HYDROGEN ENRICHED COMPRESSED NATURAL GAS – A FUTURISTIC FUEL FOR INTERNAL COMBUSTION ENGINES

by

Kasianantham NANTHAGOPAL [a*], ***Rayapati SUBBARAO*** [b], ***Thangavelu ELANGO*** [a], ***Ponnusamy BASKAR*** [a], ***and Kandasamy ANNAMALAI*** [c]

[a] Automotive Research Centre, SMBS,VIT University, Vellore, Tamilnadu, India,
[b] Department of Mechanical Engineering, Indian Institute of Technology, Madras, Chennai, India
[c] Department of Automobile Engineering , MIT Campus, Anna University, Chennai, India

Original scientific paper
UDC: 621.43.013:662.767
DOI: 10.2298/TSCI100730044N

Air pollution is fast becoming a serious global problem with increasing population and its subsequent demands. This has resulted in increased usage of hydrogen as fuel for internal combustion engines. Hydrogen resources are vast and it is considered as one of the most promising fuel for automotive sector. As the required hydrogen infrastructure and refueling stations are not meeting the demand, widespread introduction of hydrogen vehicles is not possible in the near future. One of the solutions for this hurdle is to blend hydrogen with methane. Such types of blends take benefit of the unique combustion properties of hydrogen and at the same time reduce the demand for pure hydrogen. Enriching natural gas with hydrogen could be a potential alternative to common hydrocarbon fuels for internal combustion engine applications. Many researchers are working on this for the last few years and the work is now focused on how to use this kind of fuel to its maximum extent. This technical note is an assessment of hydrogen enriched compressed natural gas usage in case of internal combustion engines. Several examples and their salient features have been discussed. Finally, overall effects of hydrogen addition on an engine fueled with hydrogen enriched compressed natural gas under various conditions are illustrated. In addition, the scope and challenges being faced in this area of research are clearly described.

Keywords: *alternative fuels, hydrogen enriched compressed natural gas, natural gas, performance, combustion and emission*

Introduction

In the last few years, the use of alternative fuel in internal combustion engines has received renewed attention. The uncertainty of petroleum-based fuel availability has created need for alternative fuels. In recent years, an emphasis on reducing pollutant emissions from petroleum-based engines has motivated the development and testing of several alternative fuels. The conventional Diesel and gasoline engines suffer from higher emissions. Upcoming stringent emission norms coupled with rising fuel costs and depleting crude-oil resources has

* Corresponding author; e-mail: nanthagopalk@yahoo.com

pushed to do research in alternate fuels that are environment friendly. With ever increasing energy demand and concern of environmental protection, clean combustion with high efficiency has got increased attention. Further reduction in engine emissions using alternative fuels has become one of the major fields in engine development. Various fuels have been considered as substitutes for hydrocarbon-based fuel. Alternative fuels that aspire to replace petroleum-based fuels include alcohols, liquefied petroleum gas (LPG), compressed natural gas (CNG), hydrogen, vegetable oils, bio gas, producer gas, and liquefied natural gas (LNG) [1, 2]. In particular, natural gas is the most widely used and popular alternative fuel in India and elsewhere. Natural gas can be used in vehicles in two forms, as compressed and liquefied (CNG and LNG). Although LNG storage has been used in few vehicles at present, refueling cost of LNG tanks is not competitive with CNG. Until such time most vehicles using natural gas will store it in compressed form. CNG produces low HC and CO_2 emissions and negligible SO_x and particulate mater (PM) emissions, making it a "clean" fuel. An additional advantageous characteristic of natural gas is its high research octane number of 130. This means that a natural gas engine may be run at higher compression ratios than petrol engine without knocking, thus increasing its thermal efficiency. However, it is important to note that methane is a greenhouse gas with high global warming factor [3]. While the relatively high lean flammability limit of HC fuel makes it difficult to achieve stable combustion near the burning regime [4] and this is even more severe for natural gas. Running the natural gas engine at lean burn condition has many advantages such as higher brake thermal efficiency and lower heat loss. Because, excess air could increase the ratio of specific heats ($\gamma = C_p/C_v$) of the burned gas and improve combustion efficiency, both of which are beneficial to the engine's thermal efficiency. Furthermore, the possibility of knock becomes smaller, since cylinder temperature decreases and it can reduce the CO and unburned HC emissions [5]. As the main component of natural gas, methane has unique tetrahedral molecular structure with large C-H bond energies, thus demonstrating some unique combustion characteristics such as high ignition temperature and low flame propagation speed [6]. Hence, there is need to enhance the combustion process of natural gas at lean condition. One way of improving is by the addition of small amount of hydrogen to methane, resulting in a fuel having much less harmful to the environment and faster rate of burning than methane.

Hydrogen has been regarded as a future secondary fuel for power system due to carbon-free operation. Rapid increase in the emission of green house gases and very strict environmental legislations are major motivating factors for the usage of hydrogen in fuel cells and internal combustion engines. It is an excellent additive to improve the combustion of HC fuel due to its low ignition energy, high reactivity, diffusivity, and burning velocity [6]. The internal combustion engines can be fueled with pure hydrogen or the mixtures of HC fuels and hydrogen. As hydrogen has lower volumetric energy density and higher combustion temperature, pure hydrogen-fueled engine produces lower power output and much higher NO_x emissions than gasoline-fueled engine at stoichiometric air-fuel ratio. Blending of hydrogen with CNG provides a blended gas termed as hydrogen-enriched natural gas (HCNG). HCNG stands for hydrogen enriched compressed natural gas and it combines the advantages of both hydrogen and methane. HCNG allows customers early hydrogen deployment with nearly commercial technology. It is being treated as the first step towards future hydrogen economy. Engines can be calibrated for lower NO_x or greenhouse gas emissions. Any natural gas engine is compatible to run on HCNG and can do so with minimum modifications. It also allows governments and agencies to promote the use of hydrogen to greater number of people at less cost. HCNG can help the hydrogen industry to develop volume and transportation solutions while reducing costs. HCNG can take advantage of existing investment in natural gas infrastructure and also has much higher volumetric energy storage density than pure hydrogen [7-8].

However, as the hydrogen fraction increases above certain extent, abnormal combustion such as pre-ignition, knock and backfire occur. Due to the low quench distance and high burning velocity, the combustion chamber walls become hotter which causes more losses to the cooling water. Therefore, the amount of hydrogen being added should be optimized to compromise the gain and loss. With the increase of hydrogen addition, the lean operation limits extend and the mean brake torque decreases [9]. This view has been the accelerant behind the renewed interest and recent progress in the research and development of HCNG engines. This paper gives a comprehensive review of HCNG characterization, experimental investigation on different internal combustion engines, merits, demerits and challenges faced by HCNG.

Fuel characteristics of HCNG

When used in an internal combustion engine, even the addition of small amount of hydrogen to natural gas (5-30% by volume) leads to many advantages, because of some particular physical and chemical properties [10]. Xu *et al.* [11] developed a new HCNG premixed system which was used to blend desired amount of hydrogen into CNG. According to Dalton's partial pressure law, hydrogen fraction was decided by the partial pressure of these two fuels in HCNG tank. The influence of gas composition on engine behaviour can be adequately characterized by Wobbe index. If the Wobbe index remains constant, change in the gas composition will not lead to a noticeable change in the air-fuel ratio and combustion rate [3]. The overall comparison of properties of Hydrogen, CNG, 5% HCNG blend is given in tabs. 1 and 2 show the characteristic values of the HCNG fuels with different hydrogen fractions. Also, these confirm that the properties of HCNG lie in between those of hydrogen and CNG. There are a number of unique features associated with HCNG that make it remarkably well suited in principle to engine applications. Some of the most notable features are:

Table 1. Comparison of properties of hydrogen, CNG, and HCNG 5 with gasoline [3]

Properties	H_2	HCNG 5	CH_4	Gasoline
Limits of flammability in air, [vol.%]	4-75	5-35	5-15	1.0 -7.6
Stoichiometric composition in air, [vol.%]	29.53	22.8	9.48	1.76
Minimum energy for ignition in air, [mJ]	0.02	0.21	0.29	0.24
Auto ignition temperature, [K]	858	825	813	501-744
Flame temperature in air, [K]	2318	2210	2148	2470
Burning velocity in NTP* air, [cms^{-1}]	325	110	45	37-43
Quenching gap in NTP* air, [cm]	0.064	0.152	0.203	0.2
Normalized flame emissivity	1.0	1.5	1.7	1.7
Equivalence ratio flammability limit in NTP* air	0.1-7.1	0.5-5.4	0.7-4	0.7-3.8
Methane number	0	76	80	–
Composition of CNG: CH_4 – 90.2%, C_2H_6 – 8.5%, C_3H_8 – 0.6%, N_2 – 0.6%, butane – 0.1%				

* NTP denotes normal temperature (293.15 K) and pressure (1atm)

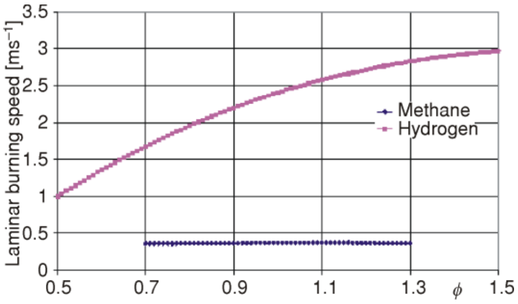

Figure 1. Laminar flame speed for methane and HCNG 15 [12]

- Addition of hydrogen increases the H/C ratio of the fuel. A higher H/C ratio results in less CO_2 per unit of energy produced and thereby reduces greenhouse gas emissions.
- Natural gas has low flame speed while hydrogen has the flame speed about eight times higher (fig. 1); therefore, when excess air ratio is much higher than the stoichiometric condition, the combustion of natural gas is not as stable as HCNG. The problem encountered using natural gas is that the engine will experience incomplete combustion (misfire) before sufficient NO_x reductions are achieved. Adding hydrogen to the fuel extends the amount of charge dilution that can be achieved while still maintaining efficient combustion [13].
- Hydrogen also has a very low energy density per unit volume and as a result, volumetric heating value of the HCNG mixture decreases (tab. 2) as the proportion of hydrogen is increased in the mixture [7].

Table 2. Properties of CNG and HCNG blends with different hydrogen content [14]

Properties	CNG	HCNG 10	HCNG 20	HCNG 30
H_2 [vol.%]	0	10	20	30
H_2 [mass%]	0	1.21	2.69	4.52
H_2 [energy%]	0	3.09	6.68	10.94
LHV [MJkg^{-1}]	46.28	47.17	48.26	49.61
LHV [MJNm^{-3}]	37.16	34.50	31.85	29.20
LHV stoichometric mixture [MJNm^{-3}]	3.376	3.368	3.359	3.349

- Addition of hydrogen in CNG allows the mixture to burn leaner. The mass fraction burned advanced as hydrogen increases. It provides shorter combustion duration at a given excess air ratio. This would result in more NO_x due to high combustion temperature. Hence spark timing should be retarded as the hydrogen fraction increases. Retarding spark timing reduces compression work and also decreases the combustion temperature. This helps in reducing NO_x formation. Spark timing selection would be very important to the tradeoff relationship between power and emissions.[3, 5, 10, 14-16]
- Blends of HCNG ranging from 15-30% extend the lean operating limit ensuring complete combustion which reduces HC and CO emissions [7].
- The laminar burning speed of hydrogen is nearly eight times higher than that of natural gas, so the addition of hydrogen can increase the burning velocity of the mixture, and it brings some advantages such as shorter combustion duration, greater degree of constant volume combustion and improved indicated thermal efficiency.
- Special properties of hydrogen as a combustion stimulant can produce leverage factors much greater than 1 by improving fossil fuels and not just displacing them, an obvious benefit of the leverage effect is that CO_2 reduction is possible even if the hydrogen used is produced by natural gas without any "sequestration" of CO_2 [16].

HCNG as an engine fuel

Application of blends of hydrogen and natural gas in internal combustion engines started in the early 90. During the last two decades, many experiments had been conducted all over the world. All the experiments had shown that the blends of hydrogen and natural gas reduce the exhaust emissions of both regulated pollutants and CO_2 and increase the efficiency of a spark ignition (SI) engine. In the Denver Hythane (a registered trademark of Hydrogen Components Inc.) project [17], comparative testing of three identical vehicles (1991 Chevrolet 5.7 liter pick-up trucks) with Hythane (15% hydrogen by volume, 85% NG) indicated that the Hythane fueled vehicle was able to meet ultra low emissions vehicle standards at sea level for NO_x, CO, and non-methane hydrocarbons. Raman *et al.* [18] investigated the usage of HCNG in lean burn SI engines, using 0, 15 and 30% volumes of hydrogen on a GM 5.71, V8 engine. With 15 and 30% volume of H_2, substantial reductions in NO_x with some HC penalty were observed as a result of very lean combustion. Munshi *et al.* [8] conducted experiments on a turbocharged lean burn natural gas engine with a blend of hydrogen and natural gas. Tests were carried out to determine the most suitable H_2-CNG blend for H_2 fractions between 20 and 30% by volume. 20% volume of H_2 was found to provide the desired benefits when the engine and vehicle performance attributes are taken in consideration. Kavathekar *et al.* [3] presented the results obtained during the optimization of a dedicated CNG injection 6 cylinder naturally aspirated engine and strategy for further upgradation to run HCNG. The original carburetor CNG Euro-III compliant engine was upgraded to meet Euro- IV norms by replacing the carburetion kit with injection kit.

Unich *et al.* [19] carried out an experimental investigation on a natural gas passenger car using natural gas and HCNG blend on a chassis dynamometer according to the European emission regulations, without any change on engine calibration. Reduction of 19% CO emission was observed with HCNG blend, while HC emissions remained constant. A 70% increment was observed in NO_x emissions with HCNG. There is no significant variation of fuel consumption on energy basis. Combustion and emission characteristics of port injection turbocharged (SI) engine fuelled with several H_2-CNG blend ratios (0-50%) under various ignition timings were investigated by Ma *et al.* [10]. Results show that with increasing hydrogen addition, the maximum brake torque (MBT) timing decreases and the indicated thermal efficiency increases. MBT gets close to top dead centre and the indicated thermal efficiency increases with decreased load. The combustion duration is reduced by increasing the hydrogen fraction in HCNG. All the NO_x, CO, and HC emissions tend to come down with the increase of spark advance angle and soar with the increase of load.

Bysveen [5] analyzed efficiency and emissions from an engine fuelled using mixtures of natural gas and hydrogen. It was reported that the brake thermal efficiency for HCNG is greater than CNG for the same excess air ratio (λ) and the difference in brake thermal efficiency between HCNG and CNG increases with increasing excess air ratio. Results also show that NO_x emissions are significantly reduced by increasing the excess air ratio and that of hydrogen addition to the CNG. This leaning out may easily be achieved without any substantial HC penalty. Xu *et al.* [14] evaluated the scenario in HCNG fueled engines comprehensively. From the results, it was observed that, replacement of natural gas with HCNG was found to have significant influence on engine performance. Experimental results indicated that under certain conditions, the maximum cylinder gas pressure, maximum heat release rate increased with the increase of hydrogen fraction. The beginning of heat release advanced with the increase of hydrogen fraction. This phenomenon was more obvious when fuel – air mixture was richer. At a given excess air ratio, more hydrogen added would bring out more NO_x emission due to the higher combustion temperature. When excess air ratio changed from 1.2 to 2.0, NO_x emission could research to an extremely low level. When excess air ratio was about 1.8, maximum cylinder pressure and maximum heat release have got more significance rise due to hydrogen addition compared to excess air ratio was 1.2. When spark timing swept from 30 to 20° bTDC, the maximum cylinder pressure reduced but NO_x emission decreased at the same time. It has been suggested that, when adding more than 20% volume into CNG, lean mixture combustion and ignition timing optimization could significantly decrease NO_x emission and maintain relatively higher thermal efficiency under certain fixed engine conditions. Collier *et al.* [13] developed a new dedicated HCNG (30% H_2 and 70% natural gas by volume) heavy duty engine for heavy duty transportation applications with lower NO_x emissions.

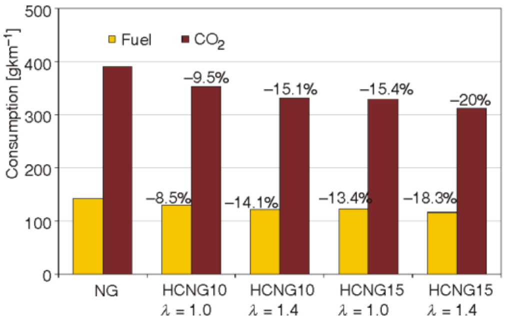

Figure 2. Gas consumption and GHG emissions of HCNG10 and HCNG 15 for λ = 1 and λ = 1.4) [22]

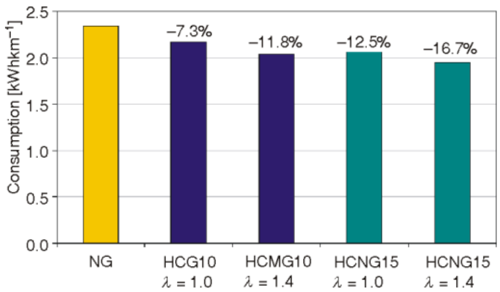

Figure 3. Energy consumption of HCNG10 and HCNG 15 for λ = 1 and λ = 1.4) [22]

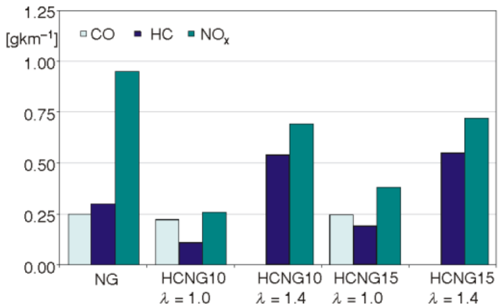

Figure 4. Local emissions of different volumes of hydrogen in HCNG [22]

Similar results obtained by many researchers [20-23]. Park *et al.* [20] investigated the influences of hydrogen on the performance and emission characteristics of a heavy duty natural gas engine. He pointed out that NO_x reduction of over 80% is possible by employing retarded spark timing with the addition of 30 vol.% hydrogen with natural gas under the condition of best thermal efficiency. Ma *et al.* [21] examined the effect of spark timing on engine's indicated thermal efficiency and NO_x emission. He concluded that at given indicated thermal efficiency, NO_x emission decreased as the increase of hydrogen fraction under optimized SI timing. Iacobazzi *et al.* [22] ran an urban bus fleet with NG, HCNG 10, and HCNG 15 of the ECE-15 driving cycle for stoichiometric condition (λ = 1 and λ = 1.4). Some of the results obtained in the 6 months test campaign by them are presented here in the form of bar charts (figs. 2-4). These figures give a very good comparison of engine performance with different operating conditions (excess air ratio, ignition timing) using different hydrogen fractions in HCNG. The use of HCNG can allow significant reduction of both global and local pollution in short term and with limited economical burden.

An experimental study on the performance and exhaust emissions of a SI fuelled with methane-hydrogen mixtures was performed at different engine speeds and excessive air ratios by Kahraman *et al.* [23] on a Ford engine. Results showed increment in speed and excessive air and decrement in CO emissions. Reduction of HC and CO emissions could be obtained by adding hydrogen into natural gas when operating with the lean mixture condition. Increasing the excessive air ratio also decreases the maximum peak cylinder pressure. Morrone *et al.* [24] developed a numerical model and used this to investigate the time evaluation of the mass burned fraction of a passenger car engine in order to estimate the variation of brake thermal efficiency for hydrogen-natural gas blends. Satisfactory agreement was found between the numerical and experimental results for a CNG fuelled engine.

Ma *et al.* [25] has developed an online natural gas-hydrogen mixing system and analyzed its effects and feasibility by spectro analysis of the sampled fuel gas mixture. It was confirmed that the developed system can produce HCNG with accurate enough blending ratio and is very suitable for HCNG engine testing. Mixing process takes place at a relatively low pressure which is good for safety operation. The effect of hydrogen addition on early flame growth of lean burn natural gas-air mixtures was investigated experimentally and numerically by Wang *et al.* [26]. It has been reported that the initial combustion process is significantly enhanced with hydrogen addition for both laminar premixed and direct-injection turbulent combustion at lean mixture condition. The enhancement of SI of lean natural gas-air mixtures with hydrogen addition is ascribed to the increase of OH and O mole fraction in the flames. The statistical analytical methods for optimizing a SI engine fueled by natural gas and hydrogen mixtures were used by Ma *et al.* [15]. They evolved a method to get the optimum hydrogen fraction, ignition timing and excess air ratio which make the overall engine's performance optimal. The comparison of optimized results and the original CNG performance showed that CH_4, CO, NO_x, and BSFC decrease by 70, 83.57, 93, and 5%, respectively.

Advantages of HCNG

From the review of literature available in the field of HCNG usage, many advantages are noticeable. The following are some of the benefits of using HCNG as fuel.

- It is usable with the existing CNG infrastructure. It requires only small hydrogen storage and a column for the mixing of hydrogen with natural gas.
- Safety properties are similar to CNG. HCNG is safer to handle than hydrogen, because of lower risk due to very low energy content from hydrogen (only up to 30 vol.%).
- It extends the lean misfire limit of CNG.
- Minor modifications are required in the engine due the moderate concentration of hydrogen in the fuel mixture; the excellent anti-knock characteristics of CNG are not undermined.
- The phenomenon of hydrogen embrittlement does not occur with respect to the engine components. Hence, no major change is anticipated in the fuel system and engine components.
- Hydrogen addition to natural gas can decrease engine's unburned hydrocarbons and NO_x emissions (by lean burn) and speed up the combustion process.
- It improves the engine efficiency and lowers fuel consumption.

Challenges of HCNG

- HCNG storage and supply infrastructure.
- Efforts to be focused on responding to fuel system performance, material compatibility.
- Emission testing with more ranges of hydrogen in HCNG blends.

- Continuous availability of HCNG needs to be assured before embarking on its major use in IC engines.
- Continued engine performance, emissions and durability testing in variety of engine types and sizes need to be developed to increase consumer and manufacturer confidence.
- Development of less expensive quality tests.

HCNG – A better option for India

It is advantageous for India to use the existing CNG infrastructure for investigating the feasibility of using HCNG as an automotive and gain experience in handling the new fuel. Furthermore, no major engine modifications are required. Government of India has taken decision to treat up to 20% HCNG blend on par with CNG. Government has also constituted a committee to frame regulations for HCNG blends above 20% hydrogen. ISO standards for HCNG and hydrogen kit component testing are being framed in ISO TC 22 SC 25 [27]. A number of research and development programs have been initiated on the use of H_2-CNG blends with the Ministry of New of Renewable Energy (MNRE), Automotive Research Association of India (ARAI) and automobile manufacturers. R&D centre of Indian oil corporation has taken major steps towards using HCNG as a fuel in automotive engines. Numerous experiments were conducted in three-wheelers with different HCNG blends and 18% HCNG blend is selected for further optimization. Field trials are in progress to study the long term effect of HCNG fuel. Vehicle optimization for suitable HCNG blends in LCV and buses are in progress. Further experimental optimization is in progress at ARAI to convert the developed CNG injection engine to run on HCNG blends and to achieve Euro- IV norms.

Conclusions

It is evident from the study made that it is advantageous to use HCNG as a fuel in internal combustion engines. Addition of hydrogen to CNG as a fuel in SI engines gives significant and positive impact on efficiency, especially close to the lean limit. HCNG makes it possible to run the engine leaner, resulting in lower emissions of CO_2, CO and HC at certain λ and higher NO_x emissions at constant excess ratio. Future experimental developments would prophesy the optimization of emissions of both urban pollutants and CO_2 along with the reduction of fuel consumption for specific vehicle driving cycle finding the best compromise after investigating a wider spectrum of λ, spark advance, compression ratio and percentage of hydrogen in the blends. Finally, it has been concluded that HCNG fuels pave the road for the use of hydrogen vehicles in the future due to expensive after treatment technologies. The entire paper discusses the application of HCNG in SI engines; it could also be extended for CI engines which would meet the thoughest Euro-V norms yet to be enforced in near future in India as shown in fig. 5 [3].

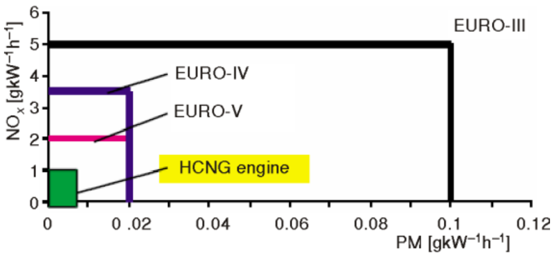

Figure 5. Emission potential of HCNG engine

A number of research works are currently in progress to make HCNG as alternate for Diesel engines with proper modifications.

Nomenclature

Greek symbols

- λ – excess air ratio
- φ – equivalence ratio

Acronyms

- BSFC – brake specific fuel consumption
- CNG – compressed natural gas
- ECE – economic commission of Europe
- GHG – green house gas
- HCNG – hydrogen-enriched natural gas
- LCV – light commercial vehicles
- LHV – low heating value
- LNG – liquefied natural gas
- LPG – liquefied petroleum gas
- MBT – maximum brake torque
- NG – natural gas
- PM – particulate matter

References

[1] Bechtold, R. L., Alternative Fuel Guidebook, SAE publication, 1997

[2] Bade Shrestha, S. O., Karim, G. A., Hydrogen as an Additive to Methane for Spark Ignition Engine Applications, *International Journal of Hydrogen Energy*, *24* (1999), 6, pp. 577-586

[3] Kavathekar, K. P., Rairikar, S. D., Thipse, S. S., Development of a CNG Injection Engine Compliant to Euro –IV Norms and Development Strategy for HCNG Operation. SAE paper 2007-26-029, 2007

[4] Naha, S, Briones, A. M, Aggarwal, S. K., Effect of Fuel Blends on Pollutant Emissions in Flames. *Combustion Sciences and Technology*, *177* (2005), 1, pp. 183- 220

[5] Bysveen, M., Engine Characteristics of Emissions and Performance Using Mixtures Natural Gas and Hydrogen, *Energy, 32* (2007), 4, pp. 482-489

[6] Turns, S. R., An Introduction to Combustion: Concepts and Applications, 2nd ed., McGraw-Hill; Boston, Mass., USA, 2000, pp. 158-159

[7] Bell, S. R., Gupta, M., Extension of a Lean Operating Limit for Natural Gas Fuelling of a Spark Ignition Engine Using Hydrogen Blending., *Combustion Sciences and Technology*, *123* (1997), 1-6, pp. 23-48

[8] Munshi, S. R., *et al*., Hydrogen Blended Natural Gas of a Operation of a Heavy Duty Turbocharged Lean Burn Spark Ignition Engine, SAE paper 2004-01-2956, 2004

[9] Hoekstra, R. L., *et al*., NO_x Emission and Efficiency of Hydrogen, Natural Gas, Natural Gas/Hydrogen Blends, SAE paper 961103, 1996

[10] Ma, F., *et al*., Combustion and Emission Characteristic of a Port Injection HCNG Engine under Various Ignition Timings., *International Journal of Hydrogen Energy, 33* (2008), 2, pp. 816-822

[11] Karner, D., Francfort, J., Freedom Car and Vehicle Technologies Program – Advanced Vehicle Testing Activity, Arizonal Public Service, Alternative Fuel (Hydrogen) Pilot Plant, US DOE; 2003

[12] Ortenzi, F., Chesisa, M., Conigli., F., Experimental Tests of Blends of Hydrogen and Natural Gas in Light Duty Vehicles, *HYSYDAYS* – 2nd World Congress of Young Scientists on Hydrogen Energy Systems. Turin, Italy, 2007, pp. 1-11

[13] Collier, K., *et al*., Emission Results from the New Development of a Dedicated Hydrogen –Enriched Natural Gas Heavy Duty Engine, SAE paper 2005-01-0235, 2005

[14] Xu, J., *et al*., Experimental Study of a Single Cylinder Engine Fueled with Natural Gas – Hydrogen Mixtures, *International Journal of Hydrogen Energy, 35* (2010), 7, pp. 2909-2914

[15] Ma, F., *et al*., An Investigation of Optimum Control of a Spark Ignition Engine Fueled by NG and Hydrogen Mixtures, *International Journal of Hydrogen Energy*, *33* (2008), 24, pp. 7592-7606

[16] Ma, F., *et al*., Experimental Study on Thermal Efficiency and Emission Characteristics of a Lean Burn Hydrogen Enriched Natural Engine, *International Journal of Hydrogen Energy, 32* (2007), 18, pp. 5067-5075

[17] ***, Technical Comparison between Hythane, CNG and Gasoline Fueled Vehicles, Report by Energy Task Force of the Urban Consortium, City and County of Denver, Alternative Fuels Unit, 1992

[18] Raman, V., *et al*., Hythane – an Ultra Clean Transportation Fuel, *Proceedings*, 10th World Hydrogen Energy Conference, Cocoa Beach, Fla., USA, 1994

[19] Unich, A., Morrone, B., Mariani., A., The Impact of Natural Gas – Hydrogen Blends on Internal Combustion Engines Performances and Emissions. SAE paper 2009 -24-0102, 2009

[20] Park, C., *et al*., The Influences of Hydrogen on the Performance and Emission Characteristics of a Heavy Duty Natural Gas Engine, *International Journal of Hydrogen Energy, 36* (2011), 5, pp. 3739-3745

[21] Ma, F., Wang., Y., Study On the Extension of Lean Operation Limit through Hydrogen Enrichment in a Natural Gas Spark-Ignition Engine, *International Journal of Hydrogen Energy, 33* (2008), 4, pp. 1416-1424
[22] Iacobazzi., A., *et al.*, Use of Blends of Hydrogen and Natural Gas in Urban Vehicles in the Transition Towards an Hydrogen Economy, 2WIH2, Ghardaïa, Algeria, 2007
[23] Kahraman, N., *et al.*, Investigation of Combustion Characteristics and Emissions in a Spark Ignition Engine Fuelled with Natural Gas-Hydrogen Blends., *International Journal of Hydrogen Energy, 34* (2009), 2, pp. 1026-1034
[24] Morrone, B., Unich., A., Numerical Investigation on the Effects of Natural Gas and Hydrogen Blends on Engine Combustion., *International Journal of Hydrogen Energy, 34* (2009), 10, pp. 4626-4634
[25] Ma, F., *et al*., Development and Validation of an Online Hydrogen – Natural Gas Mixing System for Internal Combustion Engine Testing. SAE paper 2008-01-1580, 2008
[26] Wang, J., *et al*., Effect of Hydrogen Addition on Early Flame Growth of Lean Burn Natural Gas-Air Mixture, *International Journal of Hydrogen Energy, 35 (*2010), 13, pp.7246-7252
[27] Acharya., G. K., Alternate Fuels, 12th Energy Summit Indian Oil & Gas Sector, New Delhi, 2010

Paper submitted: July 30, 2010
Paper revised: March 8, 2011
Paper accepted: March 17, 2011