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SIMULATION MODEL OF COMBUSTION ENGINE WITH DIRECT INJECTION OF HYDROGEN

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Abstract

Fuel mixture formation inside a cylinder has become used more frequently in spark ignition engines in recent years. Gas internal combustion engines can also benefit from this concept as direct injection into an engine's cylinder during the compression stroke not only increases its volumetric efficiency but also eliminates adverse anomalies in the combustion process.

This paper focuses on the development of a simulation model for a spark ignition engine with direct hydrogen injection into a cylinder. The Wave software was used for the simulation. A part of the paper depicts the model's verification.

The study utilized a three-cylinder internal combustion engine with the total cylinder volume of 1.2 dm^3*. The concept of the engine is based on new, high-pressure injectors with 10 MPa inlet pressure (gas-hydrogen injection directly into the engine cylinder).*

Utilization of internal fuel mixture formation can be beneficial due to its enabling the control of the combustion process and gaseous emission generation. From the viewpoint of the engine's design, however, internal fuel mixture utilisation is more complicated as injectors have to be built into the cylinder head. The actual engine construction is housed in laboratories of the Technical University of Liberec, Department of Vehicles and Engines.

Keywords: *Simulation model of combustion engine, direct hydrogen injection, Ricardo Wave, combustion process, spark ignition engine*

1. Introduction

The reduction of world-wide fossil hydrocarbon fuel reserves and the need to reduce global carbon dioxide (CO_2) emissions have resulted in a growing interest in hydrogen as an alternative fuel in transportation. Currently, hydrogen is considered as one of the important energy-related directions for the next 100 years. There are basically two ways in which hydrogen can be utilized in transportation: either in fuel cells to generate electric power utilisable to drive a vehicle's traction electric motor, or in direct combustion of hydrogen in piston combustion engines which will drive a vehicle. Our laboratory is occupied with the study of the second method of hydrogen's utilization in powering vehicles.

In the Department of Vehicles and Engines at the Technical University of Liberec, research and development in the area of hydrogen combustion engines has been carried out continuously for 10 years.

From the viewpoint of subjects and timing the hydrogen program can be divided into the following stages:

- testing a one-cylinder hydrogen engine OKC (1997-2002),
- testing a 12 dm^3 six-cylinder hydrogen engine (2000-2006),
- testing a 2 dm^3 one-cylinder hydrogen engine (since 2006),
- testing a 1.2 dm^3 three-cylinder hydrogen engine (since 2007).

Internal mixture formation with gaseous fuel injection directly into the cylinder's working space represents a more complex concept as far as development and design are concerned. The segregation of fuel and air during the cylinder content exchange eliminates back fire of the fuel in the induction section increases the achievable heat value of the mixture and consequently, the engine's power. Depending on the inlet pressure in the injector, the concept implementation can be divided into low pressure injection or high pressure injection.

Low-pressure injection with gas pressure of up to 2 MPa requires a longer duration of the injection and at higher loads the injection initiation has to occur within the induction stroke, i.e. while the inlet valve is open. This is undesirable due to potential pre-ignition problems and the necessity of intensive cooling.

Currently, high-pressure injection with gas pressure from 10 to 12 MPa appears to be the most modern and the most efficient concept of the internal mixture formation eliminating adverse combustion anomalies and gaining from the layered mixture preparation in combination with higher leanness of the fuel-air mixture. However, to maintain a required cruising range, higher initial pressure in the vehicle's fuel tank has to be used. 70 MPa tanks are developed by Dynetek Europe [1].

2. Testing Bench Description

The Technical University of Liberec, Department of Vehicles and Engines can verify the advantages and benefits of the high-pressure hydrogen injection directly into the engine cylinder on a testing bench in the reciprocating internal combustion engine laboratory. With this project our laboratory is extending its research program even to the area of internal mixture formation for small engines applicable to passenger cars. The engine in question is a 1.2 dm^3 three-cylinder internal combustion engine.

The engine concept is based on new high-pressure injectors with the inlet pressure of 10 MPa (direct injection into the engine cylinder). At the moment our lab is utilizing injectors from Hoerbiger Valve Tec which have been developed within the European program HylCE.

For the 1.2 dm^3 three-cylinder engine with the inlet pressure of 10 MPa and the cross-sectional area of flow of 1 mm^2 these high-pressure injectors shorten the injection duration to max. of 50 deg of crankshaft turning. This means that at the maximum output the injection can be timed only in the compression stroke after the induction valve closes. The electronic system for the controlling and monitoring of internal combustion engine modes was supplied by Adcis.

Load was applied to the engine by means of a Schenk brake and the engine was equipped with thermo sensors and pressure sensors for automatic data collection. The engine is controlled by means of a specially modified control unit supplied by ADCIS. In the course of the engine's operation, the control program may modify data in the control unit setting (ECU) and selected values can be saved for further processing. In trial operation, measurements with a manual setting of the advanced ignition, the start and duration of the gaseous hydrogen injection directly into the cylinder during the engine compression stroke and the mixture richness were conducted to verify the response of all engine operating parameters and obtain the necessary data for gradual ECU programming. An AVL Indimeter 619 with the piezoelectric pressure sensor (GU 21D) was used to collect information about the course of the combustion process. This system provided us with basic information about the burning process and after the thermodynamic analysis the data can be further used as input data of the law of combustion for the simulation model.

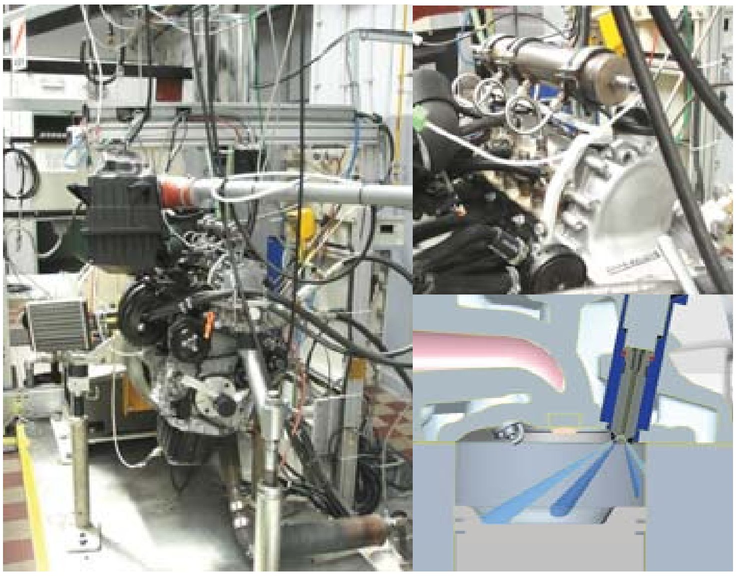

Fig. 1. Testing bench gas engine (total displacement of 1.2 dm^3)

3. Simulation Model

The objective of the work is the development of a simulation model for an air charged model of a combustion engine with a hydrogen direct injection into the cylinder in the Wave software which could be used for other simulations as well. The first phase of the simulations was focused on the developing of a gasoline-fuelled hydrogen engine model and verification based on the data measured from an actual engine. Fig. 2 shows a model of a spark ignition engine which was developed in the Wave program environment from Ricardo, which is a general 0-D program for the simulation of the engine working cycle. However, piping can be modelled using a 1-D approach [6]. Therefore we can develop a very complex simulation model. The engine simulation model was created using real engine dimensions (boring, stroke, compression ratio, dimensions of induction and exhaust manifold, fuel injector parameters etc.) including the poppet valve gear timing.

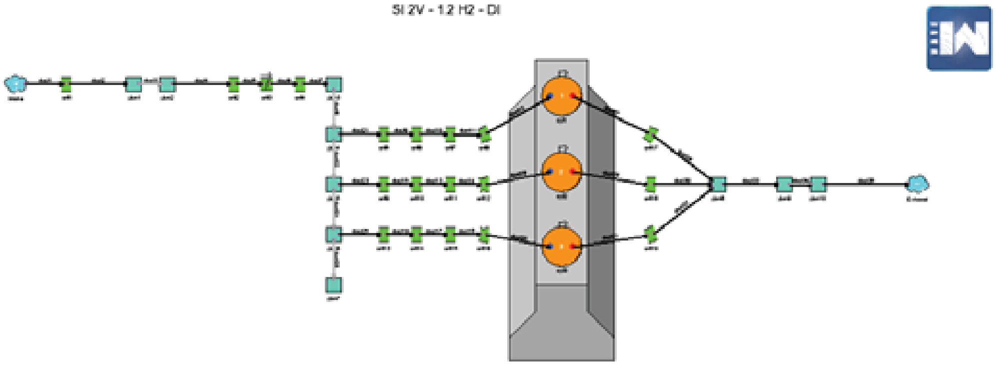

Fig.2. Simulation model of engine 1.2 H2 - DI

The combustion model used by WAVE is Vibe based (Ricardo) (Fig. 3). This model calculates the rate of mass that is burned and the formula used by WAVE is:

$$W = 1 - \exp\left(- AWI \left(\frac{\Delta\theta}{BDUR} \right)^{(WEXP+1)} \right), \tag{1}$$

where:

W - cumulative mass fraction burned,

$\Delta\theta$ - crank degrees past start of combustion,

BDUR - user-entered 10-90% burn duration in crank degrees,

WEXP - user-entered Vibe exponent,

AWI - internally calculated parameter to allow BDUR to cover the range of 10-90%.

For entering the input data for the heat generation, the values from the experimental measurements on the given engine were used.

The NOx generation was modelled by means of the Zeldovitch reaction mechanism. The internal combustion engine works with the direct fuel injection into the cylinder and with a lean concept of the fuel-air mixture. The engine works with the layered mixture and only a rough check of the NOx generation can be made.

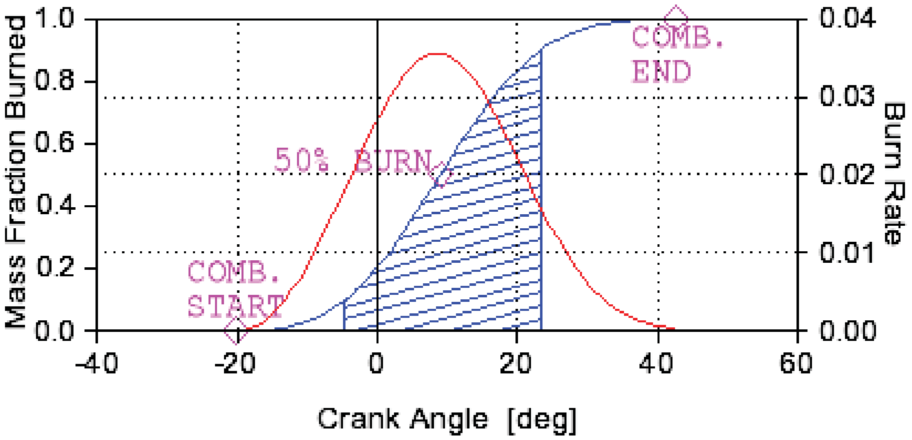

Fig. 3. Parameters of combustion – model SI Vibe

4. Simulation Results in SW WAVE – a comparison with the experiment

A simulation calculation was carried out for a model of a three-cylinder, air charged engine and it is compared with the experiment-based data. Fig. 4-9 show selected patterns of selected resulting parameters from the simulation (impact of the fuel mixture richness coefficient at the gaseous fuel injection initiation of 120 deg CA BTDC and the throttle opening of 62% at 2500 rpm).

Figure 4 compares the calculated and measured mean effective pressure. The reduction in the mean effective pressure depends on the growth of the burned fuel leanness. Fig. 9 illustrates a comparison of the specific fuel consumption. A slight difference is evident here which may result from a distortion of the values of the fuel consumption during the experimental measurement because the consumption was not measured but computed from the quantity of air and mixture richness.

Figure 8 shows a comparison between NOx concentrations in exhaust gases for the simulation and experiments. The results indicate a very strong dependence of the NOx generation on the coefficient of air excess.

Figures 10-15 show the impact of the gaseous fuel injection initiation at the constant mixture richness and the throttle opening of 62% at 2500 rpm. Injection initialization closer to the TDC leads to higher NOx generation. A higher difference in the mean indicated pressure values may be caused by the pressure measurement in only one engine cylinder and it is possible that there could be problems with the combustion of the mixture there because for the mean effective pressure no such differences are evident.

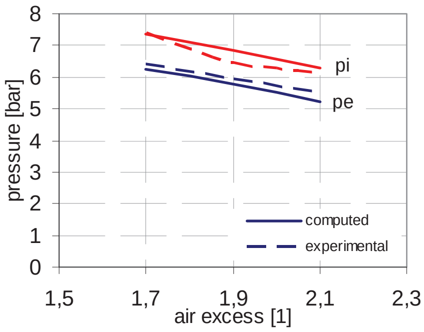

Fig. 4. Influence of air excess on imep and bmep. Spark advance 15 deg CA BTDC, throttle position 62%, 2500 rpm

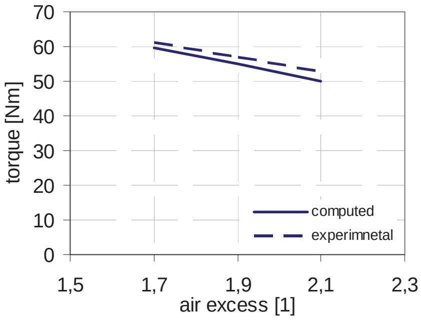

Fig.5. Influence of air excess on engine torque. Spark advance 15 deg CA BTDC, throttle position 62%, 2500 rpm

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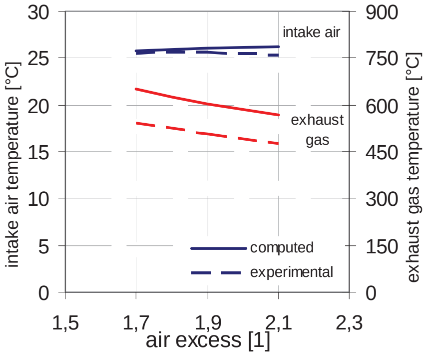

Fig. 6. Temperature of intake air and exhaust gas. Spark advance 15 deg CA BTDC, throttle position 62%, 2500 rpm

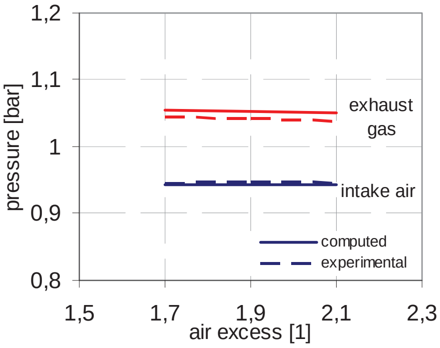

Fig. 7. Pressure of intake air and exhaust gas. Spark advance 15 deg CA BTDC, throttle position 62%, 2500 rpm

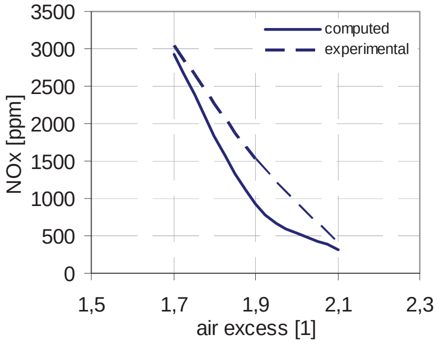

Fig. 8. Influence of air excess on NOx production. Spark advance 15 deg CA BTDC, throttle position 62%, 2500 rpm

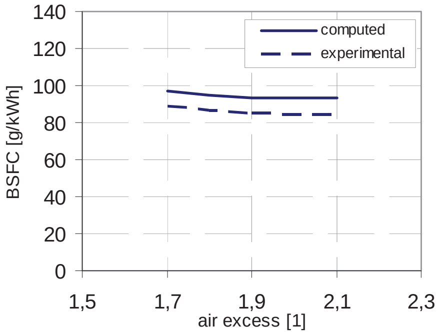

Fig. 9. Influence of air excess on BSFC. Spark advance 15 deg CA BTDC, throttle position 62%, 2500 rpm

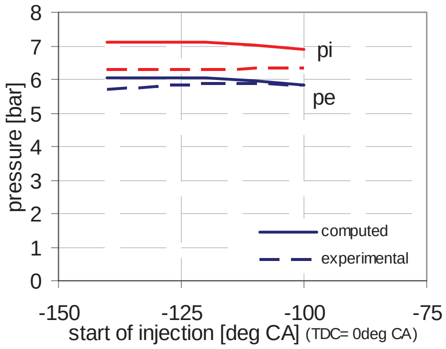

Fig. 10. Influence of start of injection fuel on imep and bmep. Spark advance 10 deg CA BTDC, throttle position 62%, 2500 rpm

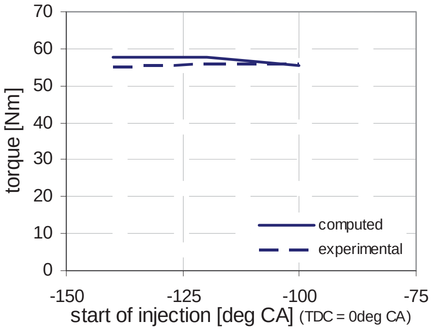

Fig. 11. Influence of air excess on engine torque. Spark advance 10 deg CA BTDC, throttle position 62%, 2500 rpm

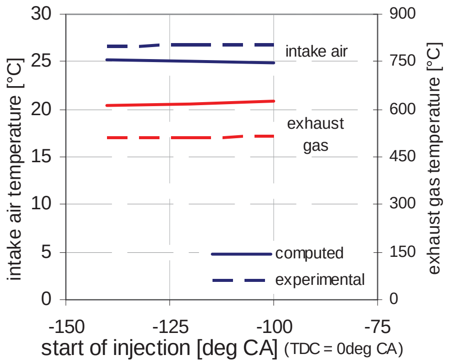

Fig. 12. Temperature of intake air and exhaust gas. Spark advance 10 deg CA BTDC, throttle position 62%, 2500 rpm

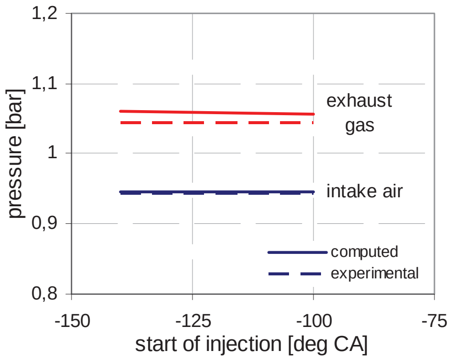

Fig. 13. Pressure of intake air and exhaust gas. Spark advance 10 deg CA BTDC, throttle position 62%, 2500 rpm

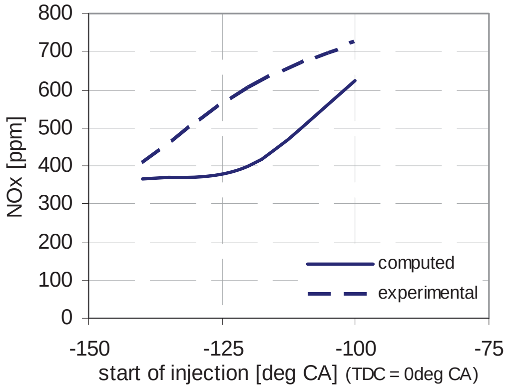

Fig. 14. Influence of start of injection fuel air excess on NOx production. Spark advance 10 deg CA BTDC, throttle position 62%, 2500 rpm

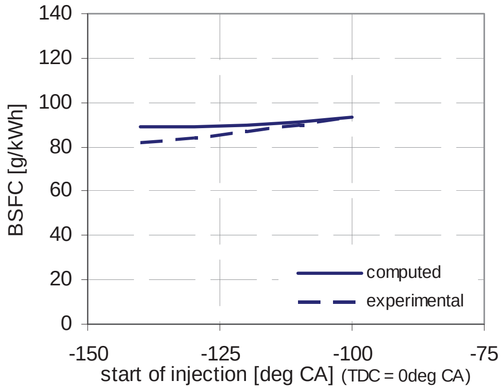

Fig. 15. Influence of start of injection fuel on BSFC. Spark advance 10 deg CA BTDC, throttle position 62%, 2500 rpm

Figures 16 and 17 compare calculated and measured pressure patterns in the engine cylinder in P-V diagram. Fig. 18 and 19 illustrate the simulation-based pressure and temperature patterns in the engine cylinder. As the pressure patters indicate, the difference in the NOx generation between the measured and computed data (Fig. 8 and 14) may be caused by the set parameters for combustion, thermal losses and heat liberation.

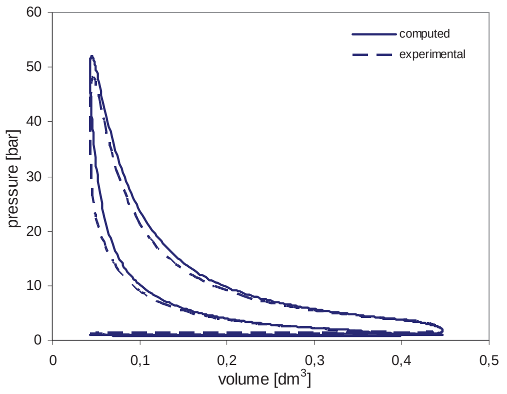

Fig. 16. P-V diagram, spark advance 15 deg CA BTDC, air excess 2.1, throttle position 62%, 2500 rpm. Start of injection 120 deg CA BTDC

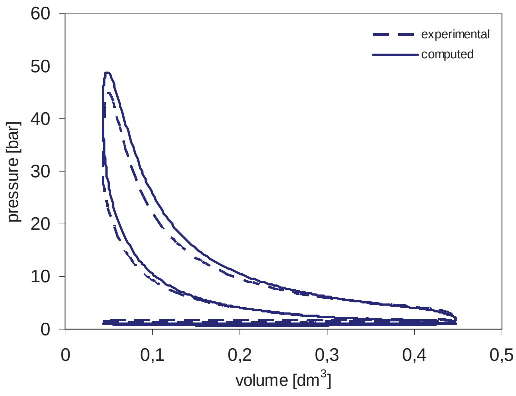

Fig. 17. P-V diagram, spark advance 10 deg CA BTDC, air excess 1.9, throttle position 62%, 2500 rpm. Start of injection 100 deg CA BTDC

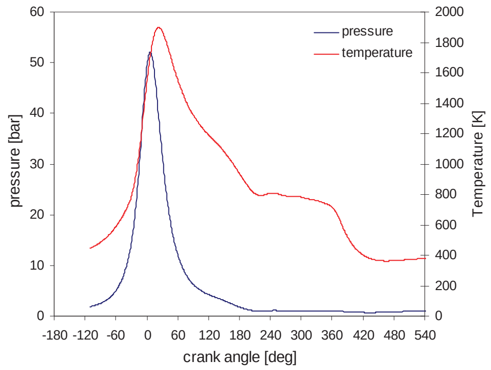

Fig. 18. In-cylinder pressure and temperature, spark advance 15 deg CA BTDC, air excess 2.1, throttle position 62%, 2500 rpm. Start of injection 120 deg CA BTDC. Wave simulation

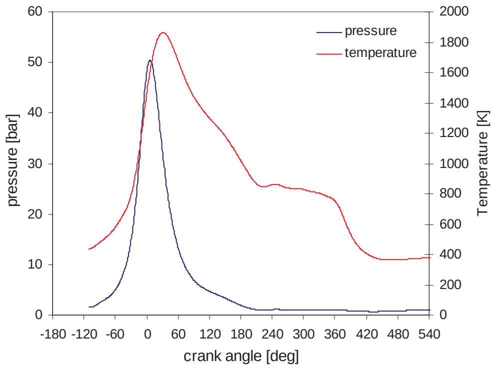

Fig. 19. In-cylinder pressure and temperature, spark advance 10 deg CA BTDC, air excess 1.9, throttle position 62%, 2500 rpm. Start of injection 100 deg CA BTDC. Wave simulation

5. Conclusion

This paper describes a simulation model of a hydrogen operated engine with a comparison to initial selected results and experimental data. The simulation-based results for the hydrogen-operated engine showed a good conformity with the measurement-based results. A great amount of measured data was used for the verification of the model. The next stage will involve a comparison of the computation-based results experimental data for other engine loads to gather sufficient input parameters for the engine control unit programming.

The conclusions of the project can be summarized as follows:

- The 0-D model provides useful data and is ready to be used for the simulation of the hydrogen-operated engine with the direct fuel injection. The model can be used in the SW WAVE to predict results in other engine modes so that significant project-related costs can be saved and necessary data for the creation of a map for the control unit can be obtained.
- Wide limits of the hydrogen mixture ignitability can be utilised and low NOx generation for very lean mixtures can be achieved.

Acknowledgments

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References

[1] Rau, S., *Compressed Hydrogen Storage for Vehicle Applications*, In.: 1st Hydrogen Internal Combustion Engines. TU Graz, Graz 2006.
[2] Podklady fy Hoerbiger Valve Tec, Vien 2006.
[3] Šiman, J., *Zástavba vysokotlakých injektorů plynného paliva do motoru 1.2dm*^{3}, Diplomová práce KSD – 351, TUL Liberec 2007.
[4] Scholz, C., *Výzkum a vývoj vodíkového motoru*, Mezinárodní konference Road Transport & Environment RT&T 2007, Brno 2007.
[5] Scholz, C., Brabec, P., *Vnitřní tvorba směsi vodíkového spalovacího motoru*, XXVIII. medzinárodná vedecká konferencia pracovníkov katedier a pracovísk spaľovacích motorov vysokých škôl na Slovensku a v Čechách, STU v Bratislavě, ISBN 978-80-227-2714-3, pp. 18, Bratislava 2007.
[6] Help softwaru Wave.
[7] Brabec, P., Blazek, J., *Simulační model spalovacího motoru*, In: International scientific konference: New trends in construction and exploitation automobiles „Vehicles 2008“. Sborník abstraktů, SPU Nitra, 22.-24.9, Nitra, ISBN 978-80-552-0105-4, pp. 10, Slovensko 2008.