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Experimental study on the effects of high/low pressure EGR proportion in a passenger car diesel engine

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HIGHLIGHTS

- The effects of the HP/LP EGR proportion on combustion and emissions were investigated in a diesel engine.
- The intake manifold temperature was decreased as the LP EGR portion increased.
- The CA 50 and MPRR were not affected by the HP/LP EGR proportion.
- The pumping loss showed a tendency to decrease with the increase of the LP EGR portion.
- The trade-off relationship between NOx and BSFC was improved with the increase of the LP EGR portion.

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ABSTRACT

An experimental study was conducted to investigate the effects of the proportion between high pressure and low pressure exhaust gas recirculation (HP/LP EGR) on engine operation. The study focused on the characteristics of combustion, emissions, and fuel consumption in a 2.2 L passenger car diesel engine. The experiments were performed under three part-load and steady-state operating conditions. The LP EGR portion was swept from 0 to 1, while the mass flow rate of fresh air and boost pressure were fixed. The results showed that the intake manifold temperature decreased gradually as the LP EGR portion increased due to its greater cooling capability by a longer supply line and an intercooler. However, the required cooling power for the intercooler increased because the LP EGR gas, which has a higher temperature than the fresh air, was induced upstream of the compressor. The lowered intake manifold temperature with the increase of the LP EGR portion led to the prolonged ignition delay of pilot injections, which resulted in a slightly higher peak heat release rate in the main combustion. A higher LP EGR portion showed a lower fuel consumption level than the HP EGR only case because the variable geometry turbocharger (VGT) nozzle opened more widely to maintain the boost pressure, which means a lower pumping loss. Nitrogen oxide (NOx) emissions were also decreased as the LP EGR portion increased due to lowered intake charge temperature. Consequently, it was possible to improve the trade-off relationship between NOx emissions and fuel consumption with the increase of the LP EGR portion under steady-state operating conditions.

1. Introduction

Diesel engines have been widely adopted for power sources of passenger cars due to their high thermal efficiency. However, the emission regulations, which are becoming increasingly stricter, are forcing manufacturers to produce cleaner diesel engines. Car manufacturers are now in a situation whereby they need to reduce the nitrogen oxides (NOx) level by more than half of the present level in order to fulfill the EURO-6 regulations while maintaining the current particulate matter (PM) level. PM emission could be reduced by equipping a technologically matured diesel particulate filter (DPF) with a filtration efficiency of more than 90% [1]. After-treatment systems for reducing NOx such as a lean NOx trap (LNT), a urea selective catalytic reduction (SCR), and other deNOx catalysts are now available; however, these show a spatial constraint when applied to passenger cars [2,3]. The upcoming regulations

Abbreviations: HP EGR, high pressure exhaust gas recirculation; LP EGR, low pressure exhaust gas recirculation; VGT, variable geometric turbocharger; NOx, nitrogen oxides; PM, particulate matter; LNT, lean NOx trap; DOC, diesel oxidation catalyst; DPF, diesel particulate filter; SCR, selective catalytic reduction; CO_2, carbon dioxide; MAF, air mass flow rate; ECU, engine control unit; CO, carbon monoxide; HC, hydrocarbons; MFB, mass fraction burned; MPRR, maximum pressure rise rate; BMEP, brake mean effective pressure; BSFC, brake specific fuel consumption.

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of carbon dioxide (CO_2) also require car manufacturers to develop more efficient diesel engines without any deterioration of emissions. For these reasons, many studies have been conducted on reducing emissions and improving fuel efficiency. Exhaust gas recirculation (EGR) is an essential technology that can inexpensively reduce NOx emissions [4–9]. It is well known that the formation of NOx during combustion could be suppressed by thermal, chemical, and dilution effects of EGR [10–13]. The traditional EGR system, which is called a high pressure (HP) EGR system, has been used to reduce NOx emissions in diesel engines for several decades [4–7]. A fraction of exhaust gas is taken from upstream of the turbocharger turbine and introduced to the intake manifold passing through an HP EGR cooler. Other layouts of the EGR system have also been suggested for improving engine efficiency and emissions [14–17]. In the low pressure (LP) EGR system, the exhaust gas is extracted from downstream of the DPF, and introduced upstream of the turbocharger compressor. A number of advantages and disadvantages of the LP EGR system exist compared with the HP EGR system. The advantages of the LP EGR system are as follows; Firstly, the LP EGR gas is cooled down by passing through a LP EGR cooler and an intercooler. Thus, it is possible that the temperature of the intake manifold is kept lower than that of the HP EGR system, which means that more NOx emissions could be reduced with the LP EGR system under the same EGR flow rate [18–20]. Secondly, the boost pressure of the turbocharger can be increased because the flow rate of LP EGR does not affect the flow rate of the exhaust gas which flows through the turbine of the turbocharger [20–22]. PM emission, therefore, can be reduced due to the enhanced air–fuel mixing due to the increased boost pressure. The nozzle of the variable geometry turbocharger (VGT) can also be opened more widely with LP EGR while maintaining the same boost pressure, which results in lower pumping loss than that with the HP EGR system [18]. Thirdly, the mixing of fresh air and LP EGR gas before flowing into cylinders is enhanced because the supply line of the LP EGR system is longer than that of the HP EGR system, which allows a more homogeneous mixture to flow into the cylinders [14,16]. This is helpful in PM emission reduction. The disadvantages of the LP EGR system are as follows. First, the response of the transient operation with the LP EGR system is slower than that with the HP EGR system due to its longer supply line. This might produce a larger NOx overshoot compared to the HP EGR system during the transient operation [18,23]. Second, the LP EGR gas might be harmful to the durability of the compressor of the turbocharger because the exhaust gas, which is induced into the compressor, includes condensed water and PM, although the LP EGR gas is filtered by a DPF [18,20].

From the above comparison, each HP EGR and LP EGR has advantages and disadvantages when applied to diesel engines, which implies that the simultaneous application of HP EGR and LP EGR to diesel engines has a potential to optimize fuel economy and emissions. Thus, the dual loop EGR system, which has both HP EGR and LP EGR systems, is being applied to diesel passenger cars. Recently, many researches on this topic have been investigated widely. The direct comparison of HP EGR system only and LP EGR system only focusing on the engine emissions and performance was carried out [3,19,22]. The simultaneous application of HP and LP EGR to diesel engines was also conducted by other researchers [15–17,20,21,24]. However, the literatures about the simultaneous application of HP/LP EGR have a limit that the conditions of HP/LP EGR proportion were limitative and not specific. Furthermore, the results from the literatures did not cover the all information including the engine emissions, performance, combustion and the EGR supply line characteristics. Therefore, in the study, the author tried to provide the basic data including the engine emissions, performance, combustion and the EGR supply line characteristics under several operating conditions and quantified HP/LP EGR proportions. The engine test had been conducted with a 2.2 L passenger car diesel engine while fixing the mass flow rate of fresh air and the boost pressure for each operating condition. The in-cylinder pressure, emissions and fuel consumption were measured. The acquired temperature and pressure data of HP EGR and LP EGR supply lines were also provided to support comparison results of HP EGR and LP EGR.

2. Experimental setup and conditions

2.1. Experimental setup

Fig. 1 depicts the schematic of the engine test. The detailed specification of the engine is shown in Table 1. The engine is a four-cylinder, 2.2 L passenger car diesel engine with a bore of 85.4 mm, a stroke of 96 mm and a compression ratio of 16. This engine is equipped with a 3rd generation Bosch common-rail system that is capable of maximum injection pressure of 200 MPa and a VGT turbocharger (Honeywell Int.) with an electronically controlled actuator. The LP EGR system (including the LP EGR cooler, a back pressure control valve, and a LP EGR valve) is equipped in addition to a conventional HP EGR system. The LP EGR gas was extracted from downstream of the DPF, and supplied upstream of the compressor. The mass flow rate of fresh air was measured by an air mass flow (MAF) sensor which is located at the downstream of an intake air filter. The in-cylinder pressure was measured using a piezo-electric tranducer (Kistler, 6065A type) mounted on the glow plug position, at every 0.1 crank angle degree (CAD). The net heat release rate was calculated using Eq. (1) [25] with the in-cylinder pressure of 100 cycles. Seven k-type thermocouples and seven pressure tranducers were mounted on the intake/exhaust manifold and EGR supply lines, which were used for investigating the variation of temperature and pressure according to the variation of the HP/LP EGR proportion. The temperature and pressure data were acquired by a data acquisition board (Graphtech, Dataplatform GL7000) for 2 min with a time resolution of 10 ms, and averaged.

$$\frac{dQ}{d\theta} = \frac{\gamma}{\gamma-1}P\frac{dV}{d\theta} + \frac{1}{\gamma-1}V\frac{dP}{d\theta} \quad (1)$$

where Q = heat, γ = Specific heat ratio, θ = crank angle, P = cylinder pressure, V = cylinder volume.

Gaseous emissions including NOx, CO_2, carbon monoxide (CO), and hydrocarbons (HC) were measured at the exhaust manifold using an exhaust gas analyzer (HORIBA, MEXA 9100D-EGR, the minimum resolution for NOx and CO: 10 ppm). In addition, the concentrations of CO_2 in the intake manifold and downstream of the intercooler were measured to calculate the total EGR rate and the HP/LP EGR proportion. It was not possible to measure the engine-out PM emission because of excessively high pressure upstream of the turbine. The intercooler was cooled by a water-shower cooler. The engine speed was kept constant using an eddy current dynamometer (AVL, Alpha 240, maximum power of 240 kW). The engine operation parameters such as the mass flow rate of fresh air (related to EGR valve position), the boost pressure, and the HP/LP EGR proportion were controlled by an ETK electronic control unit (ECU) and control software (ETAS, INCA 5.0). The temperatures of the engine coolant and diesel fuel were maintained at 353 K and 313 K, respectively, during the engine test.

2.2. Experimental conditions

Table 2 summarizes the experimental conditions of this study. The engine tests have been carried out under three operating