

Strategy for Mode Transition between Low Temperature Combustion and Conventional Combustion in a Diesel Engine

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ABSTRACT

Mode transition between low temperature combustion (LTC) and conventional combustion was performed by changing the exhaust gas recirculation (EGR) rate from 60% to 0% or vice versa in a light duty diesel engine. The indicated mean effective pressure (IMEP) before mode transition was set at 0.45 MPa, representing the maximum load of LTC in this research engine. Various engine operating parameters (rate of EGR change, EGR path length, and residual gas) were considered in order to investigate their influence on the combustion mode transition. The characteristics of combustion mode transition were analyzed based on the in-cylinder pressure and hydrocarbon (HC) emission of each cycle.

The general results showed that drastic changes of power output, combustion noise, and HC emission occurred during the combustion mode transition due to the improper injection conditions for each combustion mode. Therefore, a strategy for smooth combustion mode transition was developed by controlling the injection parameters such as injection timing, injection duration, and the number of injections on a cycle-by-cycle basis. As a consequence of gradually retarding the injection timing, gradually decreasing the injection duration, and adding a pilot injection, the differences in power output and combustion noise between the periods before and after mode transition were reduced by up to 100% and 225%, respectively, compared to those values for the case without controlling the injection parameters.

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INTRODUCTION

Low temperature combustion (LTC)-relying on high levels of exhaust gas recirculation (EGR) rate and unconventional injection timing-has been widely studied in diesel engines due to its benefit of simultaneous reduction of nitrogen oxide (NO_x) and soot emissions [1, 2, 3, 4]. However, the practical application of LTC is limited by significant carbon monoxide (CO) and hydrocarbon (HC) emissions and narrow operating range, which result from low combustion temperature and lack of intake oxygen (O₂) [5,6]. Various strategies for the reduction of CO and HC emissions in LTC have been reported by many researchers, e.g. multiple injection, high volatility and high cetane-numbered fuel, and intake boosting [6, 7, 8]. The operating range of LTC is limited to low to medium load due to insufficient O₂ for complete combustion at high load condition. Some measures to extend the operating range of LTC have been proposed.

From previous studies, it can be confirmed that intake boosting can increase power output because of the improvement of the air-fuel mixing process as well as the increased intake O₂ mass inside the cylinder even at the same O₂ concentration [9,10]. Another study concerning the operating range of LTC reported that low compression ratio can extend the range of smokeless operation to a wider EGR and indicated mean effective pressure (IMEP) due to the improvement of mixing process by longer ignition delay and lower in-cylinder temperature [11]. However, there is still a limitation in ability to cover the entire operating range. Conventional combustion should be run in the remaining operating range in which LTC is not available. Therefore, mode transition between LTC and conventional combustion is necessary for the application of LTC. Basically, fast and smooth combustion mode transition strategies are needed for better application. It is desirable to operate in LTC mode as

often as possible to maximize its benefit. Thus, each combustion mode should be switched as fast as possible. In addition, variation of power output and combustion noise should be acceptable in order to make passengers comfortable.

Most studies concerning combustion mode transition have been conducted in gasoline engines. Combustion mode transition between spark ignition (SI) and controlled auto ignition (CAI) in gasoline engines has mostly been accomplished by variable valve actuation (VVA) [12, 13, 14, 15]. Negative valve overlap (NVO) was used to trap the hot residual gas that provides thermal energy for compression ignition in CAI mode, while positive valve overlap (PVO) was employed in SI mode. Furthermore, those studies reported that the appropriate control of throttle angle, fuelling rate and spark timing was also required for the fast and smooth combustion mode transition. However, studies on combustion mode transition in diesel engines, especially those that considered transitions between LTC and conventional combustion, have not been sufficient even though this is a very important issue. The appropriate controls of EGR and injection events are important in the mode transition between LTC and conventional combustion in diesel engines. Proper strategies for these processes should be established in accordance with engine operating conditions. A parametric study with operating parameters is considered as the first step in the development of a desirable combustion mode transition strategy, and has to precede the optimization of the combustion mode transition. It provides a basic understanding on the mechanism of combustion mode transition with respect to each operating parameter.

In this study, rate of EGR change, EGR path length, and residual gas were considered as experimental parameters in an investigation of their influence on combustion mode transition between LTC and conventional combustion; the reason for this was that these parameters can affect the in-cylinder mixture condition and response time. Characteristics of combustion mode transition according to each operating parameter were analyzed by considering power output, combustion phase, peak cylinder pressure, combustion noise, and HC emission during mode transition. After determining the problems from the above results, various injection strategies were attempted for desirable combustion mode transition.

EXPERIMENTS

Research Engine

A five-cylinder, direct-injection diesel engine was employed to investigate the characteristics of mode transition between LTC and conventional combustion. A schematic diagram of the engine is shown in Fig. 1, and its main specifications are shown in Table 1. The engine was modified to run in single-cylinder mode. The combustion mode transition was implemented only in the number 5 cylinder, while the other cylinders were operated in conventional

combustion mode using a programmable electronic control unit (ECU). The intake and exhaust manifolds of the number 5 cylinder were separated from those of the other cylinders so that it was not affected by gas exchange processes from the other cylinders. The EGR rate and injection events in the number 5 cylinder were independently controlled using the programmable valve controller (Zenobalti Co., ZB-2200) and injector controller (Zenobalti Co., ZB-8010). Basically, the EGR rate was controlled by two valves placed at both the EGR (valve 1) and the intake (valve 2) lines. Each valve was used to adjust the flow of EGR and fresh air, respectively. On the other hand, in the condition used to investigate the effect of residual gas, two valves were installed at the EGR (valve 1) and exhaust (valve 3) lines while the intake line was wide open. Injection timing, injection duration, and number of injections were adjusted on a cycle-by-cycle basis. The in-cylinder pressure was acquired using a piezoelectric pressure transducer (Kistler, 6056A), and the intake manifold pressure was measured by a piezoresistive pressure transducer (Kistler, 4045A5). These pressure data were acquired with a resolution of 0.2 crank angle degrees (CAD) over 500 engine cycles.

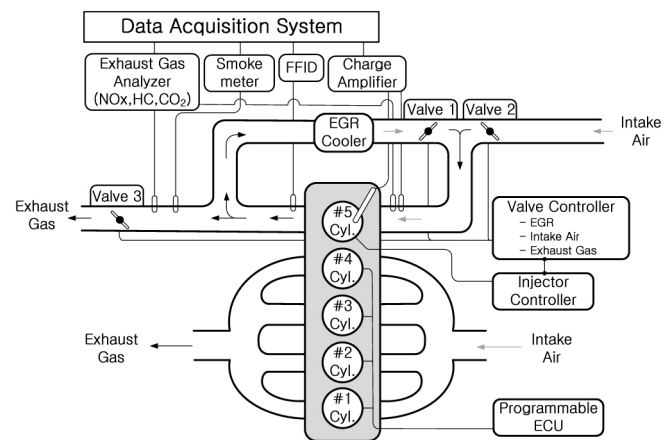


Figure 1. Schematic diagram of the research engine system

Table 1. Specifications of the research engine

Engine type	Five-cylinders, direct-injection, diesel engine
Displaced volume per cylinder	539 cc
Stroke	92.4 mm
Bore	86.2 mm
Compression ratio	17.5:1
Number of valves	4 (2 intake and 2 exhaust)
Fuel injection equipment	Common-rail injection

For the emission measurement in steady-state experiments, an exhaust gas analyzer (Horiba, MEXA-1500d) was used to measure CO, HC, NO_x, and carbon dioxide (CO₂) emissions, and smoke meter was applied to measure

Table 2. Operating conditions for the combustion mode transition

Test Condition Operating parameter	A	B	C	D
Initial IMEP (MPa)	0.45			
Injection pressure (MPa)	40			
Engine speed (rpm)	1200			
EGR rate (%)	60 → 0	0 → 60	60 → 0	60 → 0
EGR path length (m)	6.1	6.1	3.8	6.1
EGR control system (1: valve 1 + valve 2) (2: valve 1 + valve 3)	1	1	1	2

soot emission. On the other hand, HC emission in combustion mode transition experiments was measured by a fast-response flame ionization detector (FFID, Cambustion, HFR 400). The probe was installed in the exhaust port 30mm downstream from the exhaust valve stem. The FFID had a response time of roughly 0.5 ms (3.5 CAD at 1200 rpm) to changes in HC levels, allowing cycle-resolved HC measurements. The mean value of the HC emission for each cycle was represented by the cycle-averaged HC emission corresponding cycle.

Operating Conditions

Table 2 shows the operating conditions for the combustion mode transition experiments. Combustion mode was classified into two modes in terms of EGR rate. LTC mode was characterized by an EGR rate of 60%, while no EGR was used in the conventional combustion mode.

The EGR rate was defined as the ratio between the CO₂ concentration of the intake air, $X_{CO_2}^{in}$, and the CO₂ concentration of the exhaust gas, $X_{CO_2}^{ex}$.

$$EGR\ rate = \frac{X_{CO_2}^{in}}{X_{CO_2}^{ex}} \times 100\ (\%) \quad (1)$$

Initial load condition was set at an IMEP of 0.45 MPa, representing the maximum load of LTC under naturally aspirated intake conditions for this research engine. The injection pressure of 40 MPa and the engine speed of 1200 rpm were maintained in all test conditions. Initial injection timing and injection duration were determined from steady-state experiments. From these experiments, the optimized injection conditions that could satisfy the lowest exhaust emissions as well as maintain the initial IMEP were achieved for each test condition. These injection conditions were used as the initial conditions for each experiment and combustion mode transition was followed by changing the EGR rate while maintaining the other conditions. Experiments were classified into four conditions depending on the engine operating parameters. Test condition A was a baseline condition characterized by mode transition from LTC to conventional combustion at an injection pressure of 40 MPa,

EGR path length of 6.1 m, EGR control system employing valve 1 and valve 2 and engine speed of 1200 rpm. The results from this condition were compared with those from the other conditions. The influences of the rate of EGR change (Test condition B), EGR path length (Test condition C) and residual gas (Test condition D) on the characteristics of combustion mode transition were investigated through comparative analysis.

In the latter part, various injection modulations were attempted for desirable combustion mode transition. The basic means for injection modulation was to match up the injection conditions for the cycles before and after the mode transition, with optimized conditions for each combustion mode. An injection timing of -26 CAD after top dead center (ATDC) and injection duration of 860 μ s were the optimized conditions that produced the lowest exhaust emissions and maintained an IMEP of 0.45 MPa in LTC. In the same way, an injection timing of -4 CAD ATDC and injection duration of 817 μ s were chosen for conventional combustion. The cycles, in which the injection modulation was applied, were the 15th to 21st cycles; these cycles that showed a dramatic increase in MPRR in the case without injection modulation (baseline condition A).

Although the amount of EGR was changed during mode transition, the temperature in the intake manifold during mode transition was kept at 313K in every test condition. This was because EGR was sufficiently cooled down to the ambient temperature through a large EGR cooler that used tap water as a coolant.

RESULTS AND DISCUSSION

Characteristics of Combustion Mode Transition with Various Engine Operating Parameters

In this section, mode transition between LTC and conventional combustion was implemented by changing only the EGR rate without injection modulation for each set of test conditions. As a basic experiment, this provides insight into