A Study of Injection and Mixing of Gaseous Jets for Direct Injection in Spark Ignited Engines

Sutkowski M. and Teodorczyk A.
Warsaw University of Technology, ITC, Nowowiejska 21/25, 00-665 Warszawa, Poland

Xia C. and Sobiesiak A.
Department of Mechanical, Automotive and Materials Engineering, University of Windsor, Windsor, Ontario N9B 2T6, Canada

Introduction

Direct injection of gaseous fuels such as natural gas and biogas in spark ignition engines has recently attracted more interest due to technological advances of gasoline direct injection systems. Concurrently automotive applications of hydrogen fuel continue to generate interest and become more feasible every year.

Flammable mixture in direct-injection SI engine fuelled with gaseous fuel is prepared by complex dynamic interaction of fuel jet with turbulent cylinder flow. The goal is to find optimal turbulence intensity and jet characteristics to satisfy the varying requirements of fuel-air mixture for various operation conditions of the engine. In the present study the processes of fuel injection and flammable mixture formation was examined through physical experimentation and numerical simulation for methane and hydrogen jets spreading into air.

Experimental

The experimental set-up is depicted in Fig. 1(a) and a combustion chamber close-up is shown in Fig. 1(b). The combustion chamber of 10×10×10 cm has two perforated plates (shown in Fig.1(c)) that oscillate in opposing directions to generate semi-homogenous and isentropic turbulence. Pneumatic cylinders drive the perforated plates. A finite amount of gaseous fuel is injected from an injector mounted on the chamber top. The control program (LabView) allows choosing and setting: (a) injection parameters (pulse duration, number of injections, injection timing with respect to plates stop time), (b) plates' oscillation frequency and stroke (thus varying their mean speed).Change of turbulent length scales in the chamber is accomplished by use of separate plates with different size of perforation holes. The injection process is visualized and recorded using a Schlieren optical apparatus and fast CCD camera.

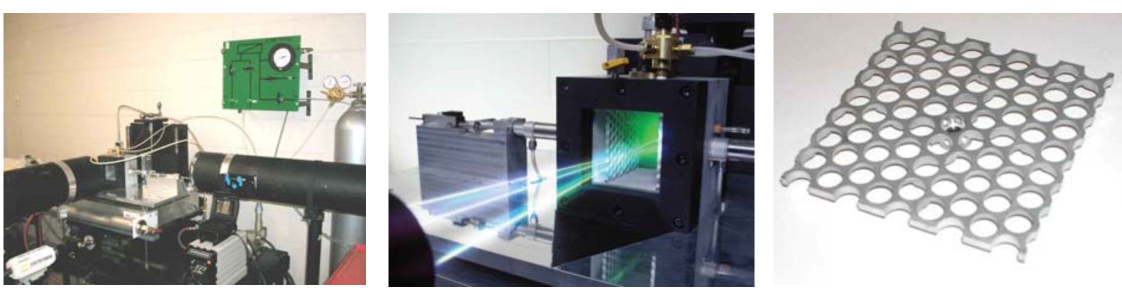
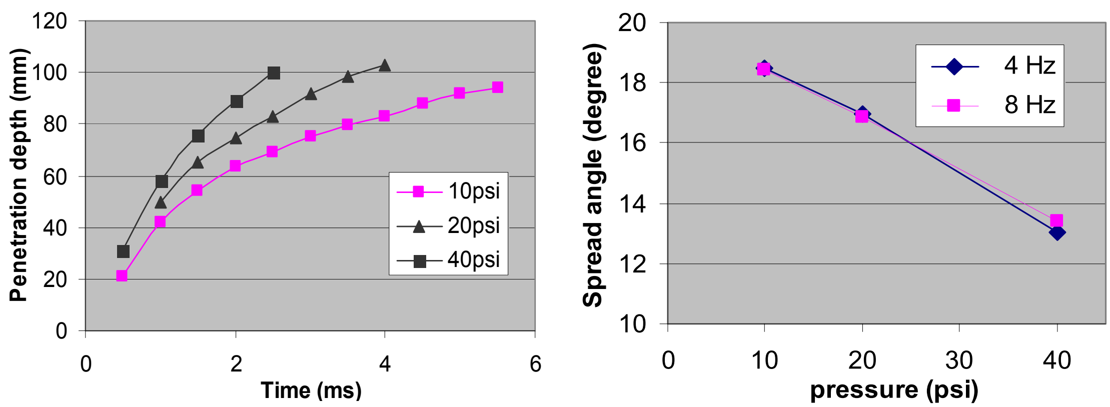


Fig. 1. Experimental set-up. (a) The view of entire system. Combustion chamber is located in the center. The Schlieren apparatus is to the front and right of the chamber. (b) Close-up view of the combustion chamber and LDA laser beams. The turbulence generating plates are shown inside. (c) Perforated plate for turbulencegeneration. The diameter of holes shown here is 10 mm.

A methane and hydrogen gas fuel discrete injections into air were studied thoroughly with different injection pressure and frequency of perforated plates to identify the factors that affect the penetration and spread angle of fuel jet. Two sets of perforated plates with different diameter of holes, one with 3 mm and the other with 10 mm, and three values of injection pressure (10 psi, 20 psi and 40 psi), were used.

For each case, the experiments were repeated ten times and a Schlieren movie was recorded for each run. Image processing is based on the averaged movie from ten individual trials. A program, written in Visual Basic and run under Matrox Inspector®, was used to extract a jet penetration depth and spread angle from the Schlieren movies. These two variables are the main raw results used in the analysis that compares the mixing processes under different injection parameters.

In Figure 2 the effect of injection pressure on penetration depth and spread angle of transient (discrete) methane jet in air for three values of injection pressure is shown.



(a) (b)

Fig. 2. Effect of injection pressure on penetration depth (a) and spread angle (b). Methane at 10, 20, 40 psi injected into chamber air; D = 3mm; f =8 Hz in (a) and 4 and 8 Hz in (b).

The results indicate that with increasing injection pressure the methane jet penetrates faster into chamber while its spread angle decreases.

There are differences in the jets penetration dynamics for different gases. For the same injection pressure the hydrogen jet was spreading slower in the near nozzle region and faster in the downstream region than the methane jet.

Numerical simulation

Numerical simulations were performed for a two-dimensional mesh with average cell size of about 0.85 mm^2. Calculations were carried out on SGI Workstation and HP Xeon computer. The computer code KIVA-3V was used for the calculations and GMV package for post-processing.

Figure 3 shows steady-state results for continuous injection of gaseous fuel to open space. Concentration of fuel (black colour represents pure fuel and white one represents pure air) at 50 μs (top row), 100 μs, 200 μs and 400 μs (bottom row) from the beginning of injection is presented. At the first phase of mixing the propagation of methane jet is significantly smaller than hydrogen one. The main reason is that hydrogen jet has about three times higher velocity at the injector nozzle than methane but methane jet has much larger inertia so the jet propagation equalizes soon. The second important difference between these two gases is the size of molecules. Hydrogen molecule is much smaller so mixing with air is better – hydrogen jet is the most dispersed one while methane jet is the most compact one.

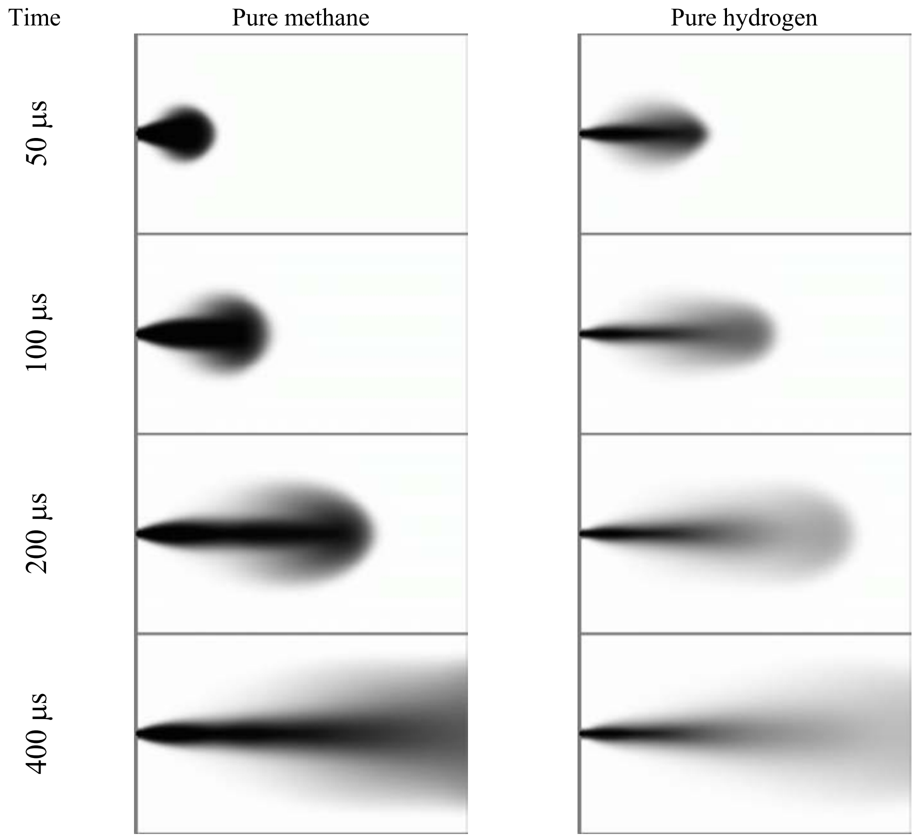


Fig.3 Gaseous fuel jet structure for continuous injection to open space

Figures 4 and 5 show the results for injection of gaseous fuel to constant volume combustion chamber. The duration of injection was equal to 1ms. Figure 4 presents concentration of fuel (black colour represents pure fuel and white one represents pure air) at 0.50 ms (top row), 1.25 ms, 2.00 ms and 2.75 ms (bottom row) from the beginning of injection. In the first phase of injection gaseous jet breaks up on the chamber wall, spreads to the sides, reaches the sidewall very quickly and breaks up once again. These two break-ups intensify mixing process significantly. Mixing of methane jet is the slower again. Even 2.75 ms after start of injection there is a large area with high concentration of fuel.

Figure 5 shows area occupied by flammable mixture in the same injection process for both fuels. White colour represents mixture that is outside of the flammability limits for each fuel. The area occupied by flammable mixture forms much faster and is bigger for hydrogen jet. At the 2.75 ms mark almost entire chamber is filled with the flammable mixture and large fraction of that area is comprised of mixture at stoichiometric composition.

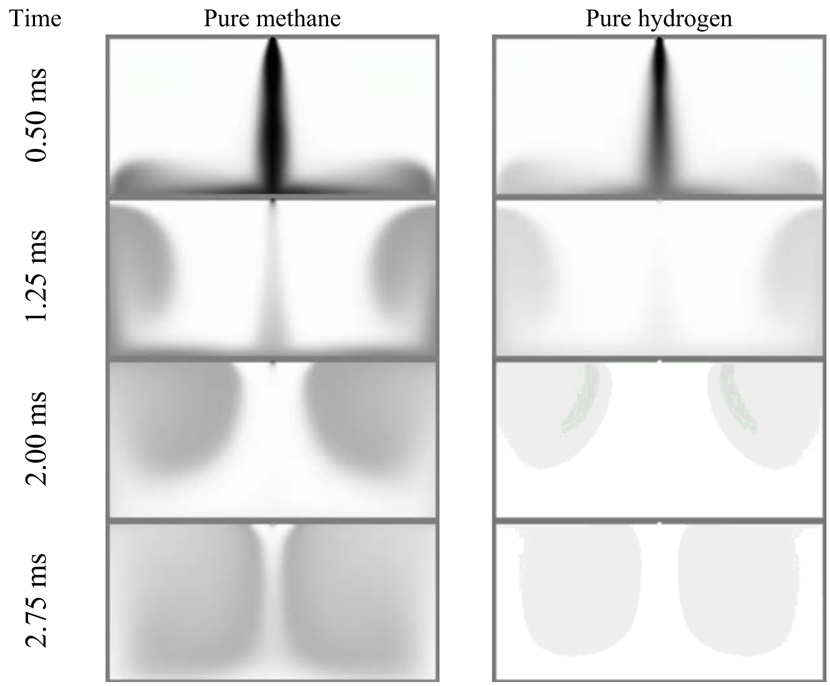


Fig.4. Gaseous fuel jet structure for injection to constant volume chamber

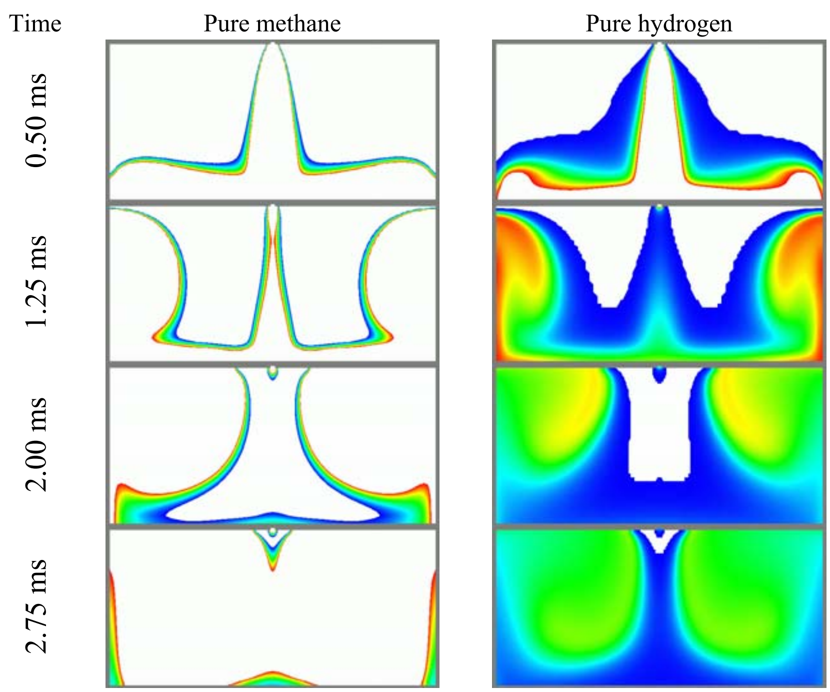


Fig.5. Flammable mixture zone for gaseous fuel injection to constant volume chamber.

Summary

The following observations were made:

1. In experiments, the transient (discrete) turbulent jet, produced by a commercial gas injector exhibited a self-similar behavior after traveling downstream the distance of about 10 nozzle diameters.
2. The range of perforated plates oscillation frequencies used in this study did not produce noticeable difference in mixing, possibly due to the fast decay of initial turbulent kinetic energy of chamber air.
3. The use of perforated plates with smaller holes inhibited the gaseous jet axial penetration and enlarged its spread angle.
4. In numerical simulations, the continuous turbulent jet of hydrogen injected into an open space penetrated faster that the jet of methane at the same injection pressure.
5. Injection of finite amount of hydrogen into a constant volume chamber has show again faster spread and flammable mixture formation than that of the discrete methane injection.