International Journal of Automotive Technology, Vol. 18, No. 6, pp. 1061−1066 (2017)
DOI 10.1007/s12239−017−0103−8

pISSN 1229−9138/ eISSN 1976−3832

DEVELOPMENT OF HYDROGEN-COMPRESSED NATURAL GAS BLEND ENGINE FOR HEAVY DUTY VEHICLES

Cheol Woong Park[1)*], Chang Gi Kim[1)], Young Choi[1)], Sun Youp Lee[1)], Sung Won Lee[1)], Ui Hyung Yi[1)], Jang Hee Lee[1)], Tae Min Kim[2)] and Duk Sang Kim[3)]

[1)]Engine Research Department, Korea Institute of Machinery and Materials, 156 Gajeongbuk-ro, Yuseong-gu, Daejeon 34103, Korea
[2)]Research and Development Center, E&D Corporation Ltd., 14 Gasan digital 2-ro, Geumcheon-gu, Seoul 08592, Korea
[3)]Advanced Engine System Development Team, Doosan Infracore, 489 Injung-ro, Dong-gu, Inchon 22502, Korea

(Received 12 December 2016; Revised 26 April 2017; Accepted 29 May 2017)

ABSTRACT−Natural gas fuel, as an alternative energy source of transportation, has been used widely since it has an advantage of low emission levels. However, new technologies are required in order to meet the reinforced emission regulations. For this purpose, research into the development of hydrogen-compressed natural gas (HCNG) blend engine was carried out to evaluate its feasibility and emission characteristics. The Engine Research Department at the Korea Institute of Machinery and Materials carried out a large number of tests based on various parameter changes that could affect the performance and emission of HCNG engine in different operating conditions. An earlier stage of the research project focused on the lean combustion of a HCNG engine for heavy duty vehicles to meet the EURO-VI standards. An 11-L/6-cylinder CNG engine was used for the test. The effects of the excess air ratio change were assessed based on various content ratios of hydrogen in the natural gas fuel. In the later part of the HCNG research, a stoichiometric mixture operation was suggested to meet reinforced emission regulation without requiring a De-NOx system. Additionally, an exhaust gas recirculation (EGR) system was introduced for the purpose of improving thermal efficiency and durability. The optimal operating conditions were selected to achieve the best thermal efficiency to meet the required emission levels. In this paper, we demonstrate that a HCNG engine can achieve a significant decrease in NOx emissions, as compared to that of a CNG engine, while meeting the requirements of the EURO-VI standards during a transient mode cycle test. EGR can suppress the weakness of stoichiometric mixture combustion strategy, such as the deterioration of the durability and thermal efficiency, while the emission level can be lowered with the use of a three-way catalyst. The possibility of further reduction of emissions and CO_2 with EGR was evaluated to access practical application of a HCNG engine in the field. From that evaluation, the HCNG engine with stoichiometric mixture operation for heavy duty vehicles was developed. The emission levels of HCNG engine were 50 % lower when compared to the EURO-VI standards with a greater than 10 % decrease in CO_2 compared to that of a natural gas engine.

KEY WORDS : HCNG, Lean combustion, Stoichiometric, EGR, CO_2

1. INTRODUCTION

Currently oil, which represents a large percentage of energy used in the world for motor vehicles, is expected to be overtaken by natural gas energy by 2020. Ultimately by the late 21st century, hydrogen energy is expected to account for the highest portion of the total energy used in motor vehicles. Natural gas is a flammable gas and is mainly composed of methane (CH_4). Additionally, natural gas is distributed to stores in regions around the world from rich reserves that guarantee a stable, long-term supply. Therefore, natural gas can be an alternative energy of petroleum. In addition, the worldwide spread of natural gas vehicles, which is well known as an excellent automobile fuel due to its relatively clean emissions, has been continuously carried out (Dickinson *et al*., 2010; Hupperich and Dürnholz, 1996). Since 2000, natural gas vehicles are currently in widespread use in Korea, especially for city buses. By November 2016, there are 23 million units worldwide and 40 thousand units in Korea in service which has contributed significantly to the improvement in urban air quality. It is clear that natural gas buses contributed to the improvement of air quality due to the cleanliness of the fuel; however, it is also true that relatively new advances in natural gas technology was small compared to diesel cars. Through ongoing technical developments, diesel cars, which were the main culprit for air pollution in the past,

**Corresponding author.* e-mail: cwpark@kimm.re.kr
*This paper was modified from the original paper presented in FISITA World Automotive Congress 2016, and recommended by the Scientific & Technical Committee for journal publication.

have significantly reduced the amount of pollutants. As of 2014, EURO-VI exhaust regulations were coming into force in Korea where the difference of the harmful exhaust gases for the buses from diesel and natural gas bus was almost eliminated except for the particulate matters (PM). Consequently, the value of the natural gas vehicles is more and more reduced.

To address the problems with natural gas vehicles, natural gas-hydrogen mixed fuel engines (HCNG or Hythane) are one of the leading technical solutions used mainly in North America and Europe where the focus is on technology development and demonstration projects. The use of natural gas-hydrogen mixed fuel will be the bridge to the future social and technical infrastructure prior to full-scale use of hydrogen as the ultimate fuel of the future (Kukkonen and Shelef, 1994). Recently, a rapid introduction of the technology through commercialization of hydrogen-compressed natural gas (HCNG) technology was undertaken in China and India in order to advance the development of hydrogen based systems. There are several advantageous reasons for mixing natural gas and hydrogen. The first is the generation of hydrogen by reforming natural gas whose hydrogen-to-carbon ratio is high. Secondly, the natural gas charging infrastructure can take full advantage of the addition resulting from the mixing of natural gas and hydrogen. Finally, the combustion front for natural gas can spread rapidly due to the high flame speed and wide flammability range of hydrogen (Kukkonen and Shelef, 1994; Collier *et al*., 2005; Karim *et al*., 1996).

Natural gas engine production companies developed a lean combustion and oxidation catalyst system to meet the exhaust regulations of EURO-V. However, to meet the new EURO-VI standards where the NO_x regulations were significantly increased, the strategies developed to satisfy the requirements were divided into two schemes. The first scheme was based on a lean combustion and De-NO_x catalyst system, while the second scheme was based on a stoichiometric mixture combustion with exhaust gas recirculation (EGR) and a three-way catalyst (Benz *et al*., 2014; Cummins Westport, 2015). However, to meet post EURO-VI requirements, i.e. EURO-VII standards that are planned for the future, it is believed that a system based on lean combustion and a De-NO_x catalyst will not satisfy the requirements. Instead, the stoichiometric mixture combustion mode is expected to be the only system that will satisfy the anticipated EURO-VII standards.

The combination of a stoichiometric mixture combustion and a three-way catalyst, which is a method most commonly used in gasoline engines, provides an advantage by minimizing harmful emissions. However, the high combustion and exhaust gas temperature can result in deterioration of the heat resistance ability and system durability. Additionally, there is a disadvantage since the engine efficiency is less than that for a lean combustion engine. Particularly, large engines are sensitive to heat resistant and durability issues when applying the stoichiometric mixture combustion unlike small-sized engines. Therefore, it is necessary to reduce the aggressive combustion temperature using EGR (Saanum *et al*., 2007; Lee *et al*., 2014). The use of EGR for recirculating exhaust gas into the intake has the effect of improving the low thermal efficiency when in stoichiometric mixture combustion mode. When EGR supplies a large amount of recirculated gas, the combustion cycle has drawbacks such as becoming unstable or a poor controllability of the EGR flow rate control.

In this laboratory, an HCNG engine of the stoichiometric mixture combustion mode is developed in order to meet the emission regulations of Post EURO-VI, which is not determined yet. However, as HCNG fuel improve the lean combustion characteristics under the influence of hydrogen, the stoichiometric mixture combustion with a high flow rate of EGR can be possible and consequently HCNG fuel can use the EGR effectively to improve the heat durability and the thermal efficiency compared to natural gas engines. In this paper, we apply the HCNG that have been recognized as the next generation fuel of natural gas to natural gas engines for the city bus, consider the benefits that can be obtained by improving the ultra-lean combustion and high EGR combustion and introduce the development trend of HCNG engines that are currently in progress.

2. EXPERIMENTAL SETUP

An 11 L / 6 cylinder compressed natural gas (CNG) engine and its fuel supply system designed for a city bus was used for this test. The test methods were the steady state test mode and the transient test. The steady state test mode allowed optimization of the engine parameters including the spark advance timing, excess air ratio and EGR rate. The transient test mode was used to assess the feasibility of the combustion and control strategy to satisfy the world harmonized transient cycle (WHTC) for the EURO-VI standards. For the steady state test, a hydrogen gas supply system was installed to control the content of hydrogen in the HCNG fuel as shown in Figure 1 which was reproduced from Ref. (Park *et al*., 2011). The hydrogen was supplied through a series of compressed hydrogen gas tanks. The pressure was controlled at 0.8 MPa, which was the same pressure as the CNG. In order to provide response to meet the fast fuel supply requirements, another series of premixed, simulated HCNG gas was used for the transient test. Operating parameters such as spark advance timing, the amount of fuel supply, and the excess air ratio were controlled by a programmable engine control unit (ECU) for both the steady and the transient tests. A 30 vol% hydrogen to 70 vol% CNG ratio of HCNG fuel was considered the most appropriate ratio based on previous research (Park *et al*., 2011). The ratio was maintained for each of the operating conditions. The thermal efficiency and exhaust emissions were subsequently analyzed.

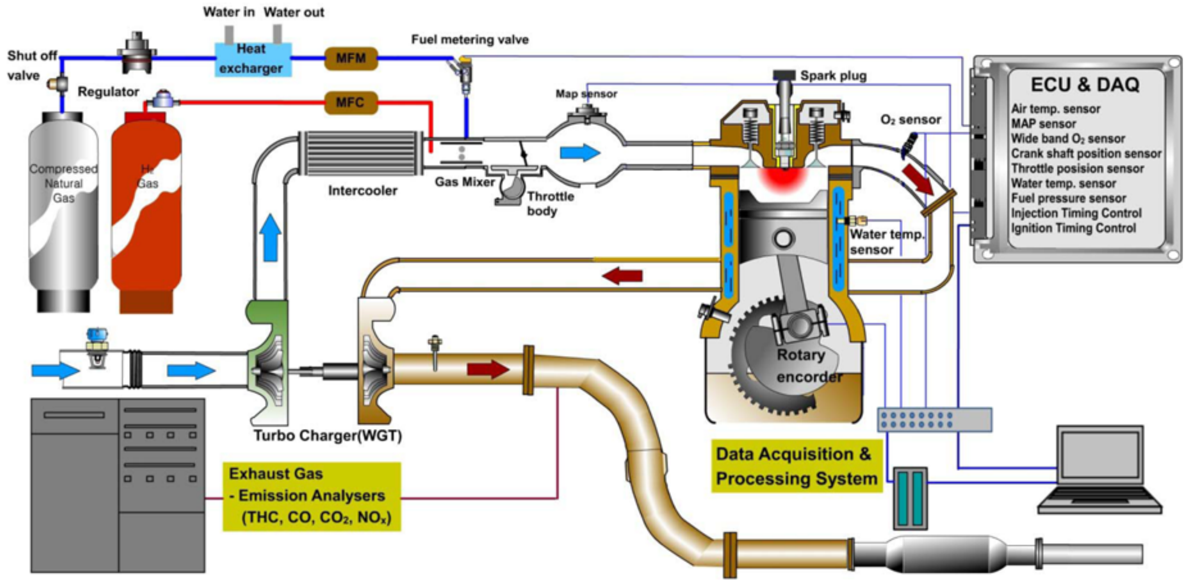

Figure 1. Schematic diagram of the experimental engine setup for steady state test. Reproduced from (Park *et al*., 2011).

In order to develop an HCNG engine with a stoichiometric mixture combustion, an EGR module composed of a valve and cooler were modified and installed into the existing test engine. The most significant change was the increase in the compression ratio to 12 to improve the thermal efficiency. However, since the higher combustion temperature due to the increased compression ratio can affect the durability of a piston, the method of the oil gallery was also changed by modifying the oil jet design of the connecting rod.

3. RESULTS AND DISCUSSION

In developing the HCNG engine, the initial proposal was intended to satisfy the reinforced exhaust regulations of EURO VI by employing the lean combustion without an expensive De-NO_x catalyst. Figures 2 and 3 present the plots of the thermal efficiency and NOx emissions versus the excess air ratio for various percentages of hydrogen in the natural gas fuel during a medium load operating condition. From these figures, it is possible to confirm that in response to an increase in the contents of hydrogen in HCNG fuel, the lean flammability limit and the thermal efficiency increased. Furthermore, it can be confirmed that according to the expansion of the lean flammability limit, the NOx emissions rapidly decreased.

As mentioned above, the engine using HCNG fuel that contained 30 % hydrogen was a development target. In

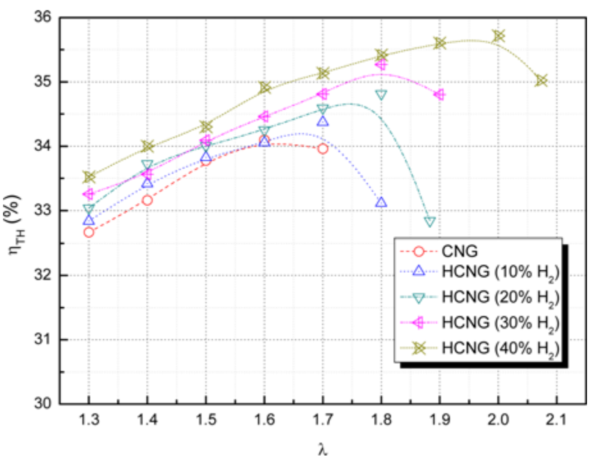

Figure 2. Variation in thermal efficiency versus excess air ratio for different percentages of hydrogen in HCNG fuel for the operating conditions of 1,260 rpm / 575 Nm. Reproduced from (Park *et al*., 2011).

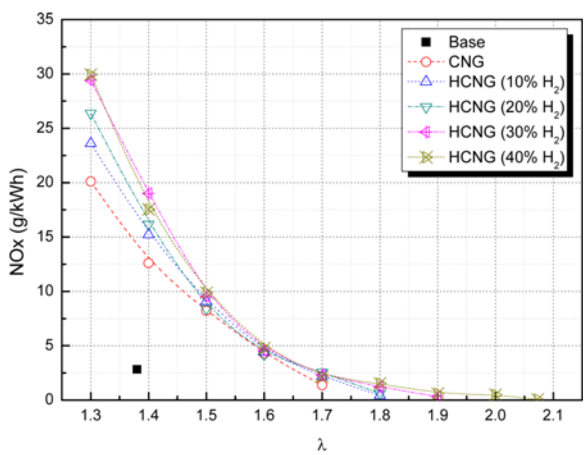

Figure 3. Variation in tail-pipe NO_x emissions versus excess air ratio for different percentages of hydrogen in HCNG fuel for the operating conditions of 1,260 rpm / 575 Nm. Reproduced from (Park *et al*., 2011).

Table 1. Comparison of the exhaust emission results between the mode test results of the lean combustion HCNG engine and EURO-VI standards.

	CO	NOx	NMHC	CH4
HCNG engine	0.012	0.347	0.017	0.165
Deterioration factor (DF)	1.2	1.1	1.2	1.2
HCNG engine* DF	0.014	0.382	0.020	0.198
EURO-VI standards	4.0	0.46	0.14	0.5
Results-to-standards ratio	0.35 %	83.0 %	14.3 %	39.6 %

order to take full advantage of the characteristics of the HCNG fuel, the design of engine core components such as the cam shaft, turbo-charger, and oxidation catalyst were changed throughout parts of the study (Park *et al*., 2011, 2012a, 2012b, 2013a, 2013b, 2013c, 2014; Lim *et al*., 2013a, 2013b, 2014). The optimization of the combustion and control of the HCNG fuel as well as the ECUs calibration and mapping were performed for the steady state and transient operating conditions. Table 1 provides the comparison of the exhaust emissions between the mode test results for the developed lean combustion HCNG engine and the regulation values required by the EURO-VI standards. Since harmful exhaust emissions satisfied all of the regulatory values, it can be confirmed that the lean combustion HCNG engine was able to satisfy the exhaust regulations of the EURO-VI standards without a De-NO_x catalyst.

Until NO_x regulations were greatly enhanced by the Euro-VI standards, the pros and cons of both a lean and stoichiometric combustion process were similar to each other with the lean combustion system presenting a slight advantage. However, the regulation of hazardous substances and non-regulated emissions after implementation of the EURO-VII standards are expected to be very difficult for accommodation of a lean combustion system even when the engine is fueled by HCNG since EURO-VII is expected to see a further reduction of NO_x to half that of EURO-VI and to focus CO_2 (Noble, 2016; Sluder, 2014). Therefore, a stoichiometric mixture combustion HCNG engine, which can meet post EURO-VI standards, was developed that ensured an increased efficiency and reduction of the exhaust gas temperature.

Figure 4 shows the characteristics and comparison of the thermal efficiency for each fuel with stoichiometric mixture combustion as the EGR rate increases to 1,260 rpm medium load operation condition. As can be seen from the results, the limit of the EGR supply of the HCNG is higher than that of natural gas by 5 %, thereby it can be confirmed that the thermal efficiency is slightly more improved. In accordance with an increase in compression ratio, it was discovered the EGR supply limit was also enhanced. The effect of the compression ratio on thermal efficiency and emissions will be analyzed and reported in another article.

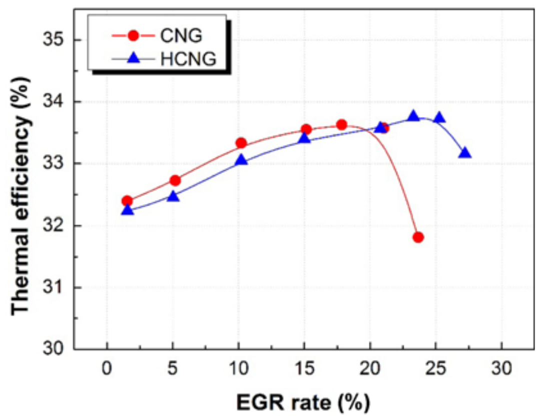

Figure 4. Thermal efficiency characteristics of the stoichiometric mixture combustion HCNG and CNG engine with various EGR rates for the operating conditions of 1,260 rpm / 575 Nm.

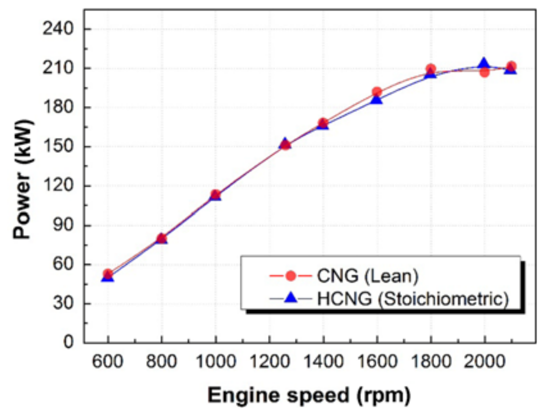

Figure 5. Comparison of power characteristics for the stoichiometric mixture combustion HCNG and lean combustion CNG engine for various engine speed conditions.

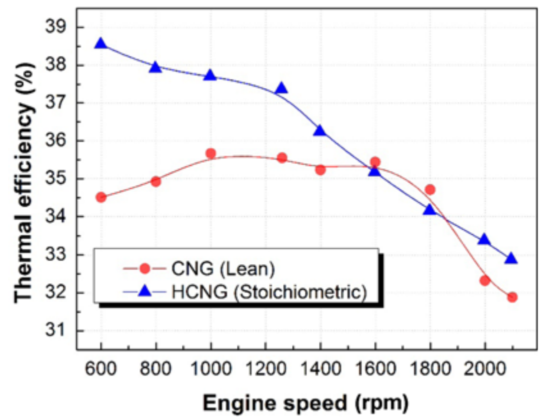

Figure 6. Comparison of thermal efficiency characteristics for the stoichiometric mixture combustion HCNG and lean combustion CNG engines for various engine speed conditions.

Based on the characteristics of a stoichiometric combustion HCNG engine as shown above, the detailed control parameters were expanded to the overall operational range to optimize the performance and emissions. Figures 5 and 6 show the results of the full load conditions as the engine speed increased. The power output matched the same level of the existing natural gas engine which employed a lean combustion strategy and satisfied the EURO-VI standards. The thermal efficiency maintained a higher level than that of the natural gas engine under most full load operational points. The reason for a higher efficiency characteristic for stoichiometric HCNG engine was attributed to the increased efficiency due to the introduction of EGR. The retarded spark advance timing was just perceptible for knocking prevention while the spark advance timing for the lean combustion natural gas engine was excessively retarded to reduce NO_x emissions to the level of the EURO-VI standards.

The control of the EGR rate in a stoichiometric HCNG engine was realized by installing a wide-band oxygen sensor at the intake manifold and monitoring the EGR flow rate using the sensor. Therefore, the spark advance timing could be optimized by checking the actual EGR flow supplied at the timing of acceleration and deceleration. Consequently, the specific fuel consumption, emission characteristics and knocking phenomena were effectively prevented. Before the transient cycle mode test, the feed-back function of the EGR control and capability of actuators were verified. It was found that the response of the actual EGR flow supplied to the intake manifold was rather slow compared to the value of the desired point when mapping previous tests. In order to increase the reaction response speed of the EGR system, the map of both the boost reference pressure and the set point of the EGR rate corresponding to the EGR valve position were edited and optimized as shown in Figures 7 and 8. The risk of overloading and knocking due to the slow response of the EGR system was resolved by correcting the spark advance timing through adaptive learning.

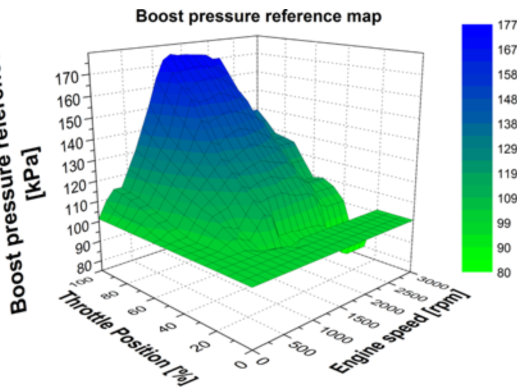

Figure 7. Optimal values of boost reference pressure for throttle position and engine speed under the entire operation range for the transient mode test.

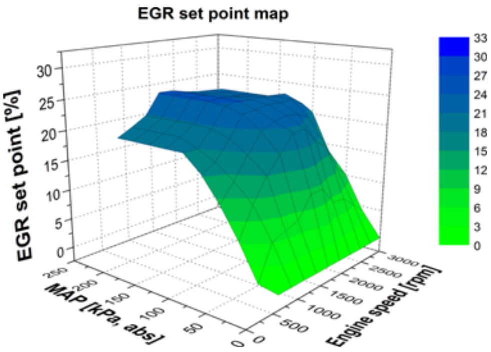

Figure 8. Optimal values of EGR set point for manifold air pressure and engine speed under the entire operation range for the transient mode test.

Table 2. Comparison of exhaust emission results between mode test results of stoichiometric combustion HCNG engine and EURO-VI standards.

	CO	NOx	NMHC	CH_4
HCNG engine	1.284	0.135	0.038	0.136
Deterioration factor (DF)	1.2	1.1	1.2	1.2
HCNG engine * DF	1.541	0.148	0.046	0.163
EURO-VI standard	4.0	0.46	0.14	0.5
Results-to-standard ratio	38.5 %	32.2 %	28.8 %	28.8 %

The mode test results for the stoichiometric HCNG engine was compared with the regulation values of the EURO-VI standards in Table 2. The test results indicate an overall low level of emissions with the exception of the CO emission levels. The reasoning for the relatively higher CO emission levels than that of the lean combustion natural gas engine, as represented in Table 1, was due to the difference of the combustion mode. Generally, CO is rarely discharged when an oxidation catalyst is employed in the lean combustion mode resulting in a rich oxygen condition of the exhaust gas. However, the oxygen to oxidize CO is not sufficient during the stoichiometric mixture mode. Hence, the richer mixture for the cold mode test caused higher CO emission levels. All of regulated emissions were at a level one third of the EURO-VI regulations. Remarkably the results indicated that the CO_2 levels were reduced by 18 % and fuel consumption improved by 8 % compared to the levels the lean combustion natural gas engine could achieve.

4. CONCLUSION

For the case of a lean combustion HCNG engine, an important component was changed to take full advantage of the fuel characteristics and the control parameters for efficient combustion were optimized. It was found that a developed lean combustion HCNG engine could satisfy the

EURO-VI emission regulations without a De-NO_x catalyst when the transient mode test was performed. Stoichiometric HCNG engines employed the oil gallery-type piston design in order to cope with high combustion and exhaust gas temperatures and a high EGR flow rate was applied to the combustion process. The HCNG engine could use EGR more effectively when compared to natural gas engines. Consequently, the HCNG engine was a more advantageous solution for solving the low efficiency and heat durability problems presented by the stoichiometric combustion strategy. A stoichiometric combustion HCNG engine was developed to accommodate post EURO-VI standards. Additionally, the development of a stoichiometric combustion HCNG engine for the performance under the steady state operating conditions was carried out. All of the regulated emissions from the mode test results were at levels one third of that for EURO-VI standard regulations. Remarkably the results indicated that CO_2 was reduced by 18 %.

ACKNOWLEDGEMENT–Support for this work was provided by the Ministry of Environment (Center for Environmentally Friendly Vehicle) under the project titled "Development of a City Bus HCNG Engine with Emission Level of Post EURO-VI". This work was performed at the Engine Research Department of Korea Institute of Machinery and Materials in Korea.

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