

Investigation of Spray Evaporation and Numerical Model Applied for Fuel-injection Small Engines

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ABSTRACT

The purpose of this research is to develop a prediction technique that can be used in the development of port fuel-injection (hereinafter called PFI) gasoline engines, especially for general purpose small utility engines. Utility engines have two contradictory desirable aspects: compactness and high-power at wide open throttle. Therefore, applying the port fuel injector to utility engines presents a unique intractableness that is different from application to automobiles or motorcycles. At the condition of wide open throttle, a large amount of fuel is required to output high power, and injected fuel is deposited as a wall film on the intake port wall. Despite the fuel rich condition, emissions are required to be kept under a certain level. Thus, it is significant to understand the wall film phenomenon and control film thickness in the intake ports. In this study, spray characteristics and film thickness have been measured with an experimental apparatus, which recreates the phenomena in an intake port. In parallel, in order to develop a prediction technique by use of general-purpose computational fluid dynamics software, numerical calculations have been performed and verified with experiment results. Based on the verification of the accuracy of the simulation, a performance prediction model for a port fuel injection small engine has been developed.

INTRODUCTION

Currently, to grapple squarely with global environmental issues as represented by global warming, governments around the world are tightening regulations for fuel consumption and smog emission standards. At the same time, continuing BRICS's rapid economic growth boosts energy demand. On another front, with oil prices soaring, the Organization of Petroleum Exporting Countries (OPEC) has announced to leave the target value for oil production unchanged next year. Therefore, all energy industries have a strong incentive to increase

replacement demand for more energy-efficient products, which produce much more power with fewer energy sources and cleaner operation. And energy engineers are taking up this mission to develop the technology for lower fuel consumption and cleaner emissions. The utility engine industry is no exception. As a fuel supply system, carburetors have prevailed for general purpose utility engines. In order to develop utility engines with better fuel consumption and emission characteristics, fuel injectors are coming into use with electric control.

Injectors are widely used in industry for fuel supply, therefore an enormous amount of research on atomization techniques have been done over the past decades. By the same token, in the field of the internal combustion engine, the port fuel injection technique has been developed because it is imperative to lower the emissions and fuel consumption of fuel injected engines, which are usually diesel or direct injection gasoline engines. Therefore, the primary characteristics of fuel injection, including droplet breakup, evaporation from droplets and wall impingement, have been studied. [1-3]

In applying the injector in general purpose utility engines to supply fuel, a unique intractableness, which is different from automobile or motorcycle applications, exists. General purpose utility engines have two desirable, but contradictory aspects: compactness and high power at wide open throttle. The latter condition especially makes applying fuel injectors challenging, because a large amount of fuel is needed and a certain quantity of fuel accumulates as fuel wall film at wide open throttle conditions that exerts a harmful influence on the exhaust gas. Therefore, the studies about the fuel wall film have been done in the past. [4-8] However, in order to apply fuel injection in general purpose utility engines, research on wall film at conditions typical for an intake port are still needed. In this study, in order to develop a prediction technique that can be used in the development of PFI small utility engines, the wall film thickness measurement and calculation in the intake port are taken into consideration.

MEASUREMENT APPARATUS

In order to investigate the film thickness in an intake port, experiments have proceeded in three steps. As the first approach to the experiment, the spray behavior itself has been measured with a simple injection chamber at atmospheric pressure and room temperature conditions with laser metrologies. In this investigation, the spray characteristics measured include the spray shape, penetration distance and particle size distribution by means of flow visualization and a laser diffraction particle size analyzer.

In the second approach to the experiment, the influence on spray behavior by the ambient conditions, including gas cross-flow velocity in the field of injection and wall temperature at the impingement surface, has been measured. These are important elements for port fuel-injection engines because they strongly effect the fuel evaporation. The experimental equipment was built up that can reproduce conditions similar to those inside an intake port of a port fuel injection engine. The flow visualization and velocity distribution measurements described above have been performed under several engine operating conditions, controlling the ambient flow velocity and the wall temperature.

Finally, the wall film thickness has been measured at several wall temperature and gas cross-flow velocity in the field of injection.

SPRAY CHARACTERISTICS

Fuel Injector

The injector is the Keihin Corporation's injector, KN-5 Short, which has 6 straight holes on the flat plate at 60 degrees of interval. The injection pressure is 350kPa.

Experiment apparatus

To measure the spray characteristics, the test chamber has been designed, which is surrounded on all four sides by glass and has ports for exchange of gases on the top plate. It is a rectangular parallelepiped with square cross section, 50 mm on a side. An injector has a port at the center of the top plate on the test chamber, and as the mass flow meter, ONO SOKKI Co., Ltd.'s FP-213S, is connected between fuel pump to injector. The fuel has been sprayed initially at atmospheric pressure and room temperature conditions.

Flow Visualization

The major spray characteristic penetration and spray shape have been analyzed from the visualized images with high-speed camera, which is an IDT Inc. XS3 CMOS camera.

Particle size distribution measurement

The measurement of the particle size distribution has been done with Malvern Instruments Ltd.'s spray particle analyzer, Spraytec™. The instrument is a laser diffraction particle size analyzer, which is based on the laser diffraction technique accepted for a wide range of industrial applications. The principle is that the angles of scattered light created from droplets cutting across a single laser beam correlate directly with their diameter. The light source is 2 mW helium-neon laser of 632.8 nm wave length. The measurable particle size range is 0.1μm to 2000μm and the maximum acquisition rate 10kHz.

AMBIENT EFFECTS ON SPRAY BEHAVIOR

Experiment apparatus

In order to recreate the conditions in an intake port, the experimental apparatus has been designed as shown in Figure 1. This apparatus consists of three sections. First, the working gas delivery system was constructed of a surge tank and pressure regulator. The second part is the test section, in which the flow visualization and wall film thickness measurement have done. The third part controls the pressure and velocity at the test section, and includes a venturi-based flow amplifier to adjust the exit pressure of the test section and an exhaust system.

The surge tank has 450 liters as the capacity, and is filled with compressed nitrogen gas under 690K Pa. The regulator attached on the outlet of surge tank controls the relief pressure. The flow rate is controlled with the valve after the regulator. A picture of the test section is shown in Figure 2. The test section has the similar structure as a typical wind tunnel, including a flow straightener, contraction tube and measurement section. The 20 millimeters square test section is surrounded on all four sides by glass windows to permit flow visualization and film thickness measurement. As the transparent glass heater, Delta Technologies Limited's CB-50IN, which has 5 to 15 W sheet resistance, has been used instead of the bottom glass plate. The velocity at the measurement part can be measured via the pressure difference between two pressure sensors, and ambient temperature and wall temperature are measured with two thermocouples at the measurement section. Additionally, an adjustable flow amplifier, which can produce the negative pressure, is attached after the measurement section for the purpose of keeping the total pressure constant. The adjustable flow amplifier is from ANVER Corp., model FT075. For the exhaust system, in order to separate the fuel droplets from the mixture gas, a gas-liquid separator is applied at the end of the experimental apparatus. The maximum operation range of this experimental apparatus is 80 m/s and 433 K as the ambient velocity and wall temperature respectively.

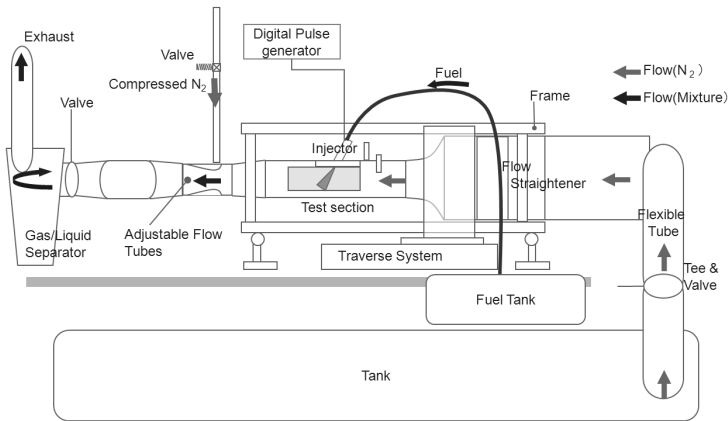


Figure 1 The experimental apparatus

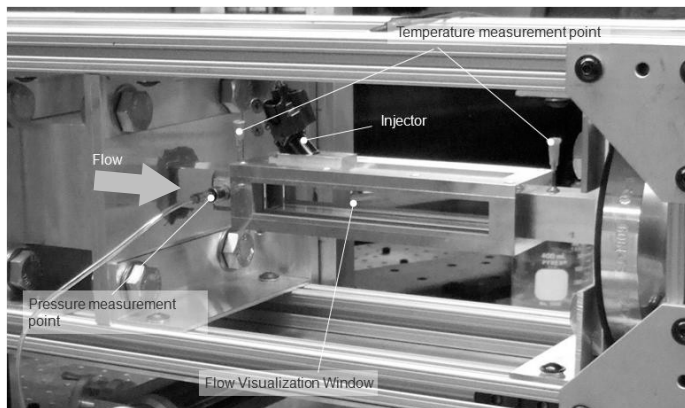


Figure 2 The test section

Flow Visualization

In order to examine the influence on spray behavior from the ambient condition, the flow visualization has been done at different gas cross-flow velocities and wall temperatures at the impingement surface. To capture the injection, the injector, a YAG laser (TSI Inc's LASERPULSE™ Y12-15) as light source, and a digital camera are controlled with a trigger output from a Berkeley Nucleonics Corp. model 555 pulse delay generator.

WALL FILM THICKNESS

Measurement principle

The film thickness is measured by use of the optical measurement system which is developed by Shedd and Newell in 1998. [9-11] The principle of this liquid film thickness measurement is based on total internal reflection from the liquid interface. When a light source passes through the two materials which have different indices of refraction, gasoline and air in this case, the light can be reflected from the surface of the liquid with an angle greater than or equal to the critical angle. Therefore, the reflected light generates a ring shaped reflection, because the light source goes through the liquid surface with an angle less than critical angle. And

the reflection angle is only a function of index of refraction of the liquid. Figure 3 shows the basic concept and the following formula explains the relationships.

$$\theta_{crit} = \sin^{-1}(1/n)$$

Where, θ_{crit} is the reflection angle from the liquid surface and n is index of refraction respectively. If the edge line of the ring can be measured, the film thickness can be calculated from the difference between ring diameter at dry condition and wet condition because the line is created from the reflected light with critical angle. The formulas show the relationship between the difference in radius and the film thickness and Figure 4 shows the reflected ring at dry and wet condition.

$$r_{wet} - r_{dry} = 2t_{film} \tan(\theta_{crit})$$

$$t_{film} = (r_{wet} - r_{dry}) / 2 \tan(\theta_{crit})$$

Where, r_{dry} and r_{wet} are radius at dry and wet condition, which is measured from the reflection ring, and t_{film} shows the film thickness respectively.

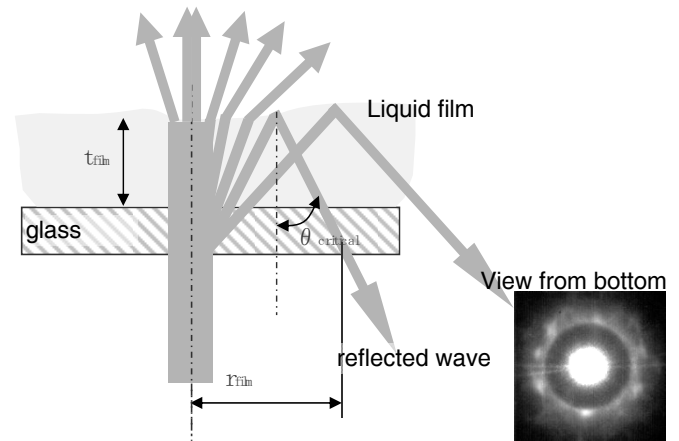


Figure 3 conceptual figure of the optical film thickness measurement system

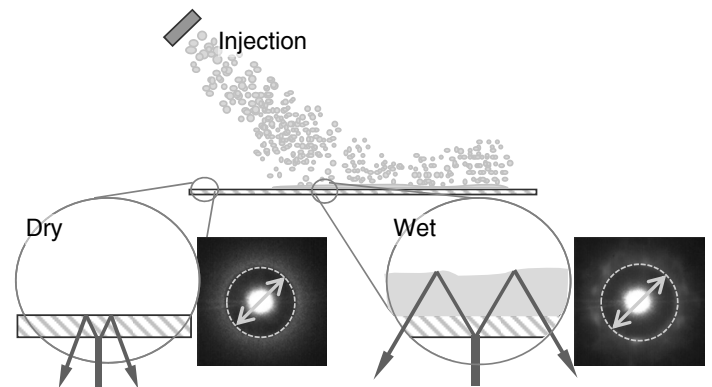


Figure 4 reflection rings at dry and wet condition

Measurement apparatus

The film thickness measurement system consists of Photonfocus AG's MV-D1024 TrackCam as camera and