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Investigations of multiple injection strategies for the improvement of combustion and exhaust emissions characteristics in a low compression ratio (CR) engine

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ABSTRACT

The experimental analysis was conducted for a better understanding of the combustion stability and reduction of exhaust emission in low compression ratio (CR) engine. The combustion stability was analyzed in terms of combustion pressure, the rate of heat release (ROHR), the indicated mean effective pressure (IMEP), and coefficient of variation of indicated mean effective pressure (COV_{IMEP}), and formation of exhaust emissions such as CO, HC, NO_X, and soot was measured and compared in the low compression ratio single cylinder CI engine.

It was revealed that maximum value of combustion pressure (P_{max}) in two pilot injections was increased to almost the same level of single injection combustion although its maximum rate of heat release (ROHR) was decreased to 47.2% compared to single injection combustion. It was also observed that two pilot injections improves combustion efficiency, and these injection strategies operate engine more stably in low compression ratio engine, based on the results of increased IMEP (2.1%) and decreased COV_{IMEP} (5.7%). Moreover, in multiple injection combustion, more CO formation and less HC emission were observed during combustion process, and remarkable simultaneous reduction of NO_X up to 58.7% and soot up to 25% can be achieved in low compression ratio engine.

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1. Introduction

Recently, a drastic reduction of NO_X emissions with low level of PM, CO, and HC emissions is a main issue in a compression ignition (CI) engine to meet the strict regulation of exhaust emissions [1–5]. Therefore, the investigations on the control of NO_X emission formed in a CI engine combustion were performed by applying delayed fuel injection timing [6,7], exhaust gas recirculation [8–10], and catalytic reduction method such as selective catalytic reduction (SCR) [11,12]. One of the most promising solutions to reach these demands is the reduction of the compression ratio (CR) in a CI engine [13]. The reduced compression ratio enhances the engine power due to the increase of specific indicated work output at low engine load. It also leads to higher thermal efficiency and lower peak rates of heat release which could be attributed to reduction of heat transfer loss. Therefore, mean gas temperature in-cylinder reduced with reduced compression ratio, and longer ignition delay time due to this low gas temperature and low oxygen concentration would be expected [14], as a results, reduction of NO_X formation can be achieved. Concurrently, low gas temperature within cylinder results in a decrease of the PM emission. However, reduction of gas temperature induces the problem of the cold start ability in CI engine since auto ignition of fuel in a engine is highly dependent on the in cylinder gas temperature at the start of fuel injection, thus, reduced gas temperature can lead to penalties in fuel vaporization and auto ignition capabilities [15].

In a multiple injection strategies, a small amount of fuel injected before the main fuel injection during a compression stroke combusts prior to the main injection, and in-cylinder gas pressure and temperature increase, as a result, ignition delay of main injection is reduced. In this point of view, the study on the multiple injections under low compression ratio (CR) condition is very interesting because it could be a method to improve the cold start ability in CI engine. The potential possibility of multiple injections for cold start problem in low compression ratio engine was evaluated by regarding the engine starting and idling condition after start [15–17]. In these researches, multiple injection strategies could improve the cold start ability of low compression ratio engine; however, unstable engine operation was still observed during the idle operating condition. Moreover, the reduction of exhaust emissions, especially NO_X or soot, was not considered in these works despite the reduction of compression ratio and multiple injection strategies have interesting effects on these exhaust emissions in CI engine.

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Nomenclature

m	injection mass of fuel (mg)
P	pressure (MPa)
t	time (ms)
Greek	
ϕ	equivalence ratio
Subscripts	
COV	coefficient of variation
inj	injection
IMEP	indicated mean effective pressure
m	main
p	pilot
SOE	start of energizing

In this work, for a better understanding of the combustion stability and emission reduction in low compression ratio engine, multiple injection strategies that are one and two pilot injection prior to main injection are applied in the idle engine operating condition and compared with single injection condition. The combustion stability was analyzed in terms of combustion pressure, the rate of heat release (ROHR), the indicated mean effective pressure (IMEP), and coefficient of variation of indicated mean effective pressure (COV_{imep}). Simultaneously, formation of exhaust emissions such as CO, HC, NO_X, and soot was measured and compared under various test conditions.

2. Experimental setup and strategies

2.1. Experimental setup

The experimental analysis was conducted in a single-cylinder compression ignition (CI) engine, because this is more suitable facility for the analysis of combustion characteristics due to the wider possibilities for controlling in-cylinder condition during measurements. The test engine used in this work was a high pressure direct injection (DI) diesel engine with 0.373 L swept volume equipped with electronically controlled fuel injection system. It was consisted of test engine with EC dynamometer, injection system with fuel tank and signal synchronizer such as fuel injection and pulse generator, data acquisition system, and exhaust gas analyzer, as shown in Fig. 1. The engine speed was controlled by Eddy current (EC) dynamometer with 150 kW absorption power, and in-cylinder pressure was monitored by means of piezoelectric pressure transducer (Kistler, 6061B), and glow plug adapter connected to a charge amplifier (Kistler, 5015). By using data acquisition system consisted of DAQ board and Labview software, the combustion pressure in-cylinder was analyzed 0.1 interval of crank angle over 50 cycle measurement, and these pressure data were compared relative to the rate of heat release (ROHR) during operating period of engine. The combustion stability was quantified by studying the coefficient of variation of indicated mean effective pressure (COV_{imep}) based on the previous researches [13]. A common-rail type injection system generated high pressure for fuel injection and was made in order to more easily control by changing electric signal. The fuel in the rail was pressurized using a couple of air-driven pumps and maintained the constant pressure level in injection system. Fuel injection signal and pulse generator controlled the start of energizing timing (t_{SOE}) with interval of multiple injection timing. The energizing duration of the fuel injector was controlled by an injector driver. A timing pulse generator was coupled with a crank angle sensor and camshaft position sensor. The detail specifications of test engine are summarized in Table 1. The measurement of HC, CO and NO_X generation was conducted with exhaust gas analyzer equipped with experimental engine. Soot from the engine was measured by smoke meter. All the results of combustion stability and exhaust emissions were measured by 50 cycles and averaged.

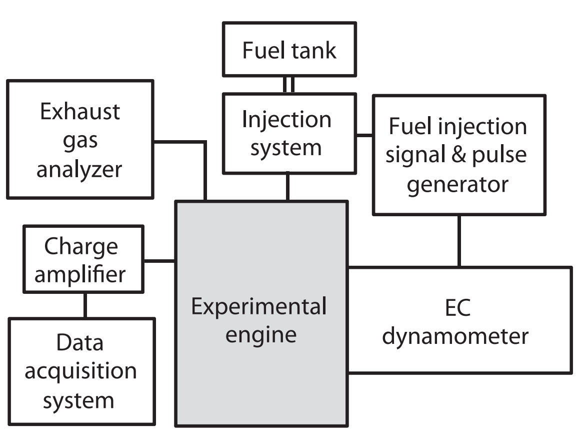

Fig. 1. Schematics of the test engine and data acquisition system.

2.2. Experimental strategies

For the analysis of the effect of multiple injection strategies on the improvement of combustion and reduction of exhaust emissions in a low CR engine, two multiple injection strategies that are one pilot and two pilot injections prior to main injection were considered and, all tests for engine performance were conducted at constant engine speed (800 rpm) and a fixed fuel injection pressure (27 MPa) to simulate the idle engine operating conditions. The reason for selecting idle speed condition is to understand the effect of multiple injection strategies on the reduction of CO, HC and NO_X formation in low idle speed condition because plenty of these exhaust emissions are generated in this condition [14,18,19]. The compression ratio of test engine was reduced to 15.3:1 by modifying the combustion chamber shape, and the combustion and exhaust emissions were analyzed under the same equivalence ratio (Φ) of 0.3. The intake air and coolant temperature of test engine were set to 30 °C and 80 °C, respectively. The test fuel used in this work was ultra low sulfur diesel (USLD). The multiple injection strategies were applied by dividing the pulse signal of a single injection into two or three pulse signals corresponding to a crank angle, and the start of energizing timing (t_{SOE}) was defined as the time when the injection pulse is first applied. Since the injection

Table 1
Specifications of test engine.

Engine system type	CRDI
Injection system type	Electronically controlled fuel injection
Bore (mm) × stroke (mm)	75 × 84.5
Displacement volume (cc)	373.25
Compression ratio	15.3
Max. power (kW/rpm)	82.5/4000
Max. torque (N m/rpm)	250/2000

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