Experimental investigation of characteristics of transient low pressure wall-impinging gas jet

Jingzhou Yu, Harri Hillamo, Ville Vuorinen, Teemu Sarjovaara, Ossi Kaario, Martti Larmi
Department of Energy Technology, Aalto University, Finland
E-mail: jingzhou.yu@aalto.fi

Abstract. This paper describes an investigation of the jet structure and mixture formation process of wall-impinging gas jet injected by a low pressure gas injector in a constant volume chamber at room conditions. The tracer-based planar laser-induced fluorescence (PLIF) technique is applied to qualitatively evaluate the mixture formation process. The macroscopic structure and concentration distribution of wall-impinging jet were studied based on a series of time evolution high-definition images. In particular, the effects of injection pressure on characteristics of turbulence were investigated. Experimental results show that vortex structure with large scale is one of important characteristics for wall-impinging jet, and the interaction among jet flow, impingement wall, and surrounding air plays a dominant role in the mixture formation. The comparative study about the effect of injection pressure on wall-impinging jet reveals higher injection leads to higher mixing efficiency and better mixture formation.

1. Introduction

According regulations for 2014 in the US, heavy-duty truck emissions will be limited to be 0.001g/bhp h of particulate matter (PM) and 0.05g/bhp h of nitrogen oxides (NOx). Relative to 1994 regulations, these aggressive targets represent reductions by factors of 150 and 100 in PM and NOx emissions, respectively (Gao et al., 2009; Mueller et al., 2004). However, it is difficult to simultaneously reduced both PM and NOx in a cost-effective manner, due to the trade-off relationship between PM and NOx. On the other hand, with the increasing industrialization and motorization of the world, the demand of conventional petroleum-based fuels, such as diesel and gasoline, are increasing rapidly. In addition, the remaining global oil resources appear to be sufficient to meet demand up to 2030 as projected in the 2006-2007 world energy outlooks by the International Energy Agency (IEA) and worldwide petroleum reserves are expected to be depleted in less than 50 years at the present rate of consumption (Gupta et al., 2010; Kjørstad & Johnsson, 2009). Therefore, how to realize a sustainable development for conventional internal combustion (IC) engines is an important task for engine manufactures.

Although many engine research centers and companies are focus on electric vehicles and fuel cells in recent years, there still some tough problems need to be solved, e.g. cost, battery capacity, top speed and the recharge and refueling infrastructures. Therefore, many IC engine experts believe that, in the near-future, the best way to sustainable development IC engines is to design high-efficiency clean combustion engines with alternative fuels. Many alternative fuels, such as natural gas, Dimethyl ether (DME), bio-diesel, ethanol, hydrogen, etc., have been investigated...
in IC engines in the last decade. Natural gas is considered as one of most promising alternative fuels for conventional IC engines providing positive effects both on the environment and energy security. That’s because natural gas is the cleanest fossil fuel, and there are huge natural gas reserves in the world (Nichols, 1994). There is nearly zero PM emissions for natural gas fuelled engines. Previous investigations reported that natural gas fuelled vehicles reduced toxic emissions by 70-85 percentage, in comparison with gasoline and diesel oil. Moreover, natural gas fuelled engines produce negligible emissions of the carcinogen mutagenic hydrocarbon species classified by the U.S. Environment Protection Agency (EPA)(Barros Zrante & Sodr, 2009). Although natural gas for intake manifold injection has been successfully used in passenger cars and city buses, natural gas for direct-injection compression ignition (DICI) engines is considered to be the final target due to the high thermal efficiency and low emissions.

However, natural gas is difficult to be compressed ignition due to its chemical properties. In order to solve this problem, natural gas direct-injection (DI) with diesel pilot ignition engine using stratified combustion concept is developing by our ongoing project. This kind of stratified operating conditions is a non-uniform mixture distribution in the combustion chamber to achieve optimum fuel efficiency by ensuring overall lean combustion whilst providing adequate fuel near the pilot diesel spray for reliable ignition. Another big problem for developing high performance DI natural gas engine is the unclear mixing process of gas jet. Because the mixture formation process for gas-fueled engines differs considerably from that of liquid-fueled compression ignition (CI) engines and spark ignition (SI) engines, e.g. there are no droplets and evaporation in the jet.

Actually, the mixture formation of high pressure gas jets has been studied by many researchers (Rubas et al., 1998; Bruneaux, 2002; Salazar & Kaiser, 2009), and research results theoretically and experimentally demonstrate the benefits of high pressure gas jets in facilitating fuel/air mixture formation in constant chamber and optical engines. However, high pressure injection needs high performance gas injector (no lubrication). In addition, high pressure gas needs too much energy consumption from compressor. From this point of view, low pressure gas jet might be preferred for future gas combustion engine, in particular in power plant gas engines. Unfortunately, low pressure gas jet has low fuel-air mixing efficiency due to its short penetration and low turbulence.

In order to enhance the mixture formation of low pressure gas jet, wall-impinging gas jets are experimentally investigated in this study. Behaviors of inclined wall-impinging jet are visualized using tracer-based planar laser-induced fluorescence (PLIF) technique. The effect of wall impingement on low pressure gas jet mixture formation is investigated to provide information on mixture formation of low pressure gas jet impingement. The fuel concentration distribution and mixture formation of the transient low pressure wall-impinging jet are investigated based on a series of high resolution PLIF images. In addition, a comparison to different low injection pressures is made.

2. Experimental apparatus and methods

2.1. Tracer selection

Nearly all aliphatic hydrocarbons, such as methane (the main component of natural gas) and propane, are transparent within the spectral range of interest, and there is no fluorescence signal emission when the laser goes through them (Schulz & Sick, 2005). Moreover, most laser pump systems are only capable of producing discrete wavelengths, thus limiting the choice of excitable molecules (Kirchweger et al., 2007). For example, the Quanta-Ray Lab-Series Pulsed Nd:YAG Laser, used in the present study, is commonly applied as an excited light source in PLIF measurement system, but it is a pulsed oscillator-only system that has only four kinds of output wavelengths (1064, 532, 355 and 266nm). Hence, it is of great importance to
select an appropriate fluorescence tracer for indirect visualization of the non-fluorescence fuel concentration distribution. For these reasons, tracer-based PLIF technique is widely used for measuring the fuel concentration distribution.

According to a number of previous studies (Lozano et al., 1992; Zhao & Ladommatos, 1998; Schulz & Sick, 2005; Salazar & Halter, 2009), several properties of the tracer should be considered in PLIF measurement system: (1) High vapor pressure at room temperature; (2) Low toxicity and low cost; (3) As similar as possible to the fuel, and stable and soluble in fuel; (4) Satisfactory fluorescence yield, because low tracer concentrations are important for low absorption and only small changes of the gaseous fuel properties; (5) Compatibility with air and sufficiently low quenching properties; (6) Absorption of the available laser wavelength; (7) The excitation and fluorescence spectra don’t overlap, so no absorption of the generated fluorescence signal takes place on its way to the detection optics; (8) High fluorescence signal levels, to maximize attainable signal-to-noise ratio (SNR). Moreover, the tracer concentration had to be low enough so that the fuel characteristics were not changed much and laser sheet attenuation across the medium was minimal, yet sufficiently high so adequate signal was obtained (Hwang et al., 2007).

Existing studies (Lozano et al., 1992; Thurber, 1999; Thurber & Hanson, 1999; Tamura et al., 2001; Wermuth & Sick, 2005) indicate that acetone (CH$_3$COCH$_3$) seems to be an ideal tracer for PLIF concentration measurements in gaseous flows. Acetone nearly meets all above requirements as a fluorescence tracer. It has good signal levels, low toxicity, and high saturation vapor pressure. Figure 1 shows the relationship between saturated vapor pressure and temperature (Lozano et al., 1992). Moreover, acetone has not only a broad absorption band stretching from 225nm to 320nm with a peak between 270nm and 280nm, but also a broad fluorescence emission, ranging from 350nm to 550nm with a peak near 445nm and 480nm. Therefore, it allows straightforward experimental implementation of acetone PLIF measurement.

2.2. Gas injector selection
In the present study, a commercial Bosch NGI2 natural gas injector was used, as shown in figure 2. It is a solenoid-valve injector, and its maximum injection pressure (Pinj) is 7bar. It was driven by a standard injector driver, and the supply voltage is 14V with dead time 0.45ms. The diameter of nozzle exit is 5.6 mm.

Figure 3 shows the injection rate of NGI2 natural gas injector under different injection pressure. The test medium is nitrogen at 23 Celsius. It can be seen that the volume flow velocity of the injector at the exit is nearly linear relationship with the injection pressure. It
indicates that the jet momentum is directly related with the injection pressure. Higher injection pressure leads to higher momentum of the jet.

2.3. Experimental setup

The general schematic of the gas jet PLIF measurement system is shown in figure 4. It mainly includes three parts: gas jet system, tracer seeding system and PLIF instrumentation. For all of the tests performed the gas being injected is N2 rather than natural gas for safety reasons. For tracer seeding system, a pressure vessel which was approximately 2/3 full of liquid acetone is used as an acetone seeder. The gas (N2) from the high pressure gas bottle was split into a main flow and a bypass flow. The bypass flow was directed through the acetone seeder with bubbling. And then the acetone vapor was homogeneously mixed with gas in the pipe and accumulator. There are two ways to adjust the concentration of acetone in the gas flow. Firstly, it can be easily adjusted by the two needle valves on the main flow pipe and the bypass flow pipe. Secondly, the acetone concentration in the gas flow can be easily adjusted by the temperature of liquid acetone. The first way was selected in the present experiment. To avoid liquid acetone backflow, a check valve was installed upstream of gas supply pipe near the pressure vessel. An inclined flat wall was mounted in the chamber to study the characteristics of impinging jet. The
impingement angle was 83 degree. In other words, the inclined angle of the flat wall was 7 with the horizontal.

In order to weaken the fluctuation of jet pressure and keep the constant injection rate during the gas injection, an accumulator was connected with the injector. The injection pressure can be controlled and adjusted by a pressure regulator near the high-pressure bottle. The gas injector was installed on the bottom of the spray chamber. The pressure and temperature in the chamber are in room conditions. In this experiment, the concentration of acetone vapor was adequate without hot water outside of the acetone pressure vessel. The room temperature was 20 Celsius and room pressure was 1 bar.

3. Results

3.1. Mixture formation of wall-impinging jet

Figure 5 demonstrates the structures and concentration fields of low pressure wall-impinging gas jet under injection pressure 7bar. The first column is the instantaneous images, and the second column is the corresponding average images. Each average image is obtained from 30 instantaneous images. It can be seen that the tip of transient free jet has arrived at the inclined impingement wall at time after start of injection (ASOI) 1.6ms. Once the jet tip impinges on the still wall, the velocity and the momentum of jet tip is considerably decreased, and then the gas fuel is accumulated on the wall. Hence, the jet impingement region has higher concentration. As time goes by, the accumulated gas is pushed by the following gas flow and forced to spread around along the wall from the impingement point, but there is air resistance in the front of the spreading jet tips. Due to its low momentum of the spreading jet tips, two rolled-up structures are formed near the tip region, as it can be seen at time ASOI 1.8ms in figure5. These rolled-up structures can also be called wall-vortex. The wall-vortex structure is the typical behavior in the wall-impinging jet, which is very helpful for air-entrainment and mixture formation.

On the other hand, the jet structure and concentration field display asymmetrical features, and the turbulence eddy, from small to large-scale structures, are noticeable. In instantaneous images, the fuel concentration field shows a sharp decay distribution, and the high fluctuation region obviously occurs at sides of the jet. Moreover, the twist structure can be clearly
Figure 5. Time evolution PLIF images of low pressure wall-impinging jets. Injection pressure: 7bar. Injection duration: 3ms.
Figure 6. Visualization of wall-vortex structure and concentration distribution of instantaneous wall-impinging jet. Note the different intensity scale for the lower right corner image. $P_{\text{inj}}=7\text{bar}$, time ASOI 2.8ms.

discerned in the free jet region (between the nozzle exit and impingement wall). All these typical characteristics of low pressure wall-impinging jet can be illustrated by the stretch and squeeze effects which is caused by shear-induced turbulence. However, all these behaviors in instantaneous images are invisible in average images. In the average image, the concentration field displays smooth decay from the jet center to the border, and the highest concentration regions are the jet center and the jet impingement regions. It also reveals that the good mixture formation region is in the tip vortex regions.

3.2. Structure of the Wall-vortex
Vortex is a typical structure of impingement jet. It is very important to analyze the internal structure of impinging jet to better understand the interaction among the gaseous fuel flow, surrounding air and the impingement wall. Generally, the formation of vortex structure in gas jet can be defined three stages: vortex cores forming stage; vortex structure growing and distorting stage and vortex structure broken-up stage. In particular, the vortex structure growing and distorting stage plays an important role to promote fuel-air mixture formation process and spatial distribution.

Figure 6 shows the typical vortex structure of fully developed instantaneous wall-impinging jet under the injection pressure 7bar. After the wall-impinging jet is fully developed, the wall-vortex structure and fuel distribution can be clearly visible. It can also be seen that the surrounding air can be significantly entrained into the vortex region. The direction of large-scale motions in the vortex region is shown by the red arrows, and the yellow arrows indicate surroundings entrainment direction. The purple circle indicated the vortex center. Based on the local concentration field in the wall jet region, it is easily imagined that air-entrainment phenomenon not only takes place in the vortex region, but also occurs in the wall jet region.

3.3. Variation of the wall-impinging jet
Figure 7 shows the variation of low pressure wall-impinging jet. The concentration fields of instantaneous images are normalized by the maximum concentration in each PLIF images. In the same injection conditions, although the tip penetrations are in the same range, the fluctuation and variation of the concentration fields and structures can be clearly observed in the instantaneous images, in particular in the vortex region and free jet region. These phenomena can be mainly explained by the variation of jet-to-jet and intensely turbulent flow of gas jet. On the other hand, although there are no cavitations inside the injector nozzle, the nozzle turbulence induced instabilities can’t be neglected, in particular in higher pressure gas jet.
3.4. Effects of injection pressure

To investigate the effects of injection pressure on the concentration distribution and mixing process, two injection pressures 3 bar and 7 bar were performed in this study. Figure 8 displays the instantaneous images (or single shot images) and the corresponding average images, respectively. Contrary to the lower injection pressure (3 bar), the eddy structure in higher pressure gas jet (7 bar) is finer in the instantaneous images, which means the mixture formation is good. It can be illustrated by the turbulence intensity. Under higher injection pressure, the shear-induced turbulence is stronger, so the fuel/air mixing process can be enhanced. In general, in lower injection pressure jet, large-scale structures are more visible, but the mixing efficiency is poor. Because the low pressure gas jet has low jet momentum, and it can be easily disturbed by the surrounding air. It means that surrounding air can go to the inside of the jet and more air can be entrained into the jet. However, there is not enough turbulence energy for molecular mixing with small-scale motions which is very important for fuel/air mixing. For high pressure gas jet, both the large-scale motions and small-scale motions have very strong turbulence energy for air-entrainment and molecular mixing. Hence, higher injection pressure jet has higher mixing efficiency.

4. Conclusions

Concentration fields and macroscopic structures of low pressure wall-impinging jet were studied with tracer-based PLIF technique based on a series of PLIF images. The effects of injection...
pressure on wall-impinging jet characteristics were compared and discussed. Results show that the interaction among jet flow, impingement wall and surrounding air plays a dominant role in the mixture formation. Vortex structures with large-scale motions are the remarkable characteristics for wall-impinging jet. The turbulence eddy structures are finer in the high pressure jet due to its higher turbulence energy. The comparative study about the effect of injection pressure on wall-impinging jet reveals higher injection leads to higher mixing efficiency and better mixture formation. Wall-impinging jet can be considered as a potentially promising approach to enhance the mixing process of low pressure gas jet.

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