant volume vessel was shown in Fig. 3. The gas solenoid valve was installed on the top of the constant volume vessel. The fuel supply system offered different gas injection pressure (up to 2.6 MPa) to gas solenoid valve. The specifications of the experimental parameters were shown in Table 1.

2.4. Definition of jet characteristic parameters

The macroscopic characteristic parameters of jet are mainly described by jet tip penetration, jet cone angle and jet volume in this paper. As shown in Fig. 4, characteristic parameters are defined as follows:

Jet tip penetration (Z_{tip}) is defined as the distance from nozzle exit to the top of gas jet front edge. Gas jet cone angle (θ) is defined as the maximum radial expand angle to the jet front. In this paper, all visual images used the same image scale. The real scale of a pixel is 188.6 μm × 188.6 μm. The calculation of jet volume (V) is based on the assumption that gas jet is space axial symmetrical. The jet is split into several equivalent cylinders whose diameter is the distance between the contour line on both sides. The height of the cylinders is a pixel (188.6 μm).

The number of repetitive experiment per test condition was statistically analyzed in order to ensure the accuracy of the data. The sample standard deviation σ was used to study the appropriate number of repetitive experiment per test condition. The standard deviation σ is expressed as Eq. (1):

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - x_{ave})^2}{n-1}} \tag{1}$$

where n is the number of test cases, x is the characteristic parameter and x_{ave} is the average value of the characteristic parameter. The sample standard deviation of jet tip penetration was calculated when $NPR = 6$, $P_b = 0.1$ MPa and $D = 1.0$ mm. The standard deviation of jet tip penetration at $t_{ASOI} = 1$ ms is 4.33 mm, 2.72 mm and 2.56 mm ($Z_{tip} = 43.65$ mm) corresponding to 5 repetitive experiments, 10 repetitive experiments and 15 repetitive experiments, respectively. It can be seen that 10 repetitive experiments is enough to meet the measurement accuracy.

An image processing program was designed in *MATLAB* environment. The effect of threshold value on gas jet tip penetration and jet cone angle was investigated. It is because the gas jet boundary