Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 187 (2017) 395 – 401

Procedia Engineering

www.elsevier.com/locate/procedia

10th International Scientific Conference Transbaltica 2017: Transportation Science and Technology

Hydrogen Addition Influence for the Efficient and Ecological Parameters of Heavy-Duty Natural Gas Si Engine

Vidas Korsakas[a], Mindaugas Melaika[a,b,*], Saugirdas Pukalskas[a,b], Paulius Stravinskas[a,b]

[a]*JSC "SG dujos Auto", Vilnius, Lithuania*
[b]*Vilnius Gediminas Technical University, Lithuania*

Abstract

The paper presents the experimental research results of heavy-duty vehicle (public transport bus), fuelled with natural gas and hydrogen fuel mixtures. Spark ignition six cylinder engine tested with different hydrogen additions (from 5% up to 20% according to volume) in the natural gas fuel. The tests were performed on heavy-duty vehicle's dyno test stand in company "SG dujos Auto" research laboratory. The tests were carried out at three load points and one engine speed. Engine had originally a port fuel injection and exhaust gas recirculation system. Experiments showed that engine fuelled with hydrogen addition was able to achieve lower fuel consumption and brake specific fuel consumption. It was also possible to achieve small increase of engine efficiency. The exhaust gas measurements showed that hydrogen addition in natural gas reduced the CO, CO_2 and HC emissions because of the H/C atom ratio change in fuel mixture and improved combustion process. The NO_x emission level was decreasing, although bigger amounts of hydrogen were used in natural gas fuel.

Peer-review under responsibility of the organizing committee of the 10th International Scientific Conference Transbaltica 2017

Keywords: natural gas, hydrogen, heavy-duty engine, efficient and ecological parameters

* Corresponding author.
E-mail address: mindaugas.melaika@vgtu.lt

Peer-review under responsibility of the organizing committee of the 10th International Scientific Conference Transbaltica 2017
doi:10.1016/j.proeng.2017.04.391

1. Introduction

Nomenclature

NGV	Natural gas vehicle	EGR	Exhaust gas recirculation
ICE	Internal combustion engine	SI	Spark ignition
RON	Researched octane number	PFI	Port fuel injection
CNG	Compressed natural gas	Rpm	Revolutions per minute
A/F	Air and fuel ratio		

Upcoming humanity's strategic objectives is to reduce significantly the fossil fuels (oil) consumption, as a radical reduction way of the greenhouse gases, especially carbon dioxide (CO_2). European Commission states that there is no single fuel solution for the future transport because the availability and cost of alternative fuels differ between the transportation modes [1]. Sudden transition to a global use of electric vehicles and alternative fuel sources is not possible, so one of the most acceptable alternatives to the "transition period" is a wider use of simple molecular structure fuel – natural gas of which resources will be sufficient for few hundred years. The increasing amount of the NGVs force to search for the new and innovative ICE technologies and new alternative fuel types, which can improve the fuel economy and reduce exhaust gas emissions [2].

The main benefit of the methane gas is that it has much higher octane number (RON > 130) as compared to petrol (RON 86) and this enables substantially higher compression ratios without knock problems. Such fuel property is more suitable for SI engines. The relationship of compression ratio and thermal efficiency of Otto cycle engine is shown below [2, 3]:

$$\eta = 1 - \frac{2}{\varepsilon^{(y-1)}}, \eta = 1 - \frac{1}{\varepsilon^{(y-1)}}, \tag{1}$$

where ε – compression ratio; γ – adiabatic index.

As CNG engines can operate with higher compression ratio, it is possible to achieve higher thermal efficiency, though some modifications have to be done [4, 5]. Hydrocarbon (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitrous oxide (NO_x) and particulate matter (PM) are significantly lower with natural gas fuel than with diesel fuel in compression ignition engines or sometimes even with petrol fuel in SI engines [6]. It was noted, that PM emissions are significantly reduced with natural gas fuels because it does not have aromatic and polyaromatic compounds and contains less sulfur compounds comparing with the liquid fuels [7]. Methane stoichiometric combustion balance can be shown as following [2, 8]:

$$CH_4 + \left(0_2 + \frac{79}{21} N_2\right) \rightarrow CO_2 + H_2O + N_2. \tag{2}$$

The results of the studies showed that the fuel features have direct impact on NGVs emissions and fuel economy. Depending on gas composition, A/F ratio varied also. For this reason, engines are designed so that they will compensate the variations of the fuel composition [7, 9].

To expand alternative fuel range, it is attractive to use energetically potential and clean fuel – hydrogen (H_2). One of the way to apply H_2 is to use natural gas and hydrogen fuel mixtures. In [10] investigation presented, where it was claimed, that hydrogen as additive in natural gas can improve such characteristics like power, efficiency and emissions, when engine was working on lean mixtures [10]. In [11] claims that heavy duty vehicles fueled with hydrogen and natural gas fuel mixtures decrease such pollutants like CO, CO_2 and HC.

Company "SG Dujos Auto" has been researching natural gas and hydrogen fuel mixtures for the wide variety of the vehicles since 2013. Heavy duty (city buses, commercial transport), light vehicles were investigated with different H_2 additions in CNG. Series of experiments showed that one of the promising fuel mixtures is 2% H_2 addition in CNG. The "H2NG" trademark for the natural gas and hydrogen fuel mixtures was registered and patented under “SG Dujos Auto” company name. Registered name shows that natural gas has H_2 addition up to 2% [12].

CNG/H_2 fuel blends cannot be used with too big hydrogen amount, when such fuels are supplied into the SI engine, in case when the engine is not modified. Using more than 5% hydrogen in CNG fuel there is a need for engine operation modification, such as spark timing optimization. Dimopoulos and Karim determined that hydrogen increased natural gas combustion speed. Correctly set spark timing can improve gas engine η_e [13, 14].

The literature overview showed that H_2 addition in natural gas fuel could have a noticeable impact on engine indicators. The aim of this research is to determine the influence of small amounts of H_2 in natural gas fuel mixtures for the heavy-duty vehicle’s engine efficient and ecological parameters, which meets recent EURO emission standards and has an EGR system. Such research could give a better understanding about natural gas / hydrogen fuel mixture’s use for the ground vehicles, which have an original manufacturer equipment and have no adaptations for natural gas fuels enriched with hydrogen element. There were many experimental investigations with research engines, but it is still relatively rare case, when the complete heavy-duty vehicle is being studied with such kind of fuel mixtures. Such type experiments are also valuable and should be carried on in order to understand alternative fuels influence for the engines, especially when new and advanced fuel injection and engine control systems are applied in new generation internal combustion engines.

2. Material and methods

The investigated vehicle was *Castrosua City Versus* city bus with heavy duty SI 6 cylinder ICE (engine model *F2BE0642H*) (Table 1). Experiments were performed in “SG dujos Auto” company laboratory “Experimental Research Laboratory of Hydrogen as Fuel or Fuel Additive, Organic Fuel Additives and Fuel Systems“, which is situated in Pabradė town, Lithuania.

Tested heavy-duty vehicle with 6 cylinder engine had a turbocharger, PFI fuel injection system for gaseous fuel (CNG) supply and which was originally mounted by vehicle manufacturer. The gas injectors injected natural gas or natural gas / hydrogen fuel mixtures into air intake manifold. Engine meets one of the newest emission standards – Euro 5 EVV. Fig. 1 shows the experimental setup of CNG heavy-duty vehicle tests.

Table 1. Technical characteristics of tested heavy-duty vehicle engine.

Parameter	Engine F2BE0642H
Number of cylinders	6
Bore x Stroke, mm	115 × 125
Displacement, dm3	7.79
Maximum engine power, kW (rpm)	213 (2000)
Maximum engine torque, Nm (rpm)	1100 (1100–1850)
Compression ratio, ε	11.5
Number of valves per cylinder	4

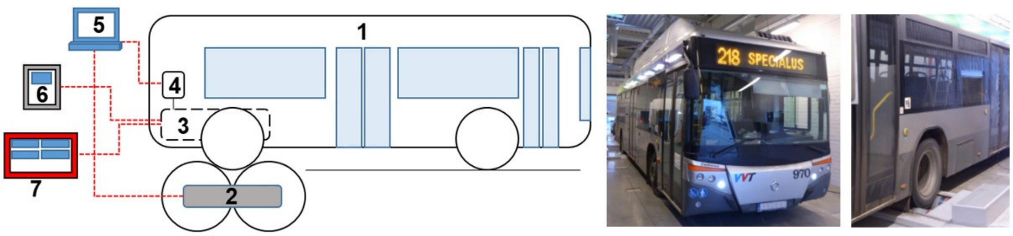


Fig. 1. City bus tests. Test scheme in the “SG dujos Auto” research laboratory
(1 – tested city bus; 2 – heavy duty vehicles’ dynamometer test bench V-Tech; 3 – city bus with SI ICE *F2BE0642H*; 4 – engine control unit;
5 – computer for data acquisition; 6 – gas mass flow meter RHEONIK RHM015; 7 – exhaust gas analyser *OPUS 40–D*) [2].

Heavy-duty vehicle tests were performed with same 1 axle dyno test bench *V-Tech VT2/T* Dynamometer (Fig. 1) as it was used previously for the same vehicle tests [2] (engine speed was 1500 rpm, three different engine loads). Dyno test bench was able to measure the maximum power on wheels and torque with inertial brake system. During present experimental investigation, engine power also was recalculated from the power on wheels (measurements with dyno test bench equipment), where the power loss due to mechanical losses were evaluated. Vehicle engine *F2BE0642H* tests were performed at two engine speeds – 1300 rpm, 1700 rpm and three loads on wheels – 30 kW, 50 kW, 100 kW. Since the experimental tests were carried with new vehicle, which has a standard manufacturer engine control unit equipment, maximum engine speeds and engine loads could not be tested due to vehicle transmission issues. Engine and gearbox control unit was not able to hold constant desired gear at maximum load.

Natural gas and natural gas/hydrogen fuels were measured by Coriolis type mass flow meter. The fuel flow meter was *Rheonik RHM 015*, which was connected into the high-pressure fuel supply system before the gas reducer. The measuring range of the flow meter was 0.004–0.6 kg/min with high measurement accuracy ±0.10%.

CNG heavy-duty vehicle engine pollutants were measured with *OPUS 40–D* exhaust gas analyser when natural gas / hydrogen fuel mixtures were tested.

3. Research results and discussion

The experiments were performed at two engine speeds (n = 1300 rpm; n = 1700 rpm) and three load points (30 kW; 50 kW; 100 kW). Such research plan could give a better view about natural gas / hydrogen fuel mixtures' influence for the engine efficient and ecological parameters, when the engine is running at slower and higher engine speeds. Originally, the bus engine had a homogenous stoichiometric combustion ($\lambda = 1$) setup (Table 2). Each testing point with different fuel mixtures were repeated for several times. Results of averaged values are presented below.

Table 2. Heavy duty vehicle *Castrosua* testing modes with natural gas/hydrogen fuel mixtures.

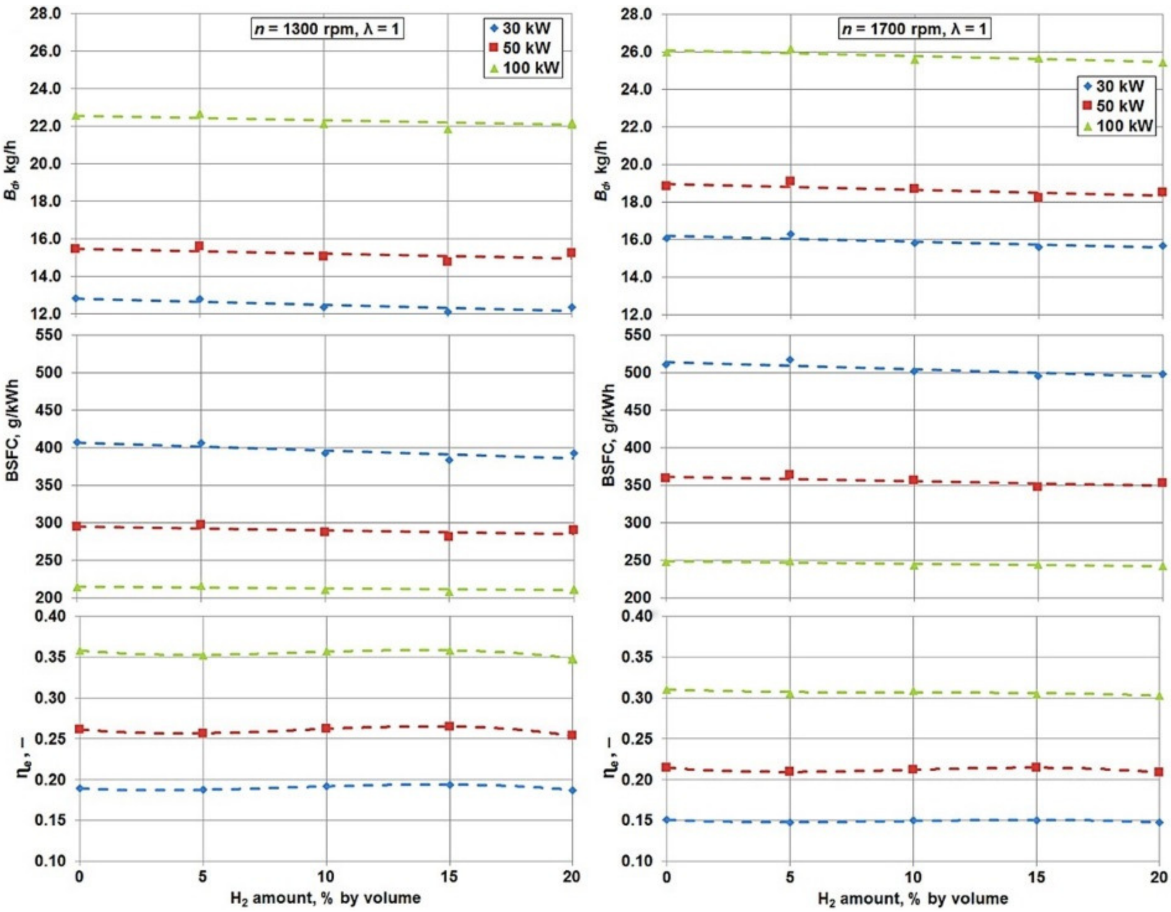
Fuel injection type	Engine speed, rpm	Tested fuels	Load on wheels	A/F mixture preparation type
PFI	1300 1700	CNG CNG + 5% H_2 CNG + 10% H_2 CNG + 15% H_2 CNG + 20% H_2	30 kW; 50 kW; 100 kW	Homogenous stoichiometric

Fig. 2 presents different fuel mixtures influence on fuel consumption (B_d), brake specific fuel consumption (BSFC) and engine efficiency (η_e). B_d decreased with increasing hydrogen addition in natural gas fuel and showed increase with higher engine speed and engine loads. For the same reason as for B_d – improved fuel mixture characteristics, the BSFC reduced with increasing H_2 addition in gaseous fuel mixture. Hydrogen element has 120 MJ/kg lower heating value (LHV). Comparing with natural gas (~50.4 MJ/kg) that is more than 2 times higher. Such bigger LHV resulted in less injected fuel mass as the cyclic energy was bigger with increasing hydrogen addition in CNG.

The highest η_e was achieved with 10–15% H_2 addition in the fuel mixture at both engine speeds and mainly all engine loads. Minor decrease of η_e was observed for the fuel mixtures with 5% H_2. However, CNG/H_2 fuel mixtures made insignificant influence on engine efficient work, when hydrogen addition was used up to 10%. More obvious engine efficiency decrease was noticed with 20% H_2 addition, possibly due to increased energy content in the fuel mixture, increased combustion temperature and higher pressure in the cylinder. Since the engine control unit is programmed to work with natural gas fuel and has minor compensation margins for the spark timing, air/fuel ratio, etc., intense changes in combustion process requires much bigger spark timing corrections as it was proved in other research works [2, 13, 14]. Spark timing should be retard towards the top dead center.

The changes of ecological indicators due to different CNG/H_2 fuel mixture at different tested engine speeds and loads presented in Fig. 3. The CO concentration with CNG fuel was ~0.68% at 1300 rpm and highest load, and

~ 0.56% at 1700 rpm. With increasing H_2 volume in the fuel mixture, the CO emissions were decreasing mainly at all tested engine speeds and power points. The lowest CO emission was achieved with 20% H_2 addition at 30 kW point (1300 rpm), which was ~7.3% lower comparing with CNG case. The CO emission was slightly lower at the highest tested engine speed (1700 rpm), if compared with 1300 rpm cases. Probably, due to increased air intake and motion in the cylinder at higher engine speed, the air and fuel mixing improved and resulted in better combustion process, which let to achieve higher emission level of full combustion products. This can be supported by increased CO_2 emission results at tested higher engine speed.



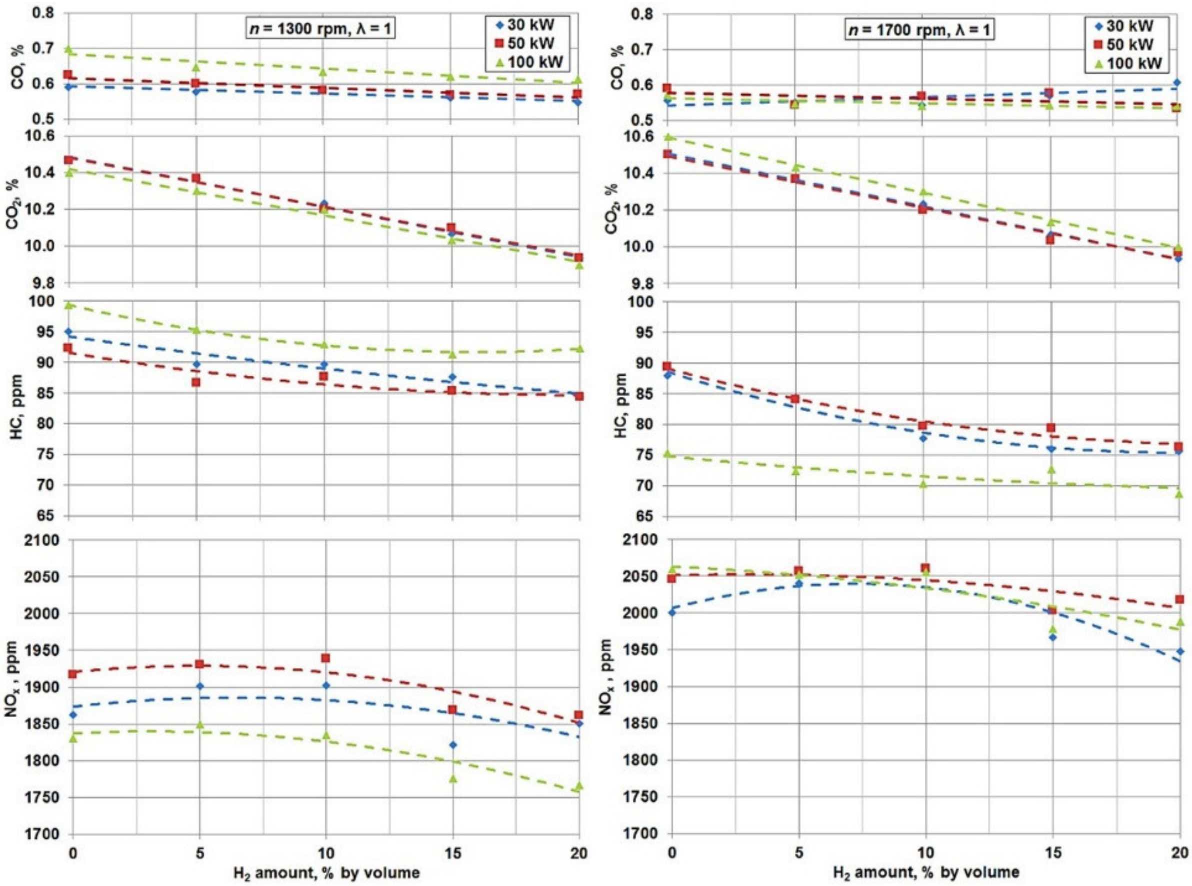
a) b)

Fig. 2. Dependence of engine fuel consumption, brake specific fuel consumption and thermal efficiency on different tested loads and natural gas/hydrogen fuel mixtures. Engine speeds: a) *n* = 1300 rpm; b) *n* = 1700 rpm.

The CO_2 emission measurements showed same tendency – CO_2 decreased steadily with increasing H_2 amount in CNG fuel. For example, the CO_2 emission was ~5.16% lower with 20% H_2 addition at 30 kW and 50 kW regimes (1300 rpm) than using pure CNG. The main reason of CO and CO_2 emission reduction is the H/C atom ratio change in fuel mixtures with H_2 addition. Less carbon elements and more hydrogen elements were present in gaseous fuel mixtures, and therefore less CO and CO_2 formed.

The HC emission decreased steadily at all tested cases with increasing H_2 amount in the fuel. Because of increased flame propagation and reduced quenching distance, due to more flammable H_2 element, which let to achieve more complete combustion process and reduced HC emissions. Similar emission (CO, CO_2, HC) tendencies obtained from 1500 rpm engine speed were analysed and presented in [2].

The NO_x emission formation was minor with increasing H_2 amount in the CNG fuel. The highest increase was observed with 5–10% H_2 at both speeds and different power loads. The NO_x emission level decreased with more than 10% of H_2. These results are different from other results of reviewed literature where the NO_x emission level was increasing due to increasing combustion temperature in the cylinder because of H_2 addition in natural gas fuel [2, 15, 16].



a) b)

Fig. 3. Exhaust gas emission dependence on different tested loads and natural gas / hydrogen fuel mixtures. Engine speeds: a) *n* = 1300 rpm; b) *n* = 1700 rpm.

Although the H_2 concentration increased in the fuel mixtures and usually gives a rise in combustion temperature [2], however, the NO_x emission level was relatively stable. It can be explained by a reduced combustion temperature due to returned part of the exhaust gas to the cylinder, because tested heavy-duty engine had an originally mounted EGR system. Lower NO_x emissions were also noticed by other researchers when CNG/H_2 fuel mixture and EGR system were used [13]. In some research cases the NO_x emission level was lower – even 15–20% [17–19].

4. Conclusions

1. The experimental research showed that it is possible to achieve better efficient parameters – lower fuel consumption, lower brake specific fuel consumption due to increased cyclic energy, which increased due to

higher H_2 lower heating value. However, the spark timing should be optimized with highest H_2 addition because of increased combustion intensity.

2. The addition of H_2 in natural gas fuel changed the overall H/C atom ratio of gaseous fuel mixture, which gave a positive effect on CO, CO_2 and HC emissions formation. The H_2 also improved combustion process, which let to reduce incomplete combustion products.
3. As it is stated by other scientists' works the addition of H_2 can increase the NO_x emission level, however, the experimental research results of heavy-duty engine fueled with CNG/H_2 revealed that it is possible to achieve stable NO_x emission level. In some tested cases, the NO_x emission can be achieved even lower, if compared with single CNG fuel.
4. Experimental research showed that with optimum H_2 addition and exhaust gas recirculation system, it is possible to achieve lower exhaust gas emissions and increased engine efficient indicators.

Acknowledgements

The authors would like to acknowledge company "SG dujos Auto" for the cooperation and possibility to do researches in "SG dujos Auto" laboratory which was funded by the EU "Intelektas LT+" funds.

References

[1] European Commision, White Paper. Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system. Brussels. 2011.
[2] M. Melaika, Research of a Combustion Process in a Spark Ignition Engine, Fuelled With Gaseous Fuel Mixtures. Doctoral Dissertation. VGTU: Technika. 2016. 157 p.
[3] J. B. Heywood, Internal Combustion Engine Fundamentals. McGraw-Hill, 1988.
[4] A. Boretti, P. Lappas, B. Zhang, S. Mazlan, CNG Fueling Strategies for Commercial Vehicles Engines – A Literature Review. SAE Technical Paper 2013–01 2812: 2013, p. 19.
[5] C. Reynolds, R. Evans, L. Andreassi, S. Cordiner,V. Mulone, The Effect of Varying the Injected Charge Stoichiometry in a Partially Stratified Charge Natural Gas Engine. SAE Technical Paper 2005-01-0247: 2005, p. 13.
[6] A. Kakaee, A. Paikani, M. Ghajar, The Influence of Fuel Composition on the Combustion and Emission Characteristics of Natural Gas Fueled Engines. Renewable and Sustainable Energy Reviews 38 (2005) 64–78.
[7] G. Karavalakis, T. D. Durbin, M. Villela, J. W. Miller, Air pollutant emissions of light-duty vehicles operating on various natural gas compositions. Journal of Natural Gas Science and Engineering 4 (2012) 8–16.
[8] S. McAllister, J. Chen, A. C. Fernandez-Pello, Fundamentals of Combustion Processes. Springer. 2011. 302 p.
[9] Y. J. Lee, G. C. Kim, Effect of Gas Composition on NGV Performance, Seoul 2000 FISITA World Automotive Congress 2000, pp. 1–6.
[10] G. A. Karim, I. Wierzba, Y. Al-Alousi, Methane-Hydrogen mixtures as fuels. International Journal of Hydrogen Energy 21 (1996) 625–31.
[11] J. F. Larsen, J. S. Wallace, Comparison of emissions and efficiency of a turbocharged lean-burn natural gas and hythane-fueled engine. Journal of Engineering for Gas Turbines and Power 119 (1997) 218–26.
[12] The State Patent Bureau of the Republic of Lithuania. "H2NG" Trademark Registration. Application No 2015 1195, Registration No 72664. Available frim Internet: http://www.vpb.lt/db/rezult3.php?appnum=2015%201195
[13] P. Dimopoulos, C. Rechsteiner, P. Soltic, C. Laemmle, K. Boulouchos, Increase of passenger car engine efficiency with low engine-out emissions using hydrogen-natural gas mixtures: A thermodynamic analysis, International Journal of Hydrogen Energy 32 (2007) 3073–3083.
[14] G. A. Karim. Hydrogen as a spark ignition engine fuel, International Journal of Hydrogen Energy 28 (2003) 569–577.
[15] S. O. Akansu, N. Kahraman, B. Ceper, Experimental study on a spark ignition engine fuelled by methane-hydrogen mixtures, International Journal of Hydrogen Energy 32 (2007) 4279–4284.
[16] F. Moreno, J. Arroyo, M. Munoz, C. Monne, Combustion analysis of a spark ignition engine fueled with gaseous blends containing hydrogen, International Journal of Hydrogen Energy 37 (2012) 13564–13573.
[17] V. Raman, J. Hansel, J. Fulton, F. Lynch, D. Bruderly, Hythane – an Ultraclean Transportation Fuel. Proceedings of 10th World Hydrogen Conference, Cocoa Beach, Florida, USA. 1994.
[18] V. Raman, The Emerging Applications of Hydrogen in Clean Transportation. American Chemical Society Conference, San Francisco. 1997, pp. 611–615.
[19] Mhy Bus, Methane and Hydrogen blend for Public Transport City Bus. Road Test Results in Public Transport with Hydromethane. Available from Internet: www.mhybus.eu. 2009. 16 p.