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Effect of partial-heating of the intake port on the mixture preparation and combustion of the first cranking cycle during the cold-start stage of port fuel injection engine

Tao Li, Kangyao Deng *, Haiyong Peng, Chongmin Wu

Institute of Internal Combustion Engine, School of Mechanical and Power Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai, PR China

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ABSTRACT

For Port Fuel Injection (PFI) engines, excessive fuel is needed for the first few cycles during the cold-start because of the unfavorable evaporation environment. The excessive fuel usually forms a fuel film which causes non-uniform mixture and becomes a major source of the Engine-Out Hydrocarbons (EOHC). In this paper, a partial-heating method was proposed to improve the evaporation of the deposited fuel film at the beginning of the cold-start of PFI engine. The partial-heating method focuses on increasing the surface temperature of the intake port end before the cranking start. In this study, the effect of the partial-heating was researched based on the first cranking cycle. The effect was experimentally investigated and discussed in terms of the mixture preparation, combustion and EOHC. The results showed that within the capacity of the on-board battery, the partial-heating led to efficient and effective heating of the surface of the intake port end. The fuel delivery efficiency was increased by over 10%. Fuel enrichment was reduced from 40 ms FPW to 30 ms FPW within 15 s of the partial-heating. Moreover, the mixture was found to burn faster in the partial-heating cases. Higher Indicated Mean Effective Pressure (IMEP) could be obtained with optimized spark timing in the partial-heating cases.

1. Introduction

The first few cycles are very important to the process of engine cold-start. Successful ignition and combustion of the first few cycles not only reduce the EOHC, but also improve the environment of the mixture formation for the following cycles. Moreover, robust torque output of the first few cycles can accelerate the engine speed efficiently and, therefore, shorten the start time.

However, preparing appropriate in-cylinder mixtures for the first few cycles is difficult. At the beginning of the cold-start, the environment of the fuel evaporation is unfavorable because the temperatures of the intake port wall and the intake valve are low. In addition, the Manifold Absolute Pressure (MAP) is close to the atmospheric pressure. Thus, a large amount of fuel is needed to overcome these unfavorable conditions and form combustible mixture for the first few cycles [1–3]. Consequently, the excessive amount of fuel is likely to deposit on the surface of the intake port end and form fuel film, which usually becomes a major source of the EOHC [4]. Moreover, the deposited fuel film in the intake port has negative influence on the mixture preparation process of the subsequent cycles and causes difficulty in the fuel control of the subsequent cycles.

Many attempts have been made to improve the fuel evaporation and reduce the deposition of the fuel film. One method is to supply more volatile fuels in the cold-start phase. More volatile fuels have higher vapor pressures and molecular diffusivity at low temperatures. Using more volatile fuels requires less fuel delivery to maintain stable combustion during the cold-start [5]. Ashford et al. [6] developed an On-Board Distillation System (OBDS) to extract, from gasoline, a highly volatile crank fuel that allows the reduction of startup fuel enrichment during cold starts and warm-up.

Other methods focus on improving the physical environment for the fuel evaporation, because the physical environment has significant influence on the fuel evaporation. Vasiliev et al. [7] and Gumus [8] developed heat storage systems to heat the entire engine before the cranking start. However, the efficiency was very low because most of the energy was wasted on non-essential places. According to Gumus [8], 600 s of heating can only increase the engine temperature by 17.4 °C, averagely.

There are some more efficient measures to heat directly against the key parts that affect the fuel evaporation, such as injector heating, intake air heating and spark plug heating. Kabasin et al. [9] used heated injectors to increase the temperature of the injection fuel and realized robust and fast ethanol cold-starts down to an ambient temperature of −5 °C without gasoline assistance. Monteiro Sales and Sodré [10] presented a system for flexible fuel engines

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* Corresponding author.
E-mail address: kydeng@sjtu.edu.cn (K. Deng).

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Nomenclature

ATDC	after top dead center
BTDC	before top dead center
CA	crank angle
CVI	closed-valve injection
DC	direct current
EOHC	engine-out hydrocarbon
FBR	fuel burn rate
FPW	fuel pulse width
IMEP	indicated mean effective pressure
MAP	manifold absolute pressure
MBT	maximum breaking torque
MCU	micro controller unit
OBDS	on-board distillation system
OVI	open-valve injection
PFI	port fuel injection
PHS	partial heating system
ppm	parts per million
TDC	top dead center

with heating of intake air and injector. And the cold-start time was successfully reduced to 1.7 s. These measures are more efficient than heating the engine entirely. But none of them address the problem of fuel deposition very well. When the injected fuel spray impinges on the cold intake port wall, the fuel spray loses heat to the cold engine wall quickly and condensates on the surface of the intake wall. In addition, the use of the hot intake air may affect the performance of the engine cold-start, because less air (in mass) can be introduced into the cylinder in the intake stroke.

In this paper, a partial-heating method is proposed to achieve a more effective and efficient pre-cranking heating. A partial-heating system (PHS) is developed to partially heat the intake port end in a short time before the cranking start. The PHS can increase the temperature of the air surrounding the fuel spray to improve the fuel evaporation. More importantly, the hot surface of the PHS can greatly reduce the deposition of the fuel film. The effect of the partial-heating method is experimentally investigated based on the first cranking cycle. The effect is compared under different partial-heating temperatures. The results are analyzed in terms of the in-cylinder mixture, engine performance and EOHC. The experiment results suggest that the partial-heating is an efficient and effective method to improve the mixture preparation. With the effect of the partial-heating, the fuel enrichment is reduced and higher IMEP could be obtained.

2. The experimental setups

2.1. The partial-heating system

The partial-heating of the intake port end was realized by the PHS. The PHS contains two thin-film heaters and a voltage adjustable Direct Current (DC) power (35 V, 150 W). The thin-film heater used flat electric resistance wire as a heat source. The flat resistance wire was 3 mm wide and 0.1 mm thick. The heating wire was, firstly, wrapped in heat-shrinkable tube in order to isolate from the metal intake port. Then the heating wire was bended to designed shape and installed at the intake port end. Fig. 1 shows the intake port end of cylinder #1 installed with a pair of thin-film heaters.

The two thin-film heaters were connected in series and powered by the voltage adjustable DC power. A temperature sensor was used to monitor the surface temperature and control the heating process. The total resistance of the two thin-film heaters was 4.4 ohm. By the adjustment of the voltage of the DC power, the PHS was able to work under different heating powers. It should be noted that, with the fixed voltage of the on-board battery (12 V, 60 A), different heating powers can also be achieved by choosing heating wire with proper resistivity.

As shown in Fig. 2, the thin-film heater is very thin (<0.5 mm). Therefore, its influence on the intake flow is negligible. The PHS has two major functions. Firstly, it increases the temperature of the air at the end of the intake port. The hot air can then promote the evaporation of the fuel spray. And it is worth noticing that, only the air at the intake port end is heated. The rest of the intake air still remains at the environmental temperature. In other words, the PHS has very limited influence on the mass of the intake air. The most important effect of the PHS is the reduction of the deposition of the fuel film. When the injected fuel impinges on the high temperature surface of the thin-film heaters, the heat transfer can increase the fuel temperature quickly and promote the evaporation of the fuel film.

By the adjustment of the voltage of the DC power, the PHS was tested under four different heating powers (20 W, 40 W, 60 W and 80 W). The increase of the surface temperature against heating time is shown in Fig. 3. The surface temperature increased almost linearly under different heating powers. With 20 W of heating power, the temperature increase rate was only 0.38 °C/s. The heating duration of 120 s could only increase the temperature by 45 °C. With higher heating powers, the temperature increased much faster. For example, with 60 W and 80 W of heating power, the surface temperature was increased from 20 °C to 110 °C in 70 s and 50 s, respectively. It is clear that the temperature increase rate was determined by the heating power.

It is important to note that, the process of making the test PHS is very limited by the manufacturing technology in our laboratory. The PHS in this test is only a proof-of-concept sample. There is plenty of room for improvement in its performance. For example, if good thermal isolation is applied, the temperature increase rate could be highly improved. A simple calculation shows that the theoretical temperature increase rate may exceed 20 °C/s with 60 W heating power. ($\Delta T = \Delta E/(m_{PHS} \cdot c_{PHS})$, $\Delta E = 60$ J, $m_{PHS} = 5.6$ g, $c_{PHS} = 480\ \mathrm{J\,kg^{-1}\,{}^{\circ}C^{-1}}$) Moreover, if the PHS is equipped in HEV, the battery set in the HEV could supply much higher heating power.

In the following experiments, the heating power was fixed at 60 W (for Cylinder #1). Under which, the PHS could realize an efficient partial-heating. The temperature increase rate was about 1.3 °C/s. And it is worth noting that if all the four intake ports are equipped with the PHS, the total power consumption is 240 W, which is within the capacity of the on-board battery (720 W).

2.2. The test engine

The experiments were conducted on a production 1.4L GM PFI engine. The specifications of the test engine are listed in Table 1. The physical properties of the fuel used in the experiments are listed in Table 2. The distillation curve of the test fuel is shown in Fig. 4.