

Effect of Hot Exhaust Gas Recirculation on the Combustion Characteristics and Particles Emissions of a Pilot-Ignited Natural Gas Engine

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ABSTRACT

Natural gas has become an attractive alternative for diesel fuel due to its higher octane number, richer reserves and lower price. It has been utilized in compression ignition engines to obtain a higher thermal efficiency compared with spark ignition engines. However, its relatively higher auto-ignition temperature increases the difficulty of compression-ignition based on present hardware devices. One optimal ignition method is that a very small quantity of diesel fuel as the only ignition resource pilot-ignites the lean natural gas-air mixture. This micro diesel pilot-ignited natural gas premixed charge compression ignition (DPING-PCCI) combustion strategy is easy to implement without major hardware modifications, and can significantly reduce the NO_x and particle mass emissions from diesel engines. Although the DPING-PCCI has so many advantages, it suffers from poor engine stability and high ultrafine particles emissions at part loads. In the present paper, the hot exhaust gas recirculation (EGR) strategy was employed in a single-cylinder DPING-PCCI engine at part loads. The aim is to investigate influences of hot EGR on combustion and emissions characteristics of the DPING-PCCI engine, especially ultrafine particles emissions. The results show that, when increasing the hot EGR rate, the ignition delay period is prolonged progressively, however the total combustion duration is shortened gradually. With the increase of hot EGR rate, the shape of particle size distribution curve appears unimodal and the peak of particle number concentration gradually shifts downwards and towards the larger particle size. The total ultrafine particle number concentration was reduced up to 57 percent. While the particle mass concentration is reduced and the coefficient of variation in indicated mean effective pressure (COV_{IMEP}) decreased 5 percent. Meanwhile, CO, HC and NO_x emissions are decreased simultaneously. The results indicate that the hot EGR has the merits to fulfill lower emissions and improve the engine stability.

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INTRODUCTION

The utilization of natural gas fuel in diesel engines has become a very promising solution for diesel engine emissions and the cost of diesel fuel [1, 2]. Natural gas, because of its abundant reserve, has an encouraging price advantage of more than 1/3 over oil on an equivalent unit energy basis [3], especially in the coming Shale Gas Revolution. Moreover, natural gas can achieve no smoke combustion and produce significantly lower CO_2 emission than diesel fuel does, due to its lower carbon-to-hydrogen ratio and no carbon-carbon bonds. Furthermore, its higher octane number makes it suitable for relatively high compression ratio diesel engines to obtain a high thermal efficiency and improve the engine performance. More importantly, the utilization of natural gas

in diesel engines under lean burn operations can significantly reduce NO_x and particle mass emissions.

The relatively high auto-ignition temperature of natural gas, however, increases the difficulty of compression ignition based on present diesel engine. One simple and practical ignition method is that a very small quantity of diesel fuel (1~5% by energy) is injected near the end of the compression stroke as the only ignition resource to pilot-ignite the lean natural gas-air mixture [4]. Consequently, it forms multi points simultaneous ignition and fulfills the diesel pilot-ignited natural gas premixed charge compression (DPING-PCCI) combustion [4, 5]. Most of DPING-PCCI engines only need to add a natural gas supply system on the conventional diesel engine, while maintaining the original diesel injection. Natural gas enters into the air intake

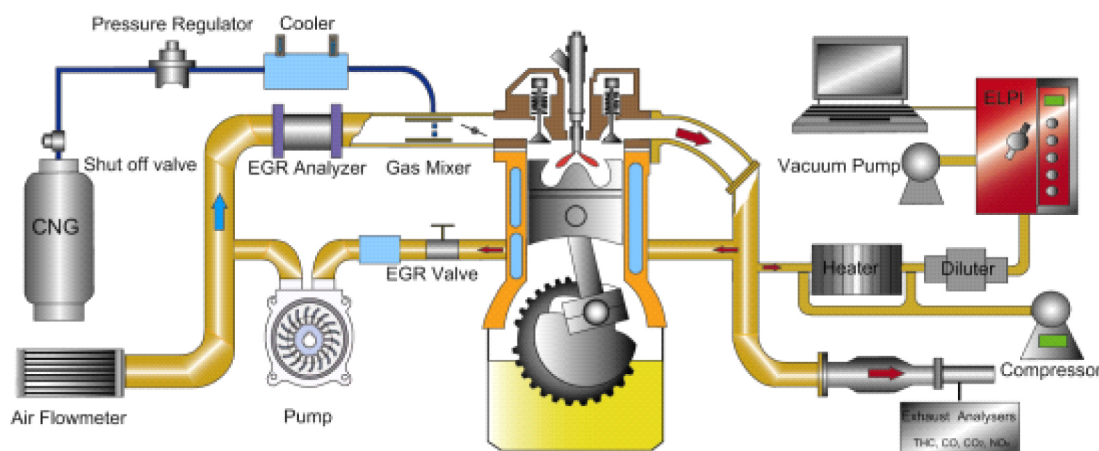


Figure 1. Schematic diagram of the experimental set-up

manifold and mixes with air. The engine power output is controlled by adjusting the amount of natural gas fuel [4, 5, 6, 7, 8].

The DPING-PCCI combustion can significantly reduce the NO_x and particle mass emissions. It is attributed to both natural gas self-characteristics (without carbon-carbon bonds, lower C/H ratio) and the PCCI combustion, which can reduce the heterogeneity of the fuel-air mixture and the flame temperature by lean burn. However, the DPING-PCCI combustion brings some negative effects on CO and HC emissions, and combustion variations, especially at low and intermediate loads. To solve these issues, several methods was used, such as adjusting injection parameters (raising the pilot diesel quantity and the injection pressure, properly advancing the injection timing) [7, 9, 10, 11], enhancing the intake air temperature [7], and blend H_2 fuel [12, 13]. Since these methods can raise the cylinder combustion temperature and combustion rate, and consequently enhance the oxidation of HC and CO. However, these also yield some negative effects on particle mass emissions, NO_x emission, and engine knocking.

To reduce simultaneously HC, CO and NO_x emissions and the variations of combustion, the hot exhaust gas recirculation (EGR) strategy can be applied in DPING-PCCI engines [4, 10, 14]. The hot EGR, which combines advantages of cold EGR and advantages of intake charge heating, can have six major effects on combustion and emissions. First, the hot exhaust can heat the intake charge, enhance the ignition stability and the combustion rate, and consequently favor the HC and CO oxidation and the NO_x formation. Second, unburned HC in the exhaust can participate in the combustion again, resulting in a reduction of HC emission and an improvement of thermal efficiency. Third, adding exhaust replaces partially the natural gas-air, resulting in the reduction in O_2 and natural gas fuel. This replacement (dilution) effect can reduce flame temperature and NO_x emission. Fourth, the introduction of CO_2 and H_2O in the exhaust can increase the specific heat capacity of the

cylinder charge, reduce the charge temperature at the end of compression stroke, and delay the ignition phase. Fifth, the chemical action of dissociation of CO_2 and H_2O absorbs the thermal energy of combustion, thereby reducing the cylinder temperature and NO_x emission. Sixth, the possible active species such as H, O, and OH in the exhaust gas may improve the ignition stability and increase the combustion rate [15]. However, it must be noted that the excessively high temperature of EGR can still increase the NO_x and particle mass emissions and engine knocking as well. Therefore, the temperature of hot EGR needs to be controlled in order to achieve the reduction in emissions and combustion variations simultaneously.

In the last two decades, particles emissions from engines have been attracted considerably more attention, especially the ultrafine particles (particle aerodynamic diameter, $D_p < 100\text{nm}$). Since particles can penetrate deep into the lungs and dissolve in body fluids to affect human health [16, 17]. Dual-fuel PCCI combustion has been considered as an effective method to reduce particle mass [18, 19]. However, several research results revealed that this reduction in particle mass emissions might be accompanied by an increase in smaller particle number [19, 20]. For the DPING-PCCI combustion, the previous works of DPING-PCCI engines primarily focused on reducing the particle mass emissions. These works are still not sufficient in extensive investigations of the particle number variations. Therefore, this present study further expands upon previous research and mainly investigates potentials of hot EGR in reduction of ultrafine particles. The aim of this present work is to investigate the effect of hot EGR on combustion and emissions characteristics of DPING-PCCI engine, especially ultrafine particles emissions.

EXPERIMENTAL SET-UP AND PROCEDURE

Experimental Engine

The test engine was converted from a single-cylinder, naturally aspirated, four-stroke, water cooled, and direct-injection diesel engine. And its intake system was modified to satisfy natural gas supply and EGR introduction. The experimental set-up and engine specifications are shown in Fig.1 and in Table 1 respectively.

Table 1. Engine specifications

Displaced volume	903 cc
Bore x Stroke	100 mm x 115 mm
Compression ratio	18:1
Diesel fuel injector	4 -holes x 0.3 mm
Diesel injection pressure	20 MPa
Rated power/speed	10 kW/ 2000r.min ⁻¹
Primary fuel	Natural gas
Gas fuel supply	Intake manifold

The natural gas supplying system is composed of a compressed natural gas fuel tank, a three-stage pressure regulator, and a venture-type natural gas-air mixer. A step motor was used to control the amount of natural gas flow. The pilot diesel fuel was supplied through the conventional diesel fuel system to obtain stable ignition resources, while the air-fuel ratio was monitored by a Horiba MEXA-700λ instrument with a measuring accuracy of 1%.

A pump was used to introduce the exhaust gas into the intake pipe through the intercooler and the EGR valve. An ECM EGR5230 analyzer [21] was used to measure the EGR rate with a 0.5% resolution. The EGR rate is defined as CO₂ concentrations in the intake and exhaust gas. The EGR rate can be calculated as follows:

$$EGR_{rate} = \frac{[CO_2]_{man} - [CO_2]_{bkg}}{[CO_2]_{exh} - [CO_2]_{bkg}}$$

$[CO_2]_{man}$, $[CO_2]_{exh}$ and $[CO_2]_{bkg}$ are CO₂ concentrations in the intake manifold, the exhaust pipe and background gas (air) respectively. The diesel injection timing, pilot mass, and natural gas amount, EGR rate and EGR temperature were controlled freely. The temperature of intake air, EGR cooler, exhaust gas, and engine cooling water were measured using type-K thermocouples.

Measurement Apparatus

The experimental system was instrumented to measure the in-cylinder pressure, air and fuel consumptions as well as exhaust emissions.

The cylinder pressure data were obtained by a Kistler 6117B piezoelectric pressure transducer and recorded at 0.2 crank angle (CA) degrees for 200 consecutive completed

cycles to analyze the combustion parameters and the cycle variations. A thermal mass flow meter was measured by a flow mete. And consumptions of natural gas and pilot diesel mass were acquired by two high-precision electronic balances with the accuracy of ±0.1 g respectively.

Exhaust gas emissions were sampled directly from the exhaust pipe. Total HC, CO and CO₂ emissions were measured by a Horiba MEXA-5541JA exhaust analyzer with accuracies of ±12ppm, ±0.06%, and 0.5% respectively, while NO_x emission was measured by MEXA-720 NO_x analyzer with an accuracy of ±30ppm.

Table 2. ELPI specification

Stage	D _{50%} (μm)	D _i (μm)
12	3.97	-
11	2.46	3.1061
10	1.61	1.9657
9	0.99	1.2393
8	0.637	0.7672
7	0.393	0.4874
6	0.255	0.3188
5	0.165	0.2036
4	0.101	0.1208
3	0.057	0.0715
2	0.029	0.0392
1	0.07	0.0208

D_{50%} represents the particle size with the 50% collection efficiency.

D_i represents the geometric mean of the D_{50%} values.

Table 3. Properties of tested fuels

Fuel properties	Diesel	Natural gas
Low heating value(MJ/ kg)	43.1	48.6
Cetane /Octane number	52.5 /-	- /130
Auto-ignition temperature (°C)	250	650
Stoichiometric air-fuel ratio	14.69	17.2
Components	-	96.1% CH ₄ etc.

The particle number concentration, particle mass concentration and particle size distribution were measured by an Electrical Low Pressure Impactor analyzer (ELPI). The ELPI was used and similar to earlier work reported by other researchers [22, 23, 24]. The measurement of ELPI covered a particle size 7nm to 10 μm with 12 filter stages as listed in Table 2. The detailed process and principle of particle measurement can be found in the references [22]. To avoid overloading the ELPI's electrometer, the exhaust gas was diluted with clean air using a two-stage diluter manufactured by Dekati. Furthermore, in order to eliminate the unexpected particle condensation and nucleation during dilution, the first stage of the diluter was heated to 200 °C and the second stage of the diluter operates at ambient temperature.

The particle diameter of the DPING-PCCI engine is primary in a small particle size (D_p < 1 μm) range, therefore,