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Full Length Article

Improvement of diesel combustion with multiple injections at cold condition in a constant volume combustion chamber

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HIGHLIGHTS

- Lower peak of flame luminosity was observed under cold start condition.
- Cold startability was improved by applying pilot injections before main injection.
- Increase in pilot injection quantity was advantageous for better main combustion.
- Fuel flow toward crevice volume was detected with first pilot injection.

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ABSTRACT

A series of diesel spray combustion tests was carried out in a constant volume combustion chamber (CVCC) to investigate the effect of multiple injection strategies on cold startability. The experiments were performed under a simulated low temperature cold start condition. In-chamber pressure analysis and high speed flame imaging were conducted to compare the effectiveness of each injection strategy on cold startability. Spray targeting visualization was also performed to examine the wall impingement of injected fuel. The diesel fuel was injected into the CVCC with an injection pressure of 35 MPa. Multiple injection strategies with different amounts of pilot injection quantities were applied to improve the diesel combustion under simulated cold start ambient condition. The flame imaging and in-chamber pressure results showed that the multiple injection strategy provided better cold startability than the single injection condition. According to the pilot injection quantity, the peak of the flame luminosity and in-chamber pressure were gradually increased with larger pilot injection quantity cases. The peak of the variation rate of the in-chamber pressure with a multiple injection strategy was approximately 2 times higher than that of the single injection case. In terms of spray targeting imaging, the results indicated that the fuel impingement and flow to the piston crevice volume were increased with a larger amount of pilot2 injection. Therefore, the increment of the pilot1 injection quantity rather than the pilot2 injection quantity was suggested not only to improve cold startability, but also to reduce unburned hydrocarbon emissions under a cold start condition in a real engine.

1. Introduction

Even though many technological innovations have been accomplished for diesel engines, cold startability at low ambient temperatures remains a serious issue. Under low ambient air temperature condition, the starting process of a diesel passenger car engine can result in long cranking periods with a large number of pollutant emissions [1–4]. These problems are caused by poor conditions for diesel auto-ignition. Under extremely low ambient temperatures, the cylinder head and cylinder block absorb most of the heat generated during the compression stroke. This process suppresses the vaporization and atomization of the injected fuel, leading to incomplete combustion [5–6]. In addition to the thermal conditions of a diesel engine, the deterioration of the fuel properties due to the low temperature also affects the mixture preparation during ignition delay. Such conditions finally result in a poor air fuel mixing process that can cause misfires, with a high amount

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Nomenclatures and Abbreviations

I	intensity of a pixel
$\dot{m}_{inj}$	total injection quantity [mg]
η_c	representative combustion efficiency [Pa/mg]
N	pixel number ρ_{amb}
P_{peak}	maximum in-chamber pressure [Pa]
$P_{w\ fuel\ spray}$	chamber pressure with fuel spray [Pa]
$P_{w/o\ fuel\ spray}$	chamber pressure without fuel spray [Pa]
t	time [s]
ρ_{amb}	ambient density [kg/m^3]
T_{amb}	ambient temperature [K]
T_f	fuel temperature [K]
u_{eff}	effective velocity at the exit of the orifice [m/s]
τ	ignition delay [s]
bTDC	before top dead center
CAD	crank angle degree
CO	carbon monoxide
CVCC	constant-volume combustion chamber
FIE	fuel injection equipment
FLOL	flame lift of length
HC	Hydrocarbon
IMEP	Indicated mean effective pressure
NO_x	nitrogen oxides
PID	Proportional integral derivative
PM	particulate matters

of hydrocarbon (HC), carbon monoxide (CO), and smoke emissions [7]. With this situation, the cold startability of passenger car diesel engines is worsening due to the current emission regulations which are becoming increasingly stricter for nitrogen oxides (NOx) and particulate matter (PM), which further reduces the compression ratio of a passenger car diesel engine [8–11]. Depending on the markets, vehicle companies are trying to reduce the compression ratio of passenger car diesel engines because of economical point of view (expensive after treatment system) and environmental concerns. The air-fuel mixing process deteriorates due to the lower compression heat as the compression ratio decreases. Therefore, in a modern diesel engine, the air temperature within the combustion chamber is increased by using an intake heater and glow plugs in order to promote ignition [12–13]. These aids are required for the current diesel engines for temperatures below 262 K and are necessary below 283 K for future applications with a reduced compression ratio [14].

With regard to the cold startability issues, several studies related to the fuel injection of diesel engine during a cold start have been conducted. A split injection strategy during the cold start has become an effective way to improve the cold startability. Brown et al. investigated a fuel injection strategy for cold starting direct-injection diesel engines [15]. Cold tests were carried out at an engine soak temperature of 263 K and the engine speed was increased up to 300 r/min before enabling fuelling. Comparing the results of single and double injection strategies indicated that the double injection strategy was superior to the single injection strategy, showing maximized indicated mean effective pressure (IMEP) produced on firing cycles. Payri et al. also showed that multiple injection strategies can improve the idling stability during the cold start condition [16]. To produce the idle phase in low temperature conditions, the engine was operated in a steady state at 900 r/min and was installed in a fully instrumented climatic chamber, which allowed controlled ambient temperatures from 243 K to 313 K. During the test, the soaking temperature of the single cylinder diesel engine was set to 263 K. They found that the appropriate pilot timing seems to promote adequate in-cylinder conditions for the subsequent injection, finally improving the main combustion. The total heat release was increased, when a larger pilot injection mass (5 mg/cycle) was split into two pilot injections (3 mg/cycle and 2 mg/cycle), regardless of the timing of the pilot injections. Pre-combustion due to the introduction of the second pilot improved the conversion efficiency, the total heat release, and IMEP. Chartier et al. studied the effect of injection strategies on the cold start performance in an optical direct injection diesel engine at a very low ambient temperature of 244 K [17]. They found that fuel evaporation was limited at a low temperature, but that the engine performance improved by using three pilot injections. The gradual increase in pilot injection quantity was advantageous for better stability and high load operation due to a reduced temperature drop in the cylinder after each injection and more favorable air-fuel mixing. In terms of injection number, a larger number of pilot injections gave a more homogeneous and better evaporated mixture before the combustion. Zhong et al. also investigated the impact of split injection on cold startability in a 4-cylinder turbocharged diesel engine [18]. The tests were performed under various ambient temperatures, ranging from 243 K to 313 K. The combustion and emission characteristics were compared between single and multiple injection cases. From the result, it was found that the split injection strategy greatly reduced the cranking period, the total fuel mass injected per cycle during cranking, and the HC emissions by almost 50%.

The comprehensive understanding of spray combustion and spray-wall interaction are very important in a compression ignition engine because all the combustion process is governed by air-fuel mixing process especially under the cold start condition. However, most previous studies are concentrated on the engine performance and emission characteristics according to the atmospheric conditions. Therefore, this study is aiming to provide a certain insight in application of multiple injection strategies linked to fuel impingement by performing high speed imaging in a constant volume combustion chamber. The in-chamber pressure analysis, including an increase in pressure and the derivative of the in-chamber pressure, were combined with high speed imaging.

2. Experimental setup and condition

2.1. Experimental equipment and test procedure

Fig. 1 shows a schematic diagram of the fuel injection equipment (FIE) system. The fuel tank was designed to control the fuel temperature within the range of from 243 K to 333 K by operating a refrigeration cycle and an electric heater. The coolant was circulated through cooling fins installed inside the fuel tank. The fuel was stirred by an internal pump for the efficient heat transfer between the fuel and cooling fins. Meanwhile, it was also possible to increase the fuel temperature by using an electric heater which was located around the fuel tank. The precise fuel temperature control within ±0.1 K was available by a proportional integral derivative (PID) control algorithm based on the thermocouple signal. All of the return lines from equipment such as the common-rail return and injector return were connected to a hot reservoir to prevent temperature increase in the fuel tank. A common-rail injection system, including a high pressure fuel pump driven by an electric motor, was utilized for the fuel injection. The fuel was injected by using a seven-hole solenoid diesel injector, and the detailed specifications of the injector are depicted in Table 1(a). To maintain the fuel at a target temperature in the injector and the rail-to-injector fuel tube, the fuel was also circulated through