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Emissions and fuel consumption characteristics of an HCNG-fueled heavy-duty engine at idle

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ABSTRACT

The idle performance of an 11-L, 6-cylinder engine equipped with a turbocharger and an intercooler was investigated for both compressed natural gas (CNG) and hydrogen-blended CNG (HCNG) fuels. HCNG, composed of 70% CNG and 30% hydrogen in volume, was used not only because it ensured a sufficient travel distance for each fueling, but also because it was the optimal blending rate to satisfy EURO-6 emission regulation according to the authors' previous studies. The engine test results demonstrate that the use of HCNG enhanced idle combustion stability and extended the lean operational limit from excess air ratio (λ) = 1.5 (CNG) to 1.6. A decrease of more than 25% in the fuel consumption rate was achieved in HCNG idle operations compared to CNG. Total hydrocarbon and carbon monoxide emissions decreased when fueled with HCNG at idle because of the low carbon content and enhanced combustion characteristics. In particular, despite hydrogen enrichment, less nitrogen oxides (NO_x) were emitted with HCNG operations because the amount of fuel supplied for a stable idle was lower than with CNG operations, which eventually induced lower peak in-cylinder combustion temperature. This low HCNG fuel quantity in idle condition also induced a continuous decrease in NO_x emissions with an increase in λ. The idle engine test results also indicate that cold-start performance can deteriorate owing to low exhaust gas temperature, when fueled with HCNG. Therefore, potential solutions were discussed, including combustion strategies such as retardation of spark ignition timing combined with leaner air/fuel ratios.

Introduction

Natural gas is a well-known alternative to diesel or gasoline in engine applications. It has the highest hydrogen-to-carbon ratio among hydrocarbon (HC) fuels, so it can emit low carbon dioxide (CO_2) when combusted in internal combustion engines. The use of natural gas also reduces carbon monoxide (CO) and non-methane hydrocarbons (NMHC) emissions [1,2]. Moreover, natural gas produces a low level of particulates compared to gasoline or diesel because of its gaseous nature. Despite these advantages, natural gas-fueled engines inherently discharge more methane (CH_4) emission because of flame quenching near the cylinder walls, adsorption in crevice volumes, and adsorption in the lubrication oil film on the cylinder walls [1]. Because CH_4 has 21 times higher global warming potential than CO_2, a proper aftertreatment system such as HC oxidation catalyst is necessary. With such a

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system in place, the deployment of natural gas engines can improve air pollution in metropolitan areas and lessen global warming.

Generally, in heavy-duty applications, a natural gas engine is turbocharged and often intercooled. This allows the engine to be operated under lean burn conditions so that thermal damage can be prevented and thermal efficiency can be increased. In particular, the EURO-5 emission regulation can be satisfied by this lean combustion or by stoichiometric combustion with a three-way catalyst [3]. However, the use of the lean burn strategy alone is not suitable for the next regulation (EURO-6) scheduled to come into force in 2014, especially for nitrogen oxides (NO_x) emissions. Therefore, a hydrogen (H_2) enriched natural gas engine is investigated as a promising alternative to address the strengthened standard [4–6]. Because of the excellent combustion characteristics of H_2, such as its fast flame propagation speed and wide lean flammability limit, ultra-lean combustion can be achieved with H_2-blended compressed natural gas (HCNG). As a result, HCNG can satisfy the NO_x regulation in EURO-6 without a de-NO_x aftertreatment system, while maintaining low levels of HC and greenhouse gas emissions [6,7]. Our previous studies [8,9] also compared engine testing results for HCNG and compressed natural gas (CNG) at various H_2 blending ratios. We found that the addition of 30% H_2 in volume with a slight spark retardation was the most appropriate to meet the NO_x regulation value in EURO-6 without affecting total hydrocarbon (THC) and CO emissions or thermal efficiency. Moreover, the use of HCNG with 30% H_2 allowed a sufficient travel distance for each fueling, compared to cases with a higher level of H_2 blending.

One feasible application of the HCNG-fueled heavy-duty engine is to substitute this engine for CNG or diesel engines in city buses in metropolitan areas. For example, there are now more than 20,000 CNG or diesel buses deployed in South Korea. Therefore, their replacement to HCNG can improve metropolitan air quality. In city bus applications, idle performance is a major factor affecting the overall performance of the engine. Because the driving pattern of a city bus consists of frequent stops in traffic jams and waiting at traffic signals, a large portion of fuel is consumed and a significant amount of exhaust emissions is generated during idle operations. In addition, passenger comfort is directly affected by engine idle stability. Owing to the low engine speed under a marginal load condition, idle combustion is vulnerable to intake disturbances such as cyclic variations in incoming charge motion and mixing, residual gas fraction, and air/fuel ratio [10,11]. Therefore, the addition of H_2 to CNG can enhance idle performance, which is another advantage of HCNG fuel.

Some researchers have examined the effect of H_2 enrichment on idle performance. Ma et al. [12,13] investigated the idle performance of a 6-L, 6-cylinder H_2-enriched natural gas engine under various H_2 addition rates and air/fuel ratios with spark timing sweep. They reported that the addition of H_2 extended the lean operation limit, enhanced combustion stability, and reduced CO and CH_4 emissions compared to neat CNG. They also suggested that the improvement in idle stability increased the indicated thermal efficiency and that the combination of H_2 addition and spark timing retardation reduced NO_x emissions in idle condition. Deng et al. [14] demonstrated similar emission results in a wider range of H_2 addition and excess air ratio (EAR or λ). Ji and Wang [15] studied combustion and emissions characteristics for a neat H_2-fueled engine at idle in various EARs and showed that stable combustion with low emissions and fuel consumption was achieved at very lean air/fuel ratios. They also examined the idle performance of a 1.6-L engine fueled by gasoline with the addition of H_2 in lean conditions and reported that thermal efficiency was improved, whereas the coefficient of variation in indicated mean effective pressure (COV_{IMEP}) and harmful emissions (THC and CO) were decreased with an increased H_2 fraction [16]. In addition to H_2 enrichment, several studies investigated other strategies such as reducing idle speed and blending alcohol fuels in order to improve idle performance of vehicles and evaluated the effect of fuel composition and air/fuel ratio on performance and emission characteristics at idle [17–20].

This study investigated the idle performance of a heavy-duty engine fueled by HCNG with 30% H_2. Fuel consumption rate as well as THC, CO, and NO_x emissions were obtained for both CNG and HCNG fuels and compared against various spark ignition timings and air/fuel ratios. In addition, lean idle operational limits were examined for both fuels and the effect of lean combustion on idle stability was assessed. Moreover, potential combustion strategies were discussed to reduce harmful emissions when using HCNG in idle operations.

Experimental procedure

Experimental setup

An 11-L, 6-cylinder, 4-stroke natural gas engine for a city bus was used in this study; its specifications are listed in Table 1. An eddy current dynamometer system (Schenck) was coupled with the engine to adjust engine rotational speeds and loads, and an exhaust gas analyzer (AMA i60, AVL) was installed downstream of the exhaust manifold to measure the emissions. λ was detected using a lambda meter (LA4, ETAS) and the crankshaft position was measured by an encoder (Autonics) with the resolution of 1 crank angle degree (CAD). An engine control unit was developed and installed to electronically control spark ignition timing and throttle duties. Engine operating variables were monitored and recorded by a data acquisition system (GL820, Graphtec) with a sampling rate of 500 ms. To assess idle stability, the cylinder pressure was measured by using a spark-plug-type pressure transducer (6117BFD17, Kistler) and analyzed by a combustion analyzer

Table 1 – Engine specifications.

Engine type	CNG: Turbocharged, intercooled
Number of cylinders	6
Bore × stroke	123 mm × 155 mm
Displacement volume	11.051 cc
Compression ratio	10.5
Idle speed	600 rpm
Idle spark timing	10 CAD, BTDC
Idle EAR	1.1
Maximum power output	213 kW at 2100 rpm
Maximum torque	1150 N m at 1260 rpm