Liquid Fuel Footprints on Combustion Chamber Wall in Port Fuel Injection Engine during Starting

Hoisan Kim, Suckju Yoon, and Ming-Chia Lai.[1], Sergio Quelhas, Rick Boyd, and Joon-Ho Yoo.[2]

1. Wayne State University Detroit, MI 48202 USA
2. Delphi Corp. Brighton, MI 48116

Unburn hydrocarbon (UBHC) emissions have been the major pollution concern for gasoline engines, and is subject to ever stricter clean air legislation. It's well known that during startingconditions, gasoline engines produce more UBHC emissions due to insufficient fuel evaporation, enrichment starting strategy, and cold catalyst aftertreatment. An experimental study was carried out to investigate the effects of fuel injector spray pattern, targetting, injection timing and engine condition on the distribution of wetted fuel footprints on the combustion chamber surfaces of a four-valve port-fuel-injection engine during starting condition. These footprints on the cylinder liner wall and piston top land are the results of mixture formation processes during starting condition, and is the major source for unburn hydrocarbon emissions in emission cerfication test cycles and oil dilution. In addition to characterizing the spray performance, spray targetting on the intake valves, the fuel film formation processes on intake valves were visualized using optically accessible engine. In order to obtain the wetted footprints in combustion chamber, a color image capturing technique using dyed fuel and high absorptive paper was developed. A small amount of Rodamine B was used as dye to be dissolved in gasoline or fuel surrogate, which was then injected through the actual fuel supplying system. The paper was attached on the inside circumference of the cylinder liner and on top of piston to collect fuel films or droplets. The results show that by comparing the locations of the wetted footprints and their color intensity, the influence of fuel injection and engine conditions can be qualitatively and quantitatively examined.

1. Introduction

Mixture formation in the combustion chamber of an engine has a major effect on the subsequent combustion process and the undesirable emission products. Most spark-ignited (SI) gasoline engines utilize indirect port fuel injection (PFI) and rely on the the subsequent air intake process for additional fuel-air mixing [1]. Due to the large amount of unburned hydrocarbon (UBHC) generated by SI engines during the cold start and warm-up cycles, mixture formation characteristics during this period have been given more attention. This is primarily due to the fact that liquid fuel injected into the cold intake port and subsequently carried into combustion chamber by intake charge motion is poorly vaporized during starting conditions. Because of the low vapor pressure of fuel in this condition, extra fuel is required to produce enough vapors for a successful ignition and stable flame propagation.

The extra liquid fuel will accumulate in liquid films or pools at the intake port and on the combustion chamber wall. Moreover, fuel films on the cylinder wall, crevices and piston top land may flow directly into the crankcase during compression and expansion stroke, and create oil dilution problem.

Pool fire on the combustion chamber surfaces may also be a source of UBHC emissions at cold start. The unburned fuel vapor escaping from the insufficient pool fire process or just vaporizing directly from the fuel film during the later expansion stroke may enter the exhaust pipe directly and result in increase in UBHC emissions. Generally, the optimum fuel preparation conditions for low HC emissions are a well atomized spray, a spray targeted at the back surface of the intake valve head for minimum intake-wall wetting, and injection timed to occur during the intake valve-closed period [2,3].

Yang et al. [4] studied the effect of port injection timing and fuel droplet size on total and speciated exhaust hydrocarbon emissions. In their study, cylinder liner wetting by large fuel droplets during open valve injection (OVI) is the main reason for the hydrocarbon emission increase, the change in the hydrocarbon species distribution in the exhaust gases and fuel losses.

Shin et al., [5] and Meyer and Heywood [6] observed the liquid fuel entry into the cylinder and its behavior through the combustion cycle by high speed CCD camera system in a transparent engine for simulated cold start and described three liquid fuel transport mechanisms into the cylinder in details: 1) strip atomization of liquid fuel by intake flow; 2) fuel film formation on the valve surface and seat; 3) liquid film squeezing by the closing valve. The observed in cylinder liquid film were also categorized: 1) thick film at the valve surface and around the valve seat formed by the liquid film flow from the back of the valve and the port surfaces; 2) thin film o the combustion chamber surfaces formed by the impingement of the droplets stream from strip atomization; 3) isolated puddles formed by the landing of the splashed drops from the intake valve closing process.

Takeda et al. [7] analyzed quantitatively the fuel amount of intake port and cylinder wall wetting, burned fuel and engine out hydrocarbon emissions, utilizing a specially designed analytical engine during cold starting and warm up. It was found that intake port wall wetting increases until 300th cycle and then decreases gradually as the engine warms up, cylinder wall wetting decreases gradually with time, and high engine out hydrocarbon emitted just after cold engine start and decreases gradually as the engine warms up.

Witze and Green [8] applied imaging techniques to investigate the evolution of liquid fuel films on combustion chamber walls during a simulated cold start of a port fuel injected engine. It was found that for closed valve injection (CVI) condition, fuel films form below the intake valve and below the squish region between the intake valves and the cylinder wall, and for OVI condition, fuel films form below the exhaust valves. It was also expected that fuel films on the head near the exhaust valves are a direct source of unburned hydrocarbon emissions and fuel films on the cylinder wall are s source of fuel blow by into the crankcase, and that pool fires are a source of soot.

Zughyer et al. [9] visualized the liquid fuel distributions and flame propagation inside a PFI gasoline engine under different injectors and engine conditions. Their study showed that significant part of the fuel droplets hit the far end of the cylinder wall at the exhaust valve side and some of the droplets were found to travel toward the short side of the intake valves. From the flame propagation visualization and in-cylinder pressure measurement, it was found that injector with better dispersion and injection under open-valve condition may provide a better fuel distribution and evaporation, and improved engine starting strategy.

2. Experiment Setup

In spite of the large number of research publications on PFI mixture formation, there has not been a direct measurements or characterization of the distribution of the fuel films or droplets impinging on the combustion chamber surfaces during the engine starting conditions. In this paper, a new color image capturing technique (CICT) was developed to investigate the effects of fuel injector spray pattern, targetting, injection timing and engine condition on the distribution of wetted fuel footprints

on the combustion chamber surfaces of a four-valve port-fuel-injection engine during starting condition.
A 0.55-liter, DOHC cylinder head was mounted on a single-cylinder optical accessible engine with transparent piston crown and extended piston [4]. In addition, a 62mm section of transparent acrylic cylinder tube was wedged between the engine head and the extended cylinder block, providing access of white light source into the chamber. The acrylic cylinder section has a slightly larger bore than the piston to accommodate the filter paper during piston motion. The cylinder block and its crevice also reduced the engine compression ratio from the original 9.5 to 8.2. A stationary 45-degree inclined mirror was installed on the cylinder block inside the elongated piston. The camera viewing through the inclined mirror could observe both film formation around intake valves and the wall wetting on the fire deck during intake processes. For the results presented in this paper, the engine was fueled with solvent fuel surrogate. The fuel injection pressure is fixed at 300 kPa using compressed nitrogen cylinder. The specification of the engine and test conditions is listed in Table 1.
Similar to previous study, spray visualizations and measurements were carried out in a spray chamber capable of presurized and vaccuum conditons [1]. Spray targetting on the intake valves were visualized inside the optically accessible intake port [3]. Fuel film formation processes on intake valves were visualized using optically accessible engine [9]. In order to characterize the liquid fuel ditribution on the cylinder liner wall and piston top land during a simulated engine started up from room temperature, a color image capturing technique (CICT) using dyed fuel and high absorptive filter paper was developed. A small amount of Rodamine B was used as dye to be dissolved in gasoline or fuel surrogate, which was then injected through the actual fuel supplying system. The filter paper was attached on the inside circumference of the cylinder liner and on top of piston to collect fuel films or droplets impinging on the surfaces.
To visualize the spray in chamber or in intake port, either a pulsed arc lamp or continuous white light source have been used. The images were recorded using a Kodak EM-1012 EKTAPRO high-speed digital camera. Collected frames were saved on videotapes, while selected movies frames were digitized. In this experiment most of the fuel injection was enabled for two cycles only to optimize the visual effect. In wall wetting visualization study inside engine, high-speed digital video images were recorded for the 4 consecutive cycles up to 1000Hz framing rate. The engine was motored to the specified constant speed before fuel injection. After filling the camera memory, engine was shut off immediately and cooled to a pretest condition and waited for 1 hour to dry out all fuels inside engine and intake port. Because of the window contamination resulting from wall wetting at cold start, optical windows and acrylic liner were cleaned after each test. Table 1 summarizes the different engine operating conditions tested in this experiment.

Table 1 Engine Specifications

Specifications	**Optical Engine**
BorexStroke	86mm x 108 mm
Compression Ratio	8.2
Engine Speed (RPM)	150, 200, 250, 300
Injection Timing	OVI: 360^{o} BTDC CVI: 102^{o} BTDC

The synchronization of fuel injection and data acquisition was controlled using LabVIEW program.

To minimize the variability in cranking speed, the engine was motored at a constant speed. Different test procedures were implemented for liquid fuel and combustion visualizations. Fig. 1 illustrates the engine control and data acquisition flow chart.

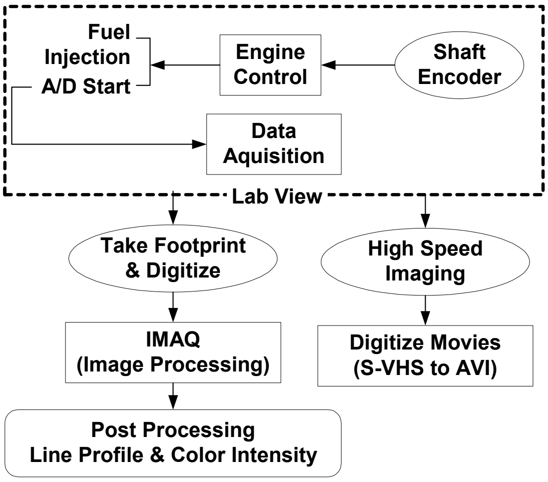


Figure 1. Flowchart of Data processing

The injectors tested are all multi-hole injectors, 3 dual-stream (DS) and 1 single-stream (SS). The injection duration is 45ms to simulate over-enrichment conditions for engine starting. Table 2 summarizes the injector examined. The injection duration used for the engine starting conditions is typical of the enrichment strategy used in current engines. The SMD is measured at the maximal flux point using PDPA.

Table 2 Injector Specifications

Injector	No. of Holes	DS/SS	Rel. Flow Rate	SMD
A	10	DS	80	110
B	12	SS	80	100
C	12	DS	130	100
D	12	DS	140	130

3. Result and Discussion

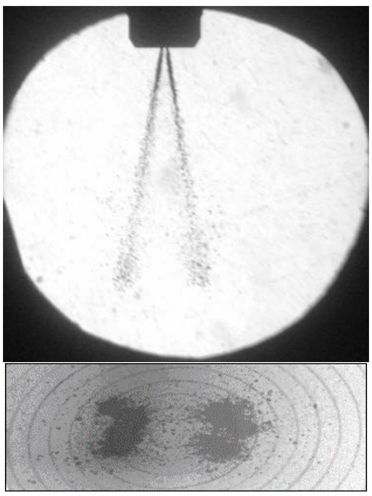


Figure 2. Typical spray behavior with Footprint at 3.2ms after SOI (Injection duration 2.5ms)

Fig. 2 shows spray backlit spray image of Injector A and its footprints at the target distance of the intake valve, which enable one to determine the quality of target point on the intake valve. The optimal targeting condition is usually taken that the centroid of the spray impingement footprint is that relative to the back surface of the intake valve head for minimum intake-wall wetting intake valve. Injector A has a narrower stream separation angle compared to the other dual-stream injectors C and D, which have better targeting performance to match the intake port geometry. Unless otherwise noted, the results shown in this paper is for Injector A.

The engine is first motored to a fixed rotation speed, before a fixed number (usually 2) of injection events take place. High-speed movies or CICT techniques were used to characterize the in-cylinder fuel-wall interactions.

For CICT, the digitized images of filter paper on the liner and piston top are analyzed. In order to quantify the image technique, the total color intensity of the images was acquired, which is the summation of each pixel of color intensity calculated from whole area. A simple test of injection directly into filter paper at targeting distance is carried out. Each spray injection has around 12mg for a 2.5ms injection duration, and

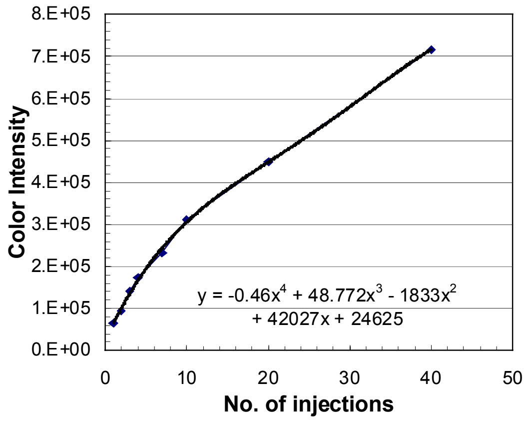


Fig. 3 Color intensity of accumulated wetted spray footprints

the accumulative effect is shown in Fig. 3. It shows that the total color intensity is not exactly linear, because of dye penetration deep into filter paper due to soaking. But at small mass of fuel injections, the color intensity can be used correlate to the liquid fuel mass on the filter.

Fig. 4 shows the cylinder-liner footprint images with different number of enrichment injections. It clearly shows serious wall wetting from fuel film running down the liner from the intake with increasing number of enrichment injection events. The intake-valve side of the cylinder liner is the main area for fuel wetting, which is caused not only by fuel film running down liner, but also fuel droplets splashing from the intake valve.

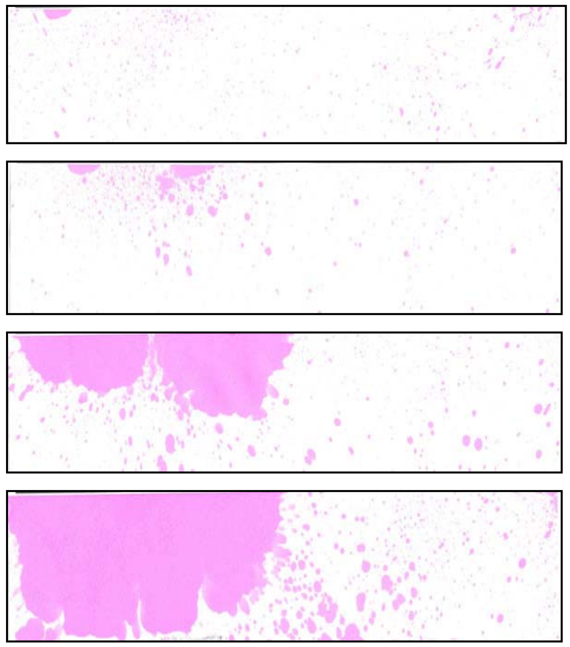


Fig. 4 Cylinder Liner Footprint of different number of injection events:

(a) 1 (b) 2 (c) 5 (d) 7

The color intensity of the digitized images is shown in Fig.5. The reason that two injection cycles were chosen for most of the test conditions is obvious: The first injection is injected into a dry intake port; therefore, not enough footprints is produced to characterize the process. More than two

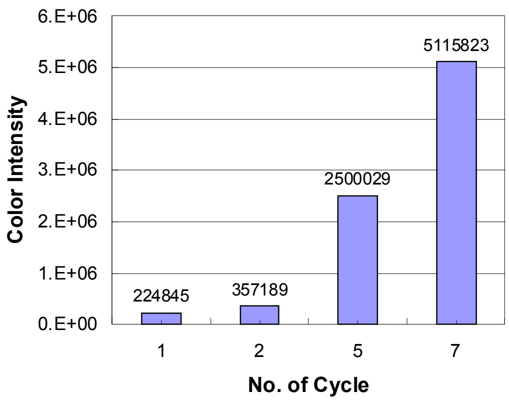


Fig. 5 Accumulative effect of injection events

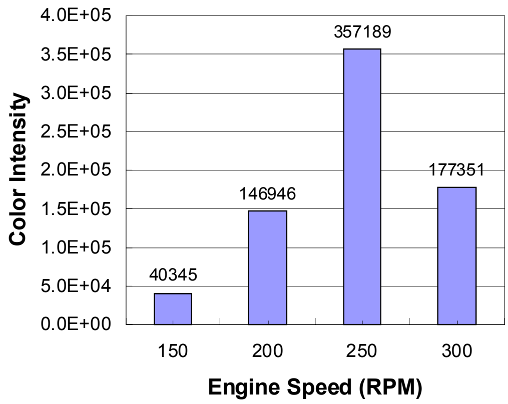
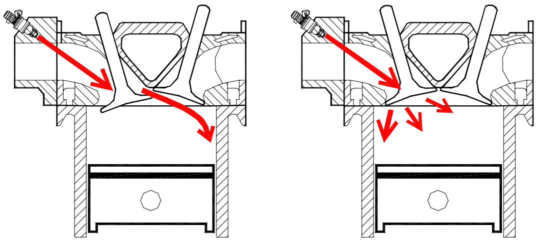


Fig. 6 Effect of Engine Speed on Color Intensity

injections, however, makes it difficult to differentiate the over-wetted patterns and is not representative of current engine starting fueling strategy.

The effects of engine cranking speed on the cylinder liner wetted footprints are also determined experimentally. Engine cranking speed increases induction air speed during intake stroke and have a significant effect on liquid fuel trajectory such as film stripping from the intake valve. As shown in Fig. 6, increasing the engine-cranking speed from 150 to 250 rpm increases the wall wetted footprint areas and the resultant color intensity. However, at the higher engine speed of 300 rpm, the behavior changes, with less fuel wetting on the liner wall possibly due to stronger turbulence mixing.

The CICT technique is applied to see the effects of two injection timing modes: CVI (closed valve injection, 102° BTDC) and OVI (Open valve injection, 360 ° BTDC) on liner wetted footprints. Due to the intake air motion, PFI ports with typical tumble flow geometry will produce wetted patterns very different patterns of wetted footprints, as envisioned in Fig. 7.



(a) OVI (b) CVI

Fig. 7 Comparison between OVI and CVI

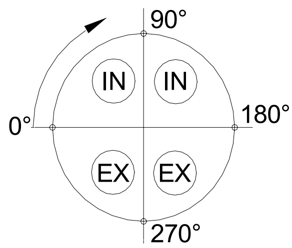


Fig. 8 Circumference

The line-integral profile of color intensity along the liner circumference was also calculated by summation of color intensity along each vertical column of the digitized footprint. The circumference angle start at the mid-plane dissecting the cylinder between the intake and exhaust valves, as shown in Fig. 8.

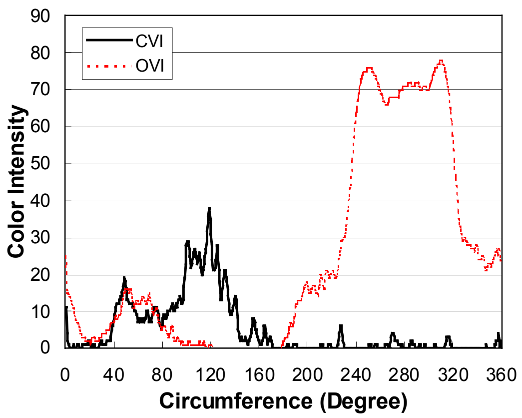


Fig. 9 Line Profile; Effect of Injection Timing

The results as shown in Fig. 9 confirm that more serious liner wall wetting was generated on the exhaust valve side with OVI, consistent with Taketa et. al. [7].

The liner and piston top footprints of different injectors are shown in Fig. 10~13 for CVI and OVI conditions. The CICT technique is shown to have enough sensitivity to investigate and reduced UBHC during engine starting conditions.

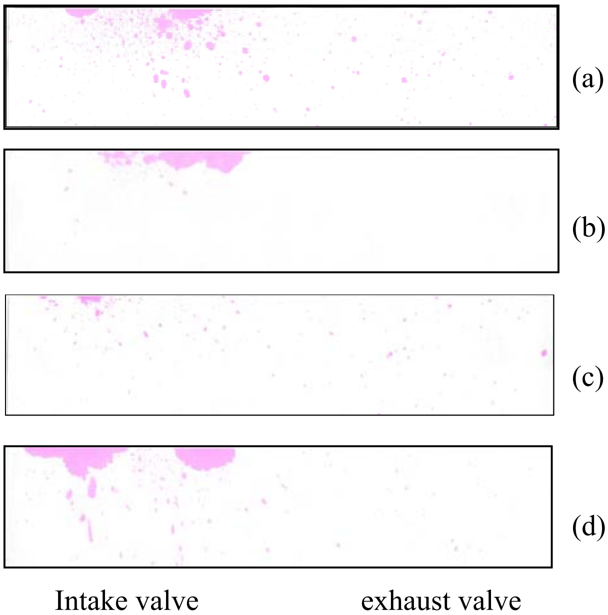


Figure 10. Cylinder liner footprint under CVI conditions with different injector: (a) A (b) B (c) C (d) D

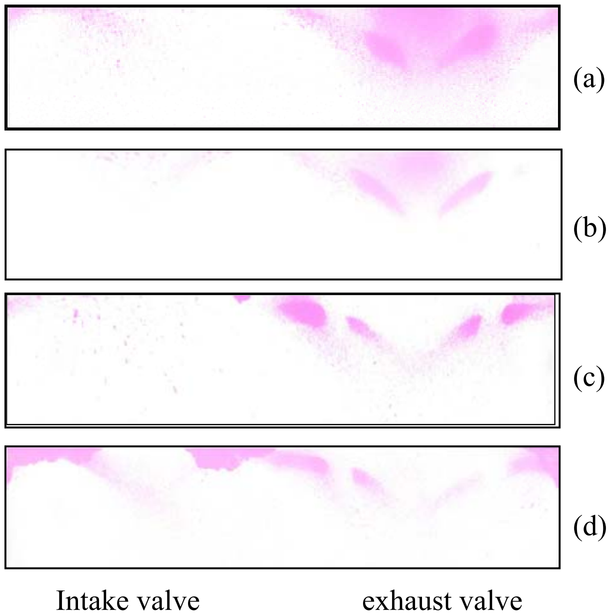


Figure 10. Cylinder liner footprint under OVI conditions with different injector: (a) A (b) B (c) C (d) D

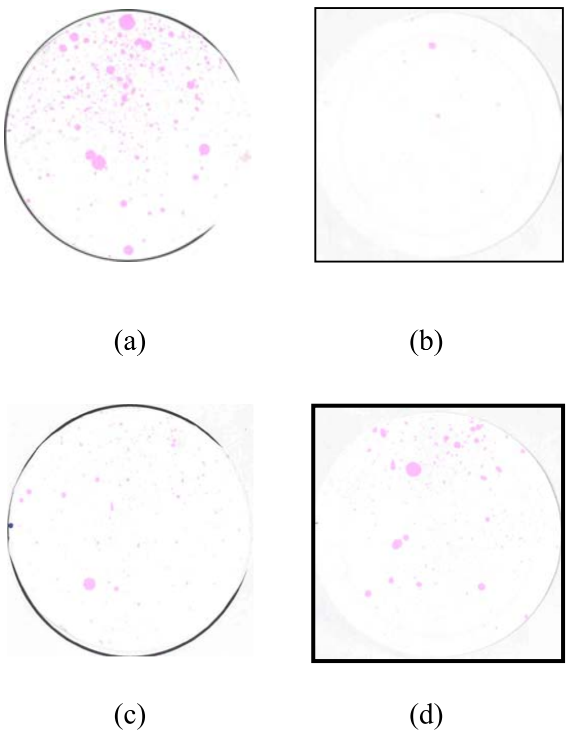


Figure 11. Piston top-land footprint under CVI conditions with different injector:

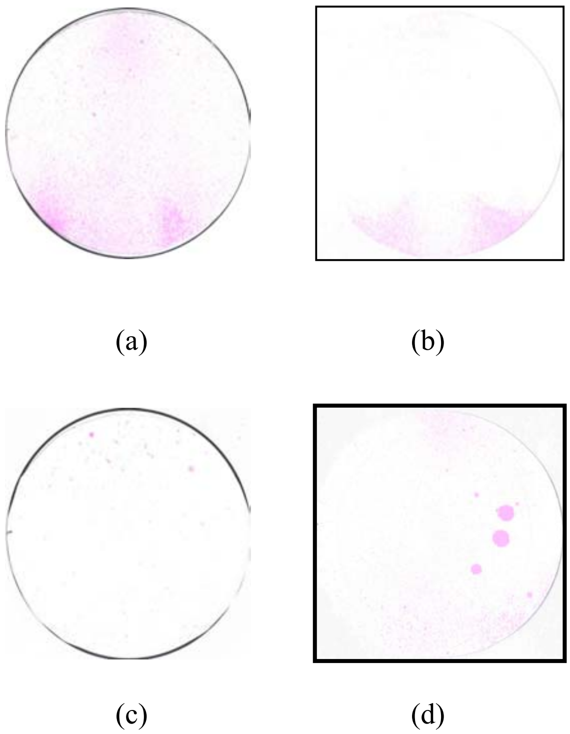


Figure 13. Piston top-land footprint under OVI conditions with different injector:

5. Conclusions

A New measuring method, color image capturing technique (CICT) was conducted to compare effects at different conditions (engine speed, injection timing, and injector type) in the optical accessible engine. At engine starting condition, CICT technique demonstrate that it can be used a tool to investigate liquid fuel distributions in combustion chamber wall and to reduced UBHC emissions. Specifically, the results of the currently investigation show the following trends:

- Effect on Engine Speed:
  As engine speed increased, color intensity increased and then decreased at 300rpm due to air motion and suction pressure at intake stroke.

- Effect on number of enrichment injection events:
  Two injections appear to show the best results in terms of sensitivity. Injecting more than 2 cycles, fuel films flow from intake port to the cylinder liner faster than that during first cycle due to fuel accumulations inside the intake port.

- Effect on Injection Timing:
  Wall wetting is main factor of engine out HC emissions. The wall wetting phenomenon is quite different between the OVI and CVI mode.

- Effect of Injector type:
  CICT techniques show great sensitive to screen injector design for minimize wall wetting. Injectors with better targeting and better dispersion can reduce the fuel wetted footprints on combustion chamber wall.

6. References

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