Energy Conversion and Management 103 (2015) 191–199

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Study on the combustion and hydrocarbon emission characteristics of direct injection spark-ignition engines during the direct-start process

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ARTICLE INFO

Article history:
Received 25 January 2015
Accepted 13 June 2015
Available online 1 July 2015

Keywords:
Direct start
Direct-injection spark-ignition engine
First-combustion cylinder
Combustion characteristics
Emissions

ABSTRACT

This study was conducted to investigate the combustion and emissions characteristics of the first-combustion cylinder in a direct-start process. The explosive energy of the first combustion is important for the success of a direct start, but this combustion was rarely addressed in recent research. For a 2.0 L direct-injection spark-ignition engine, the in-cylinder mixture concentration, cylinder pressure, engine speed and exhaust hydrocarbon concentration were detected to analyze the fuel evaporation, combustion, engine movement and engine emissions, respectively. In the first-combustion cylinder of the direct-start process, the injected fuel was often enriched to ensure that an appropriate mixture concentration was obtained for ignition without misfiring. Approximately one-third of the injected fuel would not participate in the combustion process and would therefore reduce the exhaust hydrocarbon emissions. The start position determined the amount of the total explosive energy in the first-combustion cylinder, and an optimal start position for a direct start was found to be at a 70–80° crank angle before the top dead center to obtain a better combustion performance and lower emissions. A lower coolant temperature increased the maximum explosion energy of the first combustion, but additional hydrocarbon emissions were generated. Because there was almost no problem in the direct-start capability with different coolant temperatures after an idling stop, it was necessary to maintain the coolant temperature when the engine was stopped.

1. Introduction

Engine start-stop systems are a new vehicle technology that can improve engine fuel economy and reduce emissions under idle conditions [1]. These systems will significantly contribute to the improvement of the urban environment [2], which is caused by traffic jams [3]. In a start-stop system engine is automatically shut off after a definite idle time [4], and then restarted when the driver is ready to move the vehicle forward again [5]. It has been demonstrated that by implementing start-stop technology in a spark-ignition (SI) engine, vehicle fuel economy can improve 4.8% at present [6] and an average fuel economy enhancement of approximately 3–10% per vehicle and a reduction in CO_2 emissions of approximately 20% can be expected in the future [7]. Because of the flexibility of the engine control in a direct-injection spark-ignition (DISI) engine compared with a port fuel injection (PFI) engine [8], injections and ignitions can be precisely controlled in a DISI engine [9], to increase fuel economy, improve combustion stability and reduce engine-out emissions [10]. Thus, a starterless direct start in a DISI engine (which starts only through the use of targeted injections and ignitions without help from the starter [11] and could even further improve the gasoline economy and reduce emissions) is introduced.

Many researchers currently focus on the combustion of the first-combustion cylinder in a starterless direct start [12] because it is crucial to the success of the direct start process. A specified amount of fuel is injected into the first-combustion cylinder during the compression stroke and then ignited. The explosive energy of the air–fuel mixture rotates the crankshaft backwards, and the unburned gas in the second-combustion cylinder is compressed during the power stroke. When the piston of the cylinder reaches its peak position during the power stroke, the strong combustion generated by igniting the compressed air–fuel mixture generates a powerful forward acceleration in the crankshaft. As a result, the direct start is a success after the engine goes beyond the next compression of the top dead center (TDC) of the first-combustion cylinder and the following working cycle [13]. Because there is no compression process in the first-combustion cylinder during the compression stroke, a relatively small amount of explosive energy is essential to ensure the reliability of the direct-start process. The oxygen concentration in the start cylinder is the first emphasis of

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http://dx.doi.org/10.1016/j.enconman.2015.06.031
0196-8904/

Nomenclature

I	Intercept of the linear fit formula
l	Air/fuel ratio
m	Mass
M	Molecular mass
PPM	HC concentration
S	Slope of the linear fit formula
Greek symbols	
ϕ	Air/fuel ratio
Subscripts	
0	Stoichiometric value
air	Air
C_3H_8	Propane
Abbreviations	
ASOI	After start of injection
ATDC	After top dead center
BTDC	Before top dead center
CA	Crank angle
CFD	Computational fluid dynamics
DISI	Direct-injection spark ignition
FID	Flame ionization detector
HC	Hydrocarbon
PFI	Port fuel injection
TDC	Top dead center

this paper because it determines the maximum amount of combustion energy. Kramer et al. [14] used a gas sampling valve to investigate this oxygen concentration. In their study, the oxygen concentration was determined by the average cylinder pressure and the average manifold pressure. This oxygen concentration had a maximum value of 21% (i.e. the concentration of oxygen in the atmosphere). Additionally, because fuel air mixture was enriched in the central region and diluted in the peripheral region [15], it was uncertain whether all of the oxygen would participate in the combustion. The fuel spray characteristics are another emphasis of this paper, as they determine whether the first combustion is adequate or not [16]. Using optical measurements and 3-dimensional computational fluid dynamics (CFD) simulations, Zuelch et al. [17] investigated the mixture formation. In their conclusion, the inhomogeneous mixture formation was identified as the main reason that the burning efficiency observed for the first combustion was low. However, the exact value of the injected fuel mass was indefinite, and the direct-start performance was not taken into consideration to improve the mixture formation. Because the engine was static after injection and there was no air flow in the cylinder, a considerable amount of fuel remained in the liquid state [18], such as wall film that could not participate in the combustion [19]. This led to a great deal of unburned hydrocarbon (HC) emissions and a decrease in burning efficiency [20]. The amount of fuel in the liquid state is therefore necessary in researching the first-combustion process of a starterless direct start.

There are two main factors that could affect the combustion: the start position and the engine coolant temperature. The start position determines the volume of fresh air and the total energy of the combustion. The valves of the cylinder during the compression stroke are closed, and the unburned gas volume is almost constant [21]. The explosive energy during the first-combustion is very important because if the energy is insufficient, the direct start will fail. An excessively increased volume leads to a decrease in the burning efficiency and an explosive energy in the second-combustion cylinder that is too low. Therefore, there was a compromise between the unburned gas volume during the compression stroke and of that during the power stroke [22]. Because the engine stop process is hard to precisely control [23], it is necessary to know the range of the crankshaft positions that can be applied to a direct start. A rise of the engine coolant temperature improves fuel evaporation [24] but decreases gas density and oxygen quantity [25]. Therefore, the engine temperature should be optimized to reach a compromise. The purpose of this study is to investigate the performances of a starterless direct start with different stopping positions and engine coolant temperatures. The mixture concentration around the spark plug was detected by a fast-response flame ionization detector (FID) HC measurement system [26] to obtain the portion of fuel that can participate in the combustion. The equivalence ratio of the mixture was determined. The engine performances and emissions were considered to evaluate the quality of the combustion during the compression stroke and to obtain the optimal injection strategies for different direct-start conditions.

2. Experiment apparatus and procedures

To evaluate the performance of a direct start, experiments are carried out on a 2.0 L DISI engine. Table 1 shows the parameters of this engine. The engine is equipped with a 6-hole high-pressure injector with a maximum pressure of 20 MPa. The injection pressure is approximately 3 MPa in these experiments because the fuel rail pressure is conserved for a period of time after an idling stop [8]. As opposed to the cold-start process of a DISI engine [27], the impact of the injection pressure during this experiment is not considered because the injection pressure could not be adjusted in the direct-start process. The injection characteristics of the injector have been calibrated before the experiment, and the injected fuel mass is proportional to the injection pulse width. The gasoline is used in these experiments was 95RON. A Kistler 6125B cylinder pressure sensor is used in the first-combustion cylinder to analyze the combustion, and the cross-section schematic of the cylinder is shown in Fig. 1.

A fast-response FID HC measurement system is used to measure the HC concentration. The response time of the system is less than 1.5 ms and can resolve fast HC variations, and the delay time is less than 5 ms. An in-cylinder sampling probe (shown in Fig. 1) and an exhaust sampling probe are used to detect the mixture concentration around the spark plug and the HC emissions, respectively. The

Table 1
Parameters of the engine.

Engine type	Inline 4-cylinder DISI engine
Displacement	2 L
Compression ratio	9.2
Bore	86 mm
Stroke	86 mm
Connecting rod	145.5 mm
Horsepower	164 kW@5300 r/min
Torque	350 N m@2000 r/min