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Full load performance and emission characteristics of hydrogen-compressed natural gas engines with valve overlap changes

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HIGHLIGHTS

- Altering the cam with a decreased valve overlap decreases torque at the lean limit.
- THC and the CH_4 reductions are approximately 41% for the HCNG fuel with reduced valve overlap.
- The NO_x from the camshaft with decreased valve overlap is higher than that of original camshaft.

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ABSTRACT

Natural gas vehicle engines are preferred over diesel engines because they release significantly lower amounts of nitrogen oxides (NO_x) and carbon dioxide emissions. Hydrogen-compressed natural gas (HCNG) technology is a promising alternative to that used in conventional compressed natural gas engines because hydrogen possesses stable lean combustion characteristics. Although the NO_x emissions requirements are satisfied, methane emissions must be filtered using an oxidation catalyst. An alternative is required for methane reduction because improving the conversion efficiency of methane is expensive. In this study, the strategy of varying the valve overlap was employed to reduce methane emissions. Although a torque valve cannot meet engine emission specifications, the hydrocarbon and methane emissions were reduced by approximately 41% by decreasing the valve overlap duration while using HCNG fuel. The level of NO_x emissions was approximately equivalent to or slightly higher than that of a conventional camshaft.

1. Introduction

The world energy market is attempting to diversify energy sources because of the rapid increase in the use of fossil fuels and the problem of global warming that is partially caused by automotive vehicles. Natural gas vehicles (NGVs) have the advantages of low carbon dioxide (CO_2) emissions and a wide range of application; the can be used in passenger vehicles, trucks, and buses [1,2]. NGVs were initially promoted for the consumption of overproduced natural gas. However, now, they also save energy or can be used as an alternative fuel. NGVs are preferable to diesel engine-based vehicles because of their low harmful emission characteristics. However, although the development of NGVs is a priority, it faces challenges such as the development of technology for clean diesel engines and insufficient infrastructure for recharging.

Recently, the development of NGV technology has focused, especially in the case heavy duty vehicles, on reducing NO_x and achieving high thermal efficiency through the improvement in fuel consumption [3,4]. Compressed natural gas (CNG)-hybrid engines significantly increase the cost of production, although they achieve the improvement required by the aforementioned goals. Furthermore, hydrogen-compressed natural gas (HCNG) is a promising fuel technology that can improve the performance of CNG engines. HCNG is considered to be a type of mono-fuel, and it is a mixture of 20–30 vol% of hydrogen and natural gas. The advantages of HCNG use in vehicles were proved through tests in the United States and Canada. Many research results for HCNG engines have been reported which indicate that HCNG engines can satisfy future emission regulations (e.g., as outlined in EURO-VI) and are economically feasible [5–8].

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An HCNG engine exhibits a leaner combustion than a CNG engine, which is possible because of the stable lean combustion characteristics of hydrogen. Consequently, nitrogen oxides (NO_x) and CO_2 emissions can be significantly reduced. HCNG technology can be applied in traditional CNG engines and their fuel supply systems without any modifications. Additionally, the employment of NO_x after-treatment systems is not required. NO_x emissions caused by lean combustion can meet the EURO-VI standard (0.46 g/kW h). However, carbon monoxide (CO) and total hydrocarbon (THC) emissions, including methane (CH_4), must be filtered through an oxidation catalyst (OC) to meet their corresponding standard (0.5 g/kW h) [9–11]. CH4 has a very stable molecular structure, and improvement in the conversion efficiency of the OC requires an increase in the amount of precious metal used in the OC. In order to ensure that the HCNG engine is cost-effective, a less expensive alternative is required for CH_4 reduction.

In the present study, a strategy of decreasing the valve overlap (VO) was employed to reduce CH_4 emissions. Closing the exhaust valve earlier can lessen the level of hydrocarbon and CH_4 emissions. This is because the unburned mixture retained in the crevices emerges around the valve seat as the exhaust valve opens and the piston approaches the top dead center (TDC) [12–14]. The effects of decreasing the VO on the full load performance and the emission characteristics are evaluated. The applicability of a camshaft with a reduced VO duration was assessed by taking into account its potential usability in the field.

2. Experimental procedures

2.1. Experimental setup

An 11-L 6-cylinder CNG engine (Doosan Infracore Inc., GL11K) that satisfied the EURO-V emission regulations was used in the test. The detailed engine specifications are listed in Table 1. The speed and torque of the engine were controlled and monitored using an eddy current dynamometer (Schenck). The spark ignition timing and the fuel flow rate were controlled using a computer-based universal engine control unit. An electronic throttle control and a waste gate control for the turbocharger system were employed to control the excess air ratio under each operating condition.

Fig. 1 shows the experimental setup for the engine tests. The CNG from the compressed fuel vessel, which has a pressure of approximately 15 MPa, was decompressed to 0.67 MPa using a conventional regulator for vehicles. Next, it was supplied by an eight-gas fuel-metering valve connected to a gas mixer. A series of compressed tanks for hydrogen, which had a pressure of approximately 12 MPa, were employed and connected to the pressure controller. A 3:7 volumetric ratio of hydrogen to natural gas was selected for the HCNG. This is because a 30% hydrogen concentration is considered to be the optimal ratio based on previous research [15].

The CNG and hydrogen, after passing through the regulator, were heated to 40 °C using a heat exchanger. This is because an extremely low temperature could cause malfunctioning of the fuel supply system because of the expansion of the compressed fuel in the regulator. The flow rate of CNG was measured using a mass flow meter and that of hydrogen was directly controlled using a mass flow controller. The individual in-cylinder pressure was measured using piezoelectric pressure transducers (Kistler Co., Ltd., 6117BFD17). For the analysis of the in-cylinder data, a high-precision rotary encoder with a pulse per revolution of 1800 and a combustion analyzer (Dewetron Co., Dewe 800) were used to observe the combustion stability. The excess air ratio of the air–fuel charge was monitored using a lambda meter (ETAS Co., LA4) located at the exhaust runner of an individual cylinder and downstream of the turbine.

Table 1
Engine specifications.

Type	Description
Number of cylinders	6
Bore (mm)	123
Stroke (mm)	155
Displacement volume (cc)	11,050
Compression ratio	11.5
Max. power	222 kW @ 2100 rpm
Max. torque	1150 Nm @ 1260 rpm

To evaluate the effect of the VO, the torque, in-cylinder pressure, and emissions were measured for each VO condition. The VO with the original camshaft had a crank angle degree (CAD) of 32. In comparison, the duration of the VO with the modified camshaft decreased by 50% (to 16 CAD). The intake and exhaust valve timings for each camshaft are summarized in Table 2.

For each cylinder, an exhaust gas-sampling probe was installed between the exhaust valve and the exhaust manifold. Then, the common emission of the engine was measured after the turbocharger. The composition of the exhaust gas, which included CO_2, CO, THC, and oxygen (O_2), was analyzed using an exhaust gas analyzer (AVL Co., AMA i60). The temperatures and pressures in the major parts of the engine, fuel flow, and exhaust gas concentrations were measured, and the resulting data was stored using a data acquisition system (GRAPHTEC Co., GL820).

2.2. Experimental methods

The engine was operated at 1260 rpm with 1150 Nm, which are the operating conditions of a heavy-duty natural gas engine at maximum torque with a wide-open throttle. The spark ignition timing was selected to maximize the thermal efficiency, and the maximum brake torque (MBT) was determined for each operating condition. The excess air ratio was increased, in increments of 0.1, from $\lambda = 1.3$ to the lean limit. The combustion performance and exhaust emissions were analyzed with respect to the excess air ratio for each fuel and VO duration. The temperatures of the CNG and intake air downstream of the intercooler were maintained at 42.5 ± 2.5 °C, and the engine-inlet coolant temperature was maintained at 82.5 ± 2.5 °C. Water-cooled heat exchangers were used for maintaining the temperatures.

An important criterion of the full load performance is the maximum torque value as compared to that in the engine specifications. This value is easily affected by a change in the VO that is accompanied by a change in the volumetric efficiency. The test conditions were evaluated by measuring the boost pressure with respect to the excess air ratio while maintaining the throttle angle opening. The performance and exhaust emissions for HCNG fuel were compared to those of CNG.

The mass fraction burned is a factor of combustion performance and is usually expressed as a percentage. The mass fractions burned are derived from pressure data; the timing of the mass fraction burned was compared to the spark advance timing. Mass fractions burned of 10% and 90% are typically observed at the start and end of combustion, respectively [16–18].

3. Results and discussion

3.1. Full load performance characteristics

The level of NO_x required by the enforced emissions standards can be satisfied via combustion in a lean-burning natural gas en-