Fuel 215 (2018) 111–122

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

The effects of surface temperature on the deposit behaviors of gasoline on a hot surface

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ARTICLE INFO

Keywords:
Deposit
Gasoline
Hot surface
Evaporation
Low temperature oxidation

ABSTRACT

The formation of the internal deposits inside a gasoline direct injection (GDI) injector is directly related to the oxidation of the remained gasoline in the nozzle after injection. In the present paper, an experimental facility and procedure for gasoline deposits forming on a hot surface were carefully designed to simulate the deposit behavior inside the GDI injector. In the experiments, the evaporation characteristics of gasoline droplets were observed, and the quantities of deposits at different temperatures of the hot surface were measured. Besides, the morphology, elements and components of the deposits obtained at different surface temperatures were examined to identify the variation of the components in gasoline after heating and oxidation. The experimental results showed that surface temperature influenced the evaporation form of droplets significantly, which would be reflected in the morphology of the deposits obtained, leading to the deconcentration and miniaturization trend of deposits with the increase of surface temperature. The variation in the quantities of deposits obtained with the surface temperature presents a two-peak shape, and the main components of the deposits in the two peaks differed completely in terms of morphology and elements. The heavy ends of the gasoline, such as naphthalene and its derivatives, should be responsible for the major deposits forming at low temperature, and the oxidation degree of deposits increased with the temperature. In addition, carbon-oxygen double bond was generated universally at each temperature, and the benzene ring was abundant in the deposits obtained at a lower temperature, while seldom existed in the deposits obtained at a higher temperature.

1. Introduction

Gasoline direct injection (GDI) technology has been considered to be a major development direction for future gasoline engine due to its higher efficiency and lower emissions compared with those of traditional port fuel injection (PFI) engines. However, the nozzle of GDI injector was designed to be extruded from the combustion chamber and directly exposed to the high-temperature combustion gas, which would facilitate the accumulation of deposits on it. Therefore, GDI engines faced a much severer problem of injector deposits than PFI engine did. The injector deposits could both restrict the fuel flow [1–3] and alter the spray characteristics of injectors [4–9]. In addition, the low levels of flow restriction could be adjusted by the ECU (Engine Control Unit). However, the high levels of flow restriction and any level of spray distortion could not be adequately electrically controlled, which would impose a negative effect on the combustion in cylinder, cause power loss [10–12], increase fuel consumption [10–12] and exhaust more harmful emission [9–14]. The latest work by Jiang et al. [9] who used a V8 GDI engine to study the effects of injector deposits on spray characteristics, gaseous emission and particulate matter, showed that after 30-h running, the decrease of injector flow rates was 2.21%, and the penetration length and mean droplet size significantly increased. Besides, the emission of unburned hydrocarbons caused by the injector deposits increased 30% and particulate number (PN) emission increased to maximum 5 times.

So far, numerous researchers have conducted investigations on the formation mechanism of injector deposits in GDI engines. The main conclusions included that deposits could form during continuous engine operation [1,15,16] and the internal injector deposits derived from fuel [15,16]. However, it was a rather slow process for deposits to form during the continuous engine operation. To shorten the experiment time without any diminishment of experimental effects, researchers had to use some methods to accelerate the formation of internal deposits, including using bad fuel, applying fuel-rich combustion [15] and running special engine cycles [3,11]. Even so, it would still cost a relatively long time to achieve measurable results. In general, it was difficult for deposits to form inside the injector during continuous engine operation. Paul et al. [17,18] developed a deposit formation procedure for GDI

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https://doi.org/10.1016/j.fuel.2017.11.017
Received 1 August 2017; Received in revised form 5 November 2017; Accepted 7 November 2017

engine that was similar to that for PFI engine (ASTM D5598 [19]). They added a soak period to engine operation, so that they could obtain measurable injector deposits in a relatively short time. They believed that engine soak and injector tip temperature were the most important factors contributing to injector plugging [18]. As a result, it could be concluded from these researches that a majority of the internal injector deposits were formed during the soak period after the key-off of the engine and derived from residual fuel. To be specific, the formation processes of a large proportion of internal deposits were the converting processes of residual fuel after injection to deposits during the soak period.

To conclude, the formation of most internal injector deposits was caused by the oxidation of gasoline in a certain temperature range. Kim et al. [20] investigated the deposits issue by heating the gasoline shut in a test tube with a steel coupon at 100 °C with the aim to understand the behavior of injector deposit in PFI injector. Their laboratory test results consist well with those of engine dynamometer tests. It can be found that the amounts of deposits correlate with time and increase rapidly after an induction period. Bailey et al. [21] investigated the deposit formation of spraying gasoline on heated aluminum tubes at 135 °C and 218 °C through using three different fuels. He found that all deposits studied had quite similar general characteristics, therefore, he thought that there might be a limited number of reactive species in most fuels. However, the GDI engine has been springing up in recent years. Though the deposit problem related to GDI engine has been concerned by many researchers, the understanding of this problem was still inadequate, and the mechanism of deposits formation was still not completely known. Xu et al. [22] conducted a comprehensive review on GDI injector deposits recently. In their work, the mechanism of injector deposit formation, the methodologies for injector deposit study, the impact of fuel on injector fouling as well as the effects of GDI deposit on engine performance were adequately reviewed. However, the particular deposit formation mechanism of specific gasoline components as well as the specific transition processes and results under different temperature conditions of GDI engine were seldom mentioned, due to the lack of research in related literatures. Thus, they concluded that a much more detailed mechanism for deposit formation was required.

To investigate the formation processes of internal deposits in GDI injector, a facility for gasoline depositing on a hot surface under a certain temperature was developed. The deposit formation processes at 130–185 °C were observed. Then, the changes of compositions after gasoline oxidation, as well as the quantities, morphology and main compositions of deposits were measured with high-accuracy balance, scanning electron microscope-energy dispersive spectrometer (SEM-EDS), gas chromatography-mass spectrometer (GC–MS) and microscopes Fourier transform infrared spectroscopy (Micro-FTIR). As a result, the effects of temperature on the deposit formation processes of gasoline were evaluated.

2. Experimental system and setup

2.1. Experimental system

The schematic diagram of the experimental bench is shown in Fig. 1. The experimental system was comprised of three parts, namely depositing plate, temperature controlling system and gasoline injection system.

The depositing plate was consisted of a stainless-steel tray with six grooves (30 mm × 30 mm × 2 mm) and lots of stainless steel sheets (30 mm × 30 mm × 2 mm). All the steel sheets were 2 mm thick from a same steel plate, and their surfaces were polished. In the experiments, the gasoline was dropped on the surface of the stainless-steel sheet, and converted into the deposits attached to the surface. In addition, a new steel sheet was used for each condition.

The temperature controlling system was composed of several K-thermocouples, a PID temperature controller and heating coils. The heating coils were distributed evenly under the depositing plate. One of the K-thermocouples was settled right under the center of the steel sheet in the experiments, which would send a feedback about temperature to the controller. Besides, other K-thermocouples were also set under the steel sheets in other grooves to monitor the fluctuation of temperature. The fluctuation range of the temperature was ± 0.5 °C. An infrared thermometer was applied to measure the surface temperature of the steel sheet. A correlation between the bottom and surface temperature was obtained, as shown in Fig. 2.

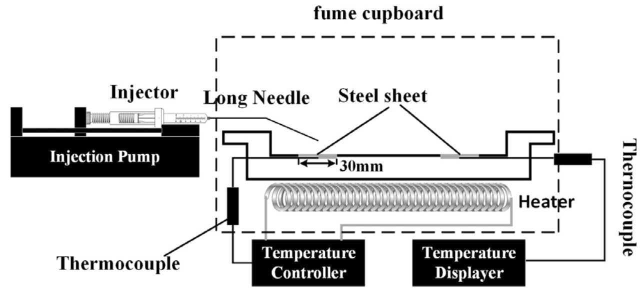

Fig. 1. The schematic diagram of experimental system.

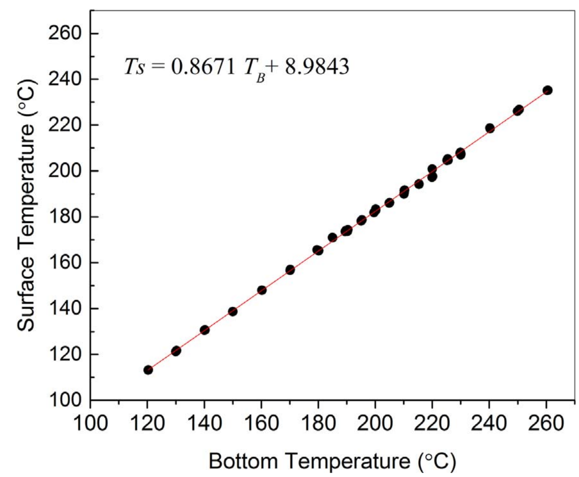

Fig. 2. The correlation of bottom temperature and surface temperature, data of three different steel sheets.

The gasoline injection system was comprised of an injection pump, an injector and a long needle. The injection range of the pump was 0.001–43.349 ml/min, and the set injection rate in the experiments was 4 ml/h. The injector was a 10-ml standard glass injector. To prevent the heat exchange between depositing plate and the injector, the needle used in the experiments was a 100 mm long stainless-steel needle with an inner diameter of 0.2 mm.

An excellent work by Arai group has been conducted to investigate the deposit behavior of diesel and biodiesel based on a similar experimental system, which was mainly related to the piston and chamber diesel deposits under a relatively high temperature [23–25]. Nevertheless, our experimental procedure and targets were totally different from theirs. Therefore, there also was a great difference in the facilities.

2.2. Experimental procedure

The experimental procedure was developed to reproduce the converting process of gasoline to deposits that occurred in the GDI injector right after the key-off of the engine with the aim to make the results measurable and repeatable. The schematic diagram of the experimental procedure is shown in Fig. 3.

The first step of the procedure was to tackle the steel sheets by washing them with a hairbrush to remove its impurity. Then, they were