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Spray Characteristic Comparisons of Compressed Natural Gas and Hydrogen Fuel using Digital Imaging

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Abstract: This study tries to characterize the spray of compressed natural gas (CNG) and hydrogen under ambient conditions using Schlieren imaging technique and image processing. A comparative analysis of the tests is presented. Both wide and narrow cone angle injectors had been used to investigate the spray development and their behaviors at different injection pressure (1.2 to 1.8 MPa). It was found that the intensity of the injected gas for narrow angle injector was higher than wide angle injector before the time reached 5.0 m sec^{-1}. Generally, both the penetration and cone angle show an increase with the increase of injection pressure. As for the spray of pure H_2, the images showed that the spray spreads faster than pure CNG and the spray has also exhibited a larger cone angle due to the lower density of hydrogen relative to CNG.

Key words: Compressed natural gas, hydrogen, schlieren imaging, spray cone angle, spray tip penetration

INTRODUCTION

Due to limited reserves of crude oil, development on alternative engine fuel has attracted more concern in the engine community. Alternative fuels are usually cleaner fuels compared to conventional liquid fuels such as gasoline and diesel fuel in the combustion process of engines. Natural gas is one of the most important alternative fuels and the use of natural gas as engine fuel has been studied for many years and realized in both spark-ignition engine and the compression-ignition engine (Cho and Bang-Quan, 2007).

Internal combustion engine using hydrogen is considered as a suitable pathway to hydrogen economy, because fuel cell technologies are considered to be more mature and cost effective (Wolf and Nordheimer, 2000). Hydrogen has been proposed as an alternative fuel due to its unique properties. Its wide flammability range allows higher efficiency. Natural gas and hydrogen gain importance as an alternative fuel. The use of natural gas blended with hydrogen is a viable alternative to pure fossil fuels because of the expected reduction of the total pollutant emissions and the increase in thermal efficiency (Wang *et al*., 2007; Huang *et al*., 2007; Blarigan and Keller, 2002). Since they have several advantages, blending fuels of CNG and H_2 may come into use in SI engine. Before that, fundamental research is necessary to clarify the fuel spray characteristics of those two alternative fuels.

The spray behavior plays an important role in engine air-fuel mixing and combustion process, which in turn influences the engine performance. To control the fuel injection, optimize combustion and reduce emissions of the engines, it is necessary and important to understand the characteristics of fuel sprays.

Fuel spray shape, spray tip penetration and spray angle are terms used to characterize the over all spray structure. Spray angle, a parameter which is the most commonly used to describe spray distribution, is important because it affects the axial and radial distribution of the fuel (Kim and Moon, 2001). Varde, (Varde, 1985; Dan *et al*., 1994) have studied the characteristics and performance of spray cone angles of traditional diesel injectors. It was discovered that the cone angle increased as the ambient pressure climbed from 0.1 to 3.3 MPa.

The spray image can be obtained using Schlieren photography technique while the processing of the images can be carried out using Digital Image Processing and the Particle Image Velocimetry (PIV) can be used to measure the spray velocity.

Schlieren systems are usually considered to be a qualitative instrument. Greig *et al.* (1997) has studied qualitative spray characterization in direct injection spark ignition engine. The paper concludes with examples of recorded images of fuels sprays inside the engine.

Several researchers used Schlieren photography technique to measure the spray characteristics of

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alternative fuels. The spray characteristics of ethanol-gasoline blends, as well as pure gasoline were studied under various ambient conditions by means of high-speed Schlieren photography technique (Gao *et al*., 2007). The results showed that when adopting fuel blends with variable ethanol-gasoline fractions in the swirl-type injector sprays at low pressure, the main spray tip penetration decreased and spray angle increased with the increased of ethanol fraction, after 3.5 m sec^{-1} start of injection, which meant a better vaporization.

The characteristics of methanol sprays were studied under different opening pressure, ambient density and nozzle diameter using Schlieren photography techniques (Yanfeng *et al*., 2007). The results showed that with an increased ambient density, the penetration length and tip velocity decreased and cone angle widened quickly.

Some researchers (Zhao *et al*., 1999; Lee *et al*., 2001) also made use of Schlieren photographs to investigate the spray characteristics of a high-pressure swirl injector for a gasoline direct injection engine under various ambient and injection conditions. The results showed that the spray tip penetration increased with the increase in injection pressure, while little influence from the injection pressure on the spray cone angle was observed except for an injection pressure of 2.0 MPa.

Recently, many digital imaging and image processing tasks are being conducted to measure the spray characteristics. The application of a direct photographic imaging and image processing system can also be employed to find the quantitative characterization of sprays. Image processing software has been developed by a few researchers. They are used to study the effect of varying pressure, tip penetration, spray angle and fuel area density (Shao and Yan, 2006; Shao and Yan, 2008; Jeong *et al*., 2007; Petit *et al*., 2007).

In order to quantify the performance of the spray characteristics, Particle Image Velocimetry (PIV) technique can be implemented. It is used to obtain instantaneous velocity measurement and related properties in fluid. Lee and Lee (2007) analyzed the spray characteristics according to the injection duration under ambient pressure conditions and the injection timing of an optical engine. The spray velocity can be calculated through the PIV method and the vorticity, in turn, can be calculated from the spray velocity component.

In general, the previous study, investigated only on detailed behavior of fuel sprays of alternative fuels such as gasoline, ethanol, methanol and diesel. However, very few works were done in area of spray evolutions and mixing behaviors in a direct CNG injection.

This study focuses on the studies of the spray characteristics of compressed natural gas and hydrogen fuels which were visualized under ambient conditions by means of high-speed schlieren photography technique. The main objectives of this work were to investigate the effects of Wide cone angles (WAI) and narrow cone angle (NAI) injectors and injection pressure on spray behaviors such as spray shape, tip penetration and spray angle. A comparative analysis of CNG and H_2 sprays is also illustrated in detail.

MATERIALS AND METHODS

Experimental set-up: In this study, two types of fuel samples were prepared for the experiments, i.e. compressed natural gas and hydrogen. The compositions of natural gas are listed in Table 1. The compressed natural gas used in the experiment was the commercial product from Malaysia. The fuel properties of natural gas and hydrogen are listed in Table 2.

According to Table 2, the lean burn capability of hydrogen is much better than that of natural gas and the laminar burning velocity of hydrogen is 7 times faster than the natural gas. Hence, the addition of hydrogen to natural gas is expected to increase the flame propagation speed and stabilize the combustion process, especially under lean mixture combustion. The quenching distance of hydrogen is one-third that of natural gas and this is beneficial to reducing the unburned HC (Liu *et al*., 2008).

Figure 1 illustrates the schematic diagram of the schlieren imaging experimental set-up which consists of high-speed video camera, source of light (lamp), a mirror, high pressure direct injector, regulator pressures for CNG and H_2 and knife edge (razor blade). The fuel rail which pressures ranging from 1.2 to 1.8 MPa was injected openly at the ambient temperature and pressure during the experiment.

Experimental procedure: The schematic diagram for the injector is in Fig. 3. For the case of pure CNG spray, both

Table 1: Composition of natural gas

Item	CH_4	C_2H_6	C_3H_8	N_2	CO_2	others
Vol-fraction%	96.16	1.096	0.136	0.001	2.54	0.067

Table 2: Fuel properties of natural gas and hydrogen

Fuel properties	Natural gas	Hydrogen
Density in 1 atm, at 300 kg m^{-1}	0.754	0.082
Stoichiometric air to fuel ratio (vol %)	9.396	2.387
Stoichiometric air to fuel ratio (wt %)	0.062	0.029
Laminar flame speed (m sec^{-1})	0.380	2.900
Quenching distance (mm^{-1})	1.900	0.600
Mass lower heating value (MJ kg^{-1})	43.726	119.220
Volumetric heating value (MJ kg^{-1})	32.970	10.220
Octane number	120.000	
C/H ratio	0.251	0.000

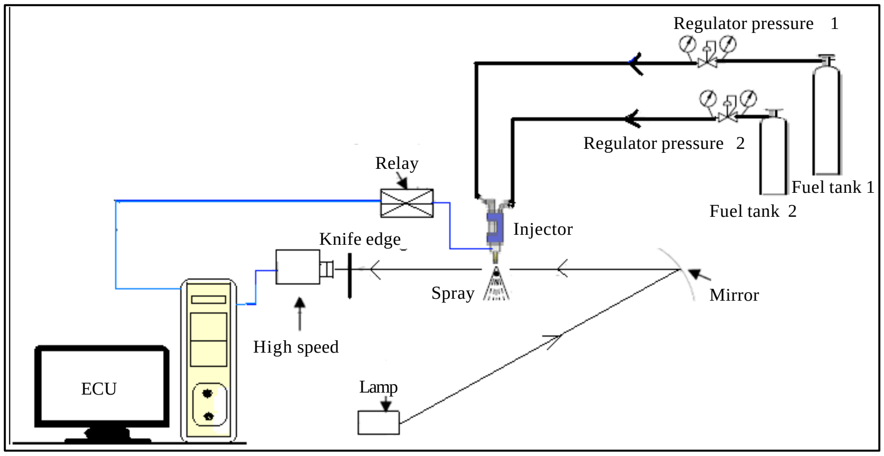

Fig. 1: Schematic diagram of experimental setup

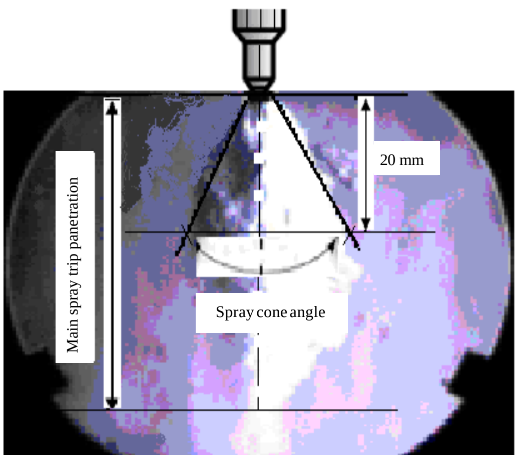

Fig. 2: Fuel injector used for testing

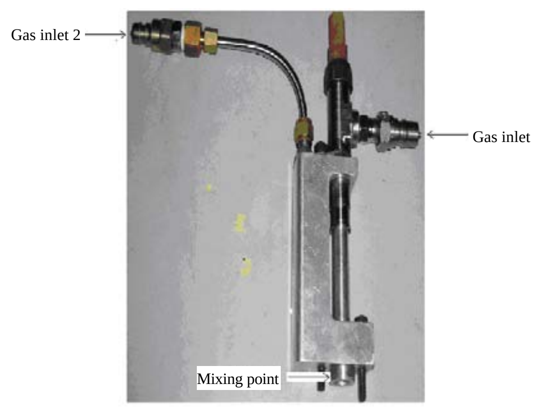

Fig. 3: Definitions of spray penetration and spray angle

inlet gas 1 and 2 are supplied with CNG. This also applies for the case of pure hydrogen. The injector used in the experiment was a special one because it did not allow the two gases to mix thoroughly. In order to avoid back flow, the pressure of gas 1 and 2 maintained to be the same.

The fuel injection of the CNG-DI system as in (Fig. 2) is fitted either with a wide angle or narrow angle injectors at injection pressures ranging from 1.2 to 1.8 MPa. The experiment was conducted in sequence with pure CNG being the first and pure hydrogen the second. Two pressure regulators were used to control each inlet pressures and this was done manually.

Both wide angle and narrow angle injectors were used one at a time to inject the fuels in pseudo motoring of 1000 rpm in an open spray. The capture of images was performed by a high speed video camera (Photron, FASTCAM-APX) operated at a speed of 4,000 frames sec $^{-1}$ with effective pixel size of 640x128. A Nikon 60 mm f/2.8D Micro-Nikkor lens was used to accompany the camera. In order to get clear images, the knife-edge was adjusted to the focal point of the light.

Image processing: In order to find the edges of an image Canny edge detection algorithm was used (Canny, 1986).

The Canny edge detection algorithm, which works by looking for local maxima of the gradient of Image intensity I, was used to find the spray boundary. The intensity gradient was calculated using the derivative of

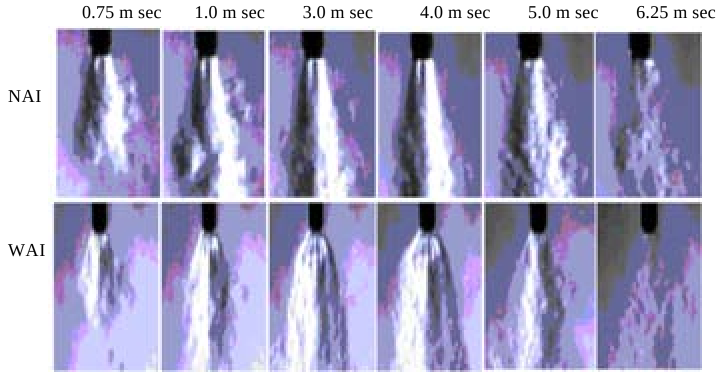

Fig. 4: Schlieren image for pure CNG at (1.2 MPa)

a Gaussian filter. The method uses two thresholds, to detect strong and weak edges and includes the weak edges in the output only if they are connected to strong edges.

Spray expansion area can be parameterized by using spray cone angle and tip penetration measurements. In order to convert pixel measurements to SI metric measurements a calibration image of a graduated scale was taken.

The value of one pixel was found out to be equivalent to 0.238 mm.

Figure 4 provides how spray tip penetration and spray cone angles are defined. The spray angles were obtained by drawing horizontal lines at 20 mm downstream from nozzle tip and measuring the angle between the edges of the spray (Dan *et al*., 1994). And the spray tip penetration can be measured along the axial distance between injector nozzle end and the furthest spray point along the spray axis of symmetry.

RESULTS AND DISCUSSION

Effect of wide and narrow cone angle injectors: Figure 4 shows the visualization results of the Schlieren spray images for CNG under ambient conditions when the fuel was injected with injection pressure in the range of 1.2 MPa. For comparison purposes, Wide Angle (WAI) and narrow cone angle (NAI) injectors were used. It was found that the intensity of the injected gas for narrow cone angle injector was higher than the wide cone angle injector before the time reached 5.0 m sec^{-1}. This phenomenon occurred because the fuel for the wide angle case had already been mixed with surrounding air. At the time of 6.25 m sec^{-1}, the images of a wide cone angle injector shows that the gas has already disappeared while the narrow angle injector shows some residual gaseous. In addition, the tip penetration for NAI was longer than WAI.

Effect of injection pressure: Figure 5 and 6 show the Schlieren photographs of spray images for CNG and H_2 respectively. Wide angle injector was used under ambient conditions and injection pressure of 1.2 and 1.8 MPa with the range of time from 0.75 to 6.25 m sec^{-1}. As shown in the spray images, the injection pressure has a large influence on the spray structure, the sprays has basically cone structures under all conditions. However, for the case of low injection pressure (1.2 MPa), a weak cone shape and lower tip penetration were observed. With an increase of the injection pressure to (1.8 MPa), a strong vortex in the spray tip plume was found to develop. Generally, both the penetration and cone angle have shown an increase with the increase of injection pressures. The increase of injection pressure leads to the increase in initial speed of the spray and thus increases in the flow rate of injection.

Figure 6 illustrates hydrogen has a larger cone angle compared to CNG. The wide spray angle of H_2 could improve mixing rate of mixture due to the larger distribution area for the injected gas.

Figure 7 is spray cone angle measurement against the time after the start of injection. The spray cone angle was measured at a distance of 20 mm from end of injector nozzle. It shows that, hydrogen has a larger cone angle for the entire injection time whereas CNG have lower cone angles throughout the injection time due to the fact that hydrogen has a lower density than CNG and it can easily mix with air.

The spray tip penetrations of two types of fuels were computed and plotted with respect to their injection time as it is depicted in Fig. 8. The injection pressure of fuels was 1.2 MPa and it is injected into ambient environment.

It is obvious that tip penetration increases as time after start of injection increases witnessed in Fig. 8. Also it can be seen that the tip penetration of two types of fuels were found to be similar up to time 0.5 m sec^{-1} except for time after 0.5 m sec^{-1} where the penetration of H_2 is higher than CNG.

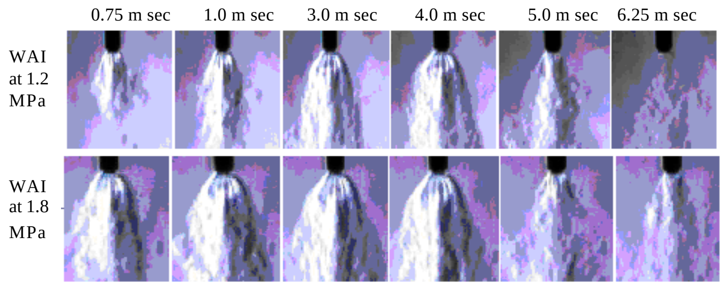

Fig. 5: Schlieren image for pure CNG at (1.2-1.8 MPa)

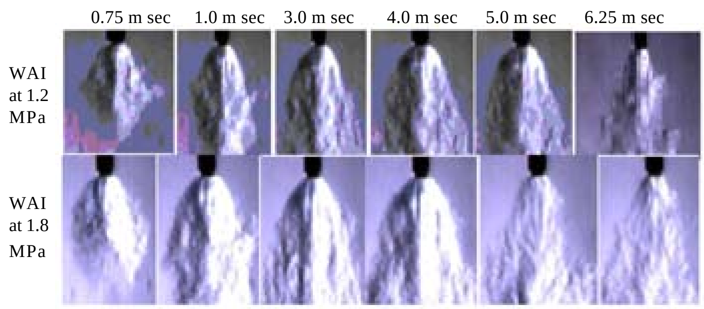

Fig. 6: Schlieren image for pure H_2 at (1.2-1.8 MPa)

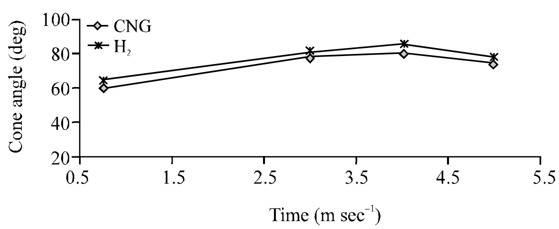

Fig. 7: Spray cone angles of CNG and H_2 against the time after start of injection at (1.2 MPa)

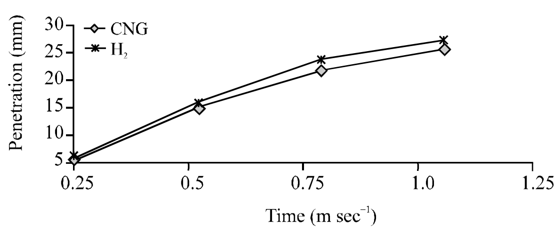

Fig. 8: Spray tip penetration of CNG and H_2 against the time after start of injection at (1.2 MPa)

CONCLUSION

The Schlieren images show the intensity of the injected gas for Narrow Angle Injector (NAI) was higher than the Wide Angle Injector (WAI) before the time reached 5.0 m sec^{-1}.

At the time of 6.25 m sec^{-1}, Wide Angle Injector (WAI) showed that the gas had already disappeared while the Narrow Angle Injector (NAI) showed some residual gases, Wide Angle Injector (WAI) has larger spray cone angle than the narrow cone angle and this is a behavior believed to be good for mixing.

The spray images have also shown, the injection pressure has a large influence on the spray structure. Generally, both the penetration and cone angle has increased with the increase of injection pressure.

As for the spray of pure H_2, the images showed that the spray spreads faster than the pure CNG and the spray also has a larger cone angle and higher tip penetration due to the lower density of hydrogen relative to CNG.

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