

Fuel Film Behavior Analysis Using Simulated Intake Port

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ABSTRACT

Transient behavior of the engine is one of the most crucial factors for motorcycle features. Characterization of the fuel film with port fuel injection (PFI) is necessary to enhance this feature with keeping others, such as high output, low emissions and good fuel consumption. In order to resolve the complicated phenomena in real engine condition into simple physical issues, a simulated intake port was used in our research with Laser Induced Fluorescence (LIF) technique to allow accurate measurement of the fuel film thickness, complemented by visualization of the film development and spray behavior using high-speed video imaging. Useful results have been conducted from the parametric studies with various sets of conditions, such as injection quantity, air velocity and port backpressure.

INTRODUCTION

Port fuel injection (PFI) system widely used for majority of the gasoline-fuelled automotive engines. Combining this with other systems, such as catalytic converter and engine control system, automotive engines perform very clean and efficient without sacrificing output. This kind of concept is now getting popular also for small engine applications due to growing demand for low environmental impact. Well sophisticated the concept has already been for automotive application, there are still technical issues for small engine applications, especially related to the fuel film on the wall of intake port. For example, transient behavior of the engine is emphasized much more for motorcycle application. Smaller displacement results in shorter distance between injector and

the wall on the other side of the intake port. Higher engine speed is also a factor that makes design difficult.

Behavior of the fuel film generated on the intake port wall is one of the most important factors determining the air/fuel mixture distribution in PFI engine that affects the engine performance; output, exhaust emissions and transient response [1,2]. Zhao et al [3] investigated ways to reduce wall wetting in intake port and suggested that the injector type and intake port design must be adequately matched for achieving this. In order to reduce wall film, some research has focused on fuel spray and atomization using an air assisted injector. For example, Maier and Wittig [4] reported better fuel atomization than conventional injectors, which helps to reduce the wall film in the intake port and thus reduce the chances of fuel reaching the engine cylinder in the form of large droplets. The implied correlation between fuel film build-up in the intake port and HC emissions was confirmed by Felton et al [5] during their research on engine cold start.

However, generation of the wall film seems very difficult to prevent with low-pressure injection, considering the size of the generated droplets of recent injectors although it is getting smaller year by year. A reference result was reported by Nemecek et al [6], who showed that droplets with diameter less than 20µm are easily entrained into airflow while SMD of state-of-art injectors is more than 70µm.

Measurement techniques to quantify the property of the fuel film and its characteristics have been studied and developed by many research groups. LeCoz and Baritaud [7] introduced a quantitative method for measuring the fuel film thickness.

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based on the laser-induced fluorescence (LIF) technique. They found that the best tracer is 2,3-hexanedione (4% mass in iso-octane), judging by its co-evaporation similarities with the research fuel, its excitation wavelength (He-Cd laser at 441.6nm) and its fluorescence intensity. An error analysis has shown a 7% maximum error and a slightly non-linear response with film thickness up to 500µm. Johnen and Haug [8] developed an alternative measurement system (using fiber bundle LIF) to quantify the fuel film development. They used an Ar+ cw laser tuned at 457.9nm as the light source and 5%-vol. 2,3-butanedione in iso-octane. The error in reproducibility of the determined fuel film thickness during calibration was claimed to be up to 5µm. Lingren et al [9] developed a wall film thickness measurement device based also on LIF and suggested the measurement accuracy to be of the order of a few microns. The light source used in their research was a pulsed Nd:YAG laser at 266nm while the fuel was iso-octane mixed 3% vol. 3-pentanone, which has similar physical properties to gasoline. Seven fibers were bundled as one centrally for transmitting the excitation light and six others were positioned coaxially for collecting the fluorescence light. Most recently, Yukihiro T. et al [10] used fiber-based LIF to measure liquid film thickness during engine cold start, where a He-Cd laser (442nm) is utilized and iso-octane is doped with 2,3-butanedione. Another technique has been reported to measure the wall film thickness without LIF by Shedd et al.[11,12,13]. The principle is based on the total internal reflection at the liquid surface of the light introduced from backside of the transparent wall. The size of light ring generated by the reflected light corresponds to the thickness of the film. This technique seems rather simple, although this needs transparent wall and image analysis to quantify the size of the light ring.

In this research, a fuel film thickness measurement system based on LIF has been developed, which has a rather simple setup and high accuracy. Complemented by high-speed visualization, the fuel film measurement technique in a simulated intake port has provided very interesting results about the film development; a representative sample of the results are presented here and discussed followed by conclusions.

EXPERIMENT APPARATUS

FUEL FILM THICKNESS MEASUREMENT SYSTEM

Various setups have been proposed for LIF-based quantitative fuel film thickness measurement [7,8,9,10] in intake ports of gasoline PFI engines; the common requirements are compatibility of the tracer with the fuel (iso-octane), sufficient fluorescence intensity of the mixture and high measurement precision and accuracy.

Shown in Fig. 1 is the schematic setup of the optical devices. All the optical components are concentrated onto a small cubic optical box instead of being mounted on an optical bench. A fiber cable, the sensor of the system, is installed at any location on the wall measurement of the fuel film thickness. A single fiber cable is used to both transmit the excitation light and collect back the fluorescence light. The light source is an Ar+ cw laser tuned at 457.9nm. A 45° dichroic mirror is used to separate the collected fluorescence from the excitation laser light. It also reflects a small

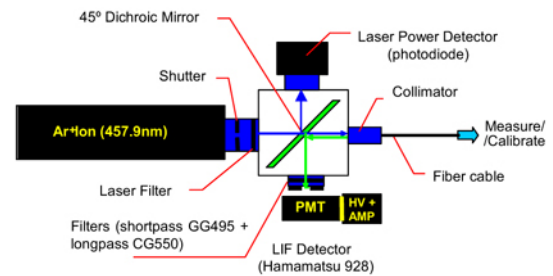


Fig. 1. Schematic setup of the optical devices

fraction of the laser light (around 2% of total power) to a photodiode as the laser power reference. Due to high sensitivity to the light intensity, a photo multiplier (PM) is used to quantify the intensity of the fluorescence. In front of the photo multiplier tube, filters are introduced to remove any unwanted light and improve the S/N ratio. In addition, a shutter is introduced to switch the passing of the laser beam for calibration purposes.

The theory behind the fuel film thickness measurement based on LIF can be described by the following equations. First, the Lambert-Beer's law shows the relationship of the incident light intensity and the light transmitted through a liquid fuel film, stated as:

$$\frac{I_{out}}{I_{in}} = \exp(-\alpha \cdot c \cdot \delta) \quad (1)$$

Then the intensity of the fluorescence generated within the fuel film excited by the laser is given by:

$$I_{fluor} = Q \cdot I_{in} \cdot (1 - \exp(-\alpha \cdot c \cdot \delta)) \quad (2)$$

For thin film, (2) can be approximated by the linear relationship:

$$\frac{I_{fluor}}{I_{in}} = Q \cdot (\alpha \cdot c \cdot \delta) \quad (3)$$

Based on this formula (3), fuel film thickness can be obtained from the laser power monitored by a photodiode and the fluorescence intensity measured by the photo multiplier, as follows:

$$\delta = k \cdot (I_{PM} / I_{PD}) \quad (4)$$

where k is determined by calibration, while the ratio inside the parenthesis is defined as the normalized LIF signal.

CALIBRATION OF FILM THICKNESS MEASUREMENT

Intensity of the LIF must be converted to fuel film thickness data using calibration data. It has been obtained by using calibration rig. An optical fiber from the same optical devices has been introduced into the rig. Fuel film thickness has been controlled using micrometer in the rig.

In this research, 5% vol. 2,3-hexanedione has been added to iso-octane as dopant. The co-evaporation characteristics of the mixture have been summarized by LeCoz and Baritaud [7]. The result of the calibration for iso-octane is shown in Fig. 2, which indicates a linear relationship for film thickness between 0 and 200 μm . At a confidence level of 95%, the accuracy of the fuel film measurement using this in-house LIF system for iso-octane is estimated to be $\pm 7\mu\text{m}$.

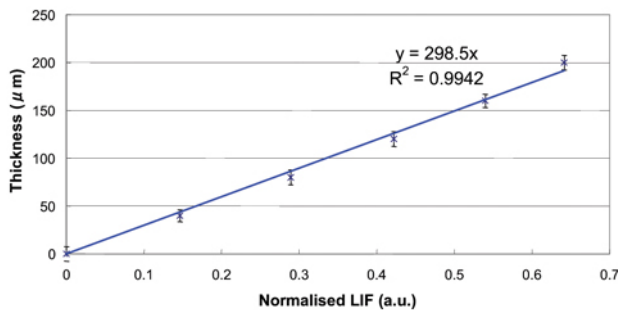


Fig. 2. Calibration curve for iso-octane doped with 5% vol. 2,3-hexanedione at ambient temperature (26°C)

We have also tried to test conventional gasoline as fuel in order to know the effect of the fuel property. The calibration data for conventional gasoline without dopant has been obtained as shown in Fig. 3. This result shows similar intensity level of the fluorescence to that with the doped iso-octane. Within the range of fuel film thickness examined in the calibration (0-200 μm), the measurement accuracy at a confidence level of 95% is also estimated to be $\pm 7\mu\text{m}$. This data has encouraged us to test also gasoline without dopant as fuel.

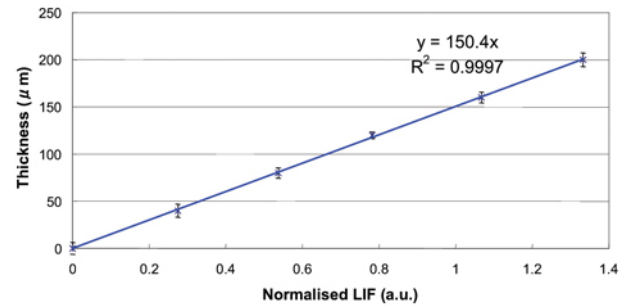


Fig. 3. Calibration curve for conventional gasoline at ambient temperature (26°C)

FLOW TEST RIG

Figure 4 shows the diagram of steady flow test rig. It consists of a flow meter, an upstream dumping barrel, a throttle, and a wind tunnel called “simulated intake port”, the downstream dumping tank and a blower. The simulated intake port comprises a wind tunnel with a square section of 20mm×20mm, three transparent walls (one top and two sides) and a bottom wall whose surface is finished as cast aluminum. The wall temperature is controlled between ambient and 90°C. A fuel injector is installed on the top wall injecting fuel towards the bottom wall where the fuel film develops. The angle between injection direction and airflow is 45 degrees. The optical fiber is allowed to access the fuel film through a small hole on the wall for measuring the fuel film thickness. It is located at 50mm downstream of the injection tip location. The airflow in the simulated intake port can achieve velocity up to 100m/s and/or a depression of 0.5bar, which are representative conditions of those prevailing in an engine intake port under a typical operating regime.

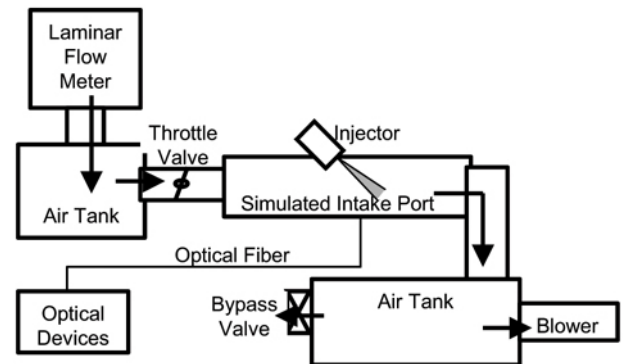


Fig. 4. Diagram of Flow test rig

Figure 5 describes setup of the visualization experiments including a high-speed video to visualize the formation and development of the fuel film in the simulated intake port. The angle and location of the camera and the illuminating lamp are optimized to guarantee high quality film images. The