INFLUENCE OF ADDITIVE HYDROGEN COMBUSTION ON ENERGY EFFICIENCY AND ON EMISSIONS OF SPARK IGNITION ENGINE

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ABSTRACT

Hydrogen represents a promising low-carbon fuel that enables the decarbonisation of transportation without the need for a radical replacement of the piston combustion engines. The presented study analyses the influence of adding hydrogen to the intake air in a turbocharged spark-ignition engine, focusing on fuel combustion process and on gaseous pollutant emissions. The experimental part of this work was complemented by the numerical simulations in order to validate the observed trends. The obtained results show that hydrogen increases the maximum engine cylinder pressure, accelerates the combustion process of fuel-air mixture, as well as it improves the heat release efficiency, thereby shortening the combustion duration and enhancing overall engine efficiency. A reduction in emissions was also observed. The findings support the use of hydrogen as an additive fuel during the transitional period towards zero-emission mobility. They also highlight the need for further research in optimizing of fuel combustion process at higher hydrogen proportions and under various engine load conditions.

KEYWORDS

Hydrogen, emission, combustion engine

1 INTRODUCTION

The use of low-carbon fuels such as methanol and methane or utilisation of the carbon-free fuels like hydrogen, ammonia or synthetic fuels can be a suitable option for reduction of the CO_2 emissions without the need to replace the internal combustion engines. Among the above-mentioned fuels, hydrogen stands out due to its physic-chemical properties, including high octane number, wide flammability limits, high calorific value and rapid combustion, making it an attractive alternative to the traditional fossil fuels [Park 2021, Niu 2022, Molina 2023].

This alternative aligns fully with the goals of the "European Green Deal", which aims to achieve climate neutrality by 2050. The European Union, through the legislative package "Fit for 55," is tightening emission limits for transportation as well as is promoting adoption of the environmentally friendly technologies, including the renewable sources of energy, alternative fuels, and also hydrogen mobility.

Hydrogen as a fuel enables to reduce the greenhouse gas emissions while allowing the existing infrastructure and combustion engine technologies to be maintained. This is advantageous from an economic transition perspective, technological compatibility, and in protecting jobs in the automotive industry [Teoh 2023]. If hydrogen is produced from the renewable energy sources (i.e. the so-called „green hydrogen"), it can significantly contribute to decarbonisation of the transport sector, which is one of the main emitters of CO_2 in the EU [Pana 2023, Hosseini 2023].

Therefore, from the perspective of sustainability, hydrogen represents a promising solution that can be a part of comprehensive package of measures to achieve the EU's climate goals and for transition to a circular economy.

According to the several performed studies, hydrogen has a potential significantly to reduce pollution originating from transportation. Combustion of hydrogen produces only minimal amounts of CO_2, CO and unburned hydrocarbons, whereas its high combustion speed contributes to a stable and efficient burning [Shi 2022, Chitragar 2021]. Hydrogen offers a great potential across all the transportation sectors, but each sector faces specific technical and economic challenges, such as storage costs, distribution, infrastructure, and the need for standardized policies [Ling-Chin, 2020, Purayil 2023].

A large amount of the performed research work is focused on application of hydrogen as a fuel determined for electricity generation in the fuel cells. Despite high efficiency of the fuel cells, their widespread adoption is limited by the costs, the need for high-purity of hydrogen (≥99.97%), and a lack of infrastructure [Teoh 2023]. For these reasons, hydrogen in internal combustion engines appears to be a more realistic and immediately applicable alternative, especially when hydrogen is combined with such modern technologies as it is direct injection, which allows a better control of the fuel mixture combustion and reduces negative phenomena like backfire or pre-ignition [Park 2021, Molina 2023].

In the study [Park 2021], it was demonstrated that implementing of the HDI technology (Hydrogen Direct Injection) into a 2-liter spark-ignition engine resulted in 35.9% increase of engine torque and in improvement of the Brake Thermal Efficiency (BTE) from 34% to 40%. Precise timing and charging of hydrogen in the HDI configuration also allowed a stable combustion even with ultra-lean mixtures, while eliminating backfire what is a frequent problem within the Port Fuel Injection (PFI) system. The study also highlights a reduced variability in combustion cycles, which contributes to smoother engine operation and to higher global engine efficiency.

In the study [Chitragar 2021], similar positive results were recorded when testing a 4-cylinder spark-ignition engine with a gradually increasing hydrogen volume share from 0% to 10%. At 8% hydrogen addition, the engine's brake power output increased by 11.8%, the BTE level rose by 8%, and the overall engine efficiency increased by 5.78%. Harmful emissions also decreased significantly: CO emissions by 16.33% and HC emissions by 13.48%. However, it was also confirmed that NO_x emissions increase with a higher hydrogen share in the mixture, which highlights the need for accompanying technologies to reduce these emissions, such as the Selective Catalytic Reduction (SCR) or the Exhaust Gas Recirculation (EGR). Exceeding a 10% hydrogen share may negatively impact combustion stability due to a too-lean mixture.

[Molina 2023] performed a comparison between the HDI and PFI injection systems on a single-cylinder engine and concluded that the HDI technology clearly outperforms the PFI system under comparable operating conditions. HDI demonstrated higher Indicated Mean Effective Pressure (IMEP), which means more engine power output per unit of volume. Combustion occurred with lower cyclic variability and with simultaneous reduction of NO_x emissions, even under lean conditions (λ = 3.2). Molina determined a thermodynamic efficiency of 41.2% for HDI compared to 40% for PFI, highlighting HDI's capability effectively to combust very lean mixtures without loss of engine power output. These results emphasize the technical maturity of HDI as a suitable solution for the transitional period between the fossil-based fuel technologies and zero-emission combustion technologies.

These results consistently indicate that a properly implemented hydrogen fuel system, integrated with direct in-cylinder injection, can enhance engine power output and reduce engine gaseous emissions without requiring a radical re-design of the combustion engine construction. This approach represents a compromise, yet highly efficient solution within the context of greening the transport sector and meeting the EU's emission targets [Puskar 2017 & 2022].

Table 1 presents the selected physic-chemical properties of hydrogen in comparison with those of gasoline. Among the main advantages of hydrogen belong the wide flammability limits, which allow engines to operate with very lean mixtures and to achieve higher efficiency. However, there are also challenges, such as increased NO_x production at higher hydrogen ratios that can be reduced, for example, by using the EGR or SCR technologies [Ozyalcin 2021].

Table 1. Properties of Hydrogen and Gasoline

	Hydrogen	Gasoline
Chemical formula	H_2	C_8H_{18}
Mass composition C [%] / H [%] / O [%]	0/100/0	85.4/14.2/0.4
Amount of O_2 for stoichiometric combustion [kmol/kg of fuel]	0.2500	0.1065
Amount of air for stoichiometric combustion [kmol/kg of fuel]	1.1900	0.5073
Molar mass [kg/kmol]	114	2.016
Stoichiometric ratio air/fuel [kg/kg]	34.4	14.7
Diffusion coefficient [cm²/s]	0.63	0.05
Lower calorific value [kJ/kg]	119.617	42.690
Self-ignition temperature [K]	845	740–810
Research Octane Number (RON)	>130	90–98

The main task of this work is to analyse the influence of hydrogen usage in the form of its injection in turbocharged spark-ignition engine on the engine energy efficiency, on fuel mixture combustion and on pollutant emissions. The experimental study was complemented by theoretical research using numerical simulation under similar operating conditions [Puskar 2010 & 2012].

2 EXPERIMENTAL ANALYSIS

The experiments were performed on a 1,500 cm³ gasoline engine. Hydrogen was injected into the engine's intake ports using hydrogen injectors controlled by the Electronic Control Unit (ECU). Using the port-fuel injection of hydrogen, the maximum available intake air capacity in the intake manifold was achieved. The electronic control unit also controlled the gasoline injectors, as it was an open-type of ECU. The control software made it possible to adjust opening times of the fuel injector. When supplying hydrogen, the opening time of the gasoline injectors was shortened, and the opening time of the hydrogen injectors was extended until the original air-fuel equivalence ratio, corresponding to gasoline operation, was achieved. With a constant throttle position and at fixed ignition timing, the hydrogen injector opening time was set so that the maximum thermal efficiency of the engine was reached for the given hydrogen amount charge per one working cycle. At the same time, it was ensured that the maximum pressure in the combustion chamber did not increase excessively depending on the amount of hydrogen used. Before the actual measurements, all the equipment and measuring instruments were calibrated. During the experimental research, the individual engine operational parameters were monitored, such as gasoline and hydrogen consumption, intake air flow, gaseous pollutants and greenhouse gas (CO_2) emission levels, charging pressure, engine tuning parameters, in-cylinder pressure profiles, and related parameters such as the heat release rate. Reference values were determined during engine operation with gasoline only. Subsequently, gasoline was partially replaced by hydrogen with the aim to maintain the same effective engine power output as during pure gasoline operation, and at the same air-fuel equivalence ratio (λ=1). During the experiments, the proportion of hydrogen used to replace gasoline was set to the level at which the maximum thermal efficiency was achieved, with unchanged ignition timing, under stoichiometric combustion conditions (λ = 1), at the engine speed level 2,500 rpm and at 50% of engine load.

The novelty and contribution of this article consists in optimization of settings among the engine speed, engine load, cyclic hydrogen and gasoline charging, charging pressure, exhaust gas temperature, and ignition timing at a stoichiometric air-fuel equivalence ratio in the given operating mode. The innovation also consists in achieving the main objective of the article, which is the use of small amounts of hydrogen injected into the intake port through an electronic hydrogen injection system, integrated with the gasoline injection system, within a ready-to-use system that is easily adaptable to any engine equipped with the Electronic Fuel Injection (EFI). Fulfilling this specific goal led to the primary aim of this work, i.e. to improve engine power output in terms of thermal efficiency and emission levels by using a small amount of hydrogen injected into the intake air through the intake valves.

3 THEORETICAL ANALYSIS

The simulation of engine operation was performed using a pre-defined simulation model of spark-ignition engine, which was designed for numerical simulations of gasoline engine operation. The given simulation model was adapted to correspond to the experimental parameters.

This model uses a combustion chamber with variable pressure and volume as well as it considers heat transfer to the walls and the related losses. For the fuel simulation, the parameters derived from the chemical formula of the fuel were used, and its calorific value was specified. The model was based on the general hypothesis that the cylinder charge consists of a chemically and thermally homogeneous mixture of ideal gases. Calculations were performed starting from the beginning of the compression process up to the beginning of the exhaust process. Each calculation step was divided into the individual small increments of 1° crankshaft rotation angle (°CA).

Just before reaching the top dead centre, corresponding to the crankshaft angle θ_2, fuel ignition occurs, and combustion continues during the crankshaft rotation by an angle $\Delta\theta$. The mass fraction of burned fuel relative to the total fuel mass is often described by the Wiebe function, which expresses its dependence on the crankshaft rotation angle θ and is given in the form:

$$x_b = 1 - e^{-\alpha \cdot \left(\frac{\theta - \theta_2}{\Delta\theta}\right)^{m+1}} \quad (-),$$

where α and m are adjustable parameters describing the course of fuel combustion.

When heat is supplied by fuel combustion (Fig. 20), heat exchange with the surroundings occurs, work is performed, and there is a simultaneous change in internal energy. A portion of the heat released during combustion dQ_{pal} is lost to the surroundings as the heat losses dQ_c and the "First law of thermodynamics" is thus expressed in the form:

$$dQ_{\text{pal}} - dQ_c = dU + dW \text{ (J)}.$$

The amount of heat released during fuel combustion is directly proportional to the calorific value q_n, to the mass of fuel m_p and to the elemental change in the value dx_b :

$$dQ_{\text{pal}} = q_n \cdot m_p \cdot dx_b \text{ (J)}.$$

The heat transferred to the surroundings is described by the Newton's law, and in order to calculate the energy, this transferred heat must be multiplied by the time differential dτ:

$$dQ_c = \alpha_c \cdot (S_0 + L \cdot \pi \cdot D) \cdot (T - T_v) \cdot d\tau \quad \text{(J)}$$

where α_c is overall heat transfer coefficient (W·m^{-2}·K^{-1}),

S_0 – sum of the inner surface area of the cylinder head and the top area surface of the piston (m^2),

D – diameter of cylinder (m),

T_V – average surface temperature of cylinder and piston (K).

Using the basic definition of angular speed, the time differential can be expressed, and thus the change in time can be described in terms of the change in angle dθ:

$$d\tau = \frac{d\theta}{\omega} \text{ (s)}$$

where ω – angular speed (s^{-1}).

A set of three measurements was recorded for the investigated operating mode using gasoline alone and fuel mixture gasoline-hydrogen.

The methodology for ensuring the repeatability of numerical tests was incorporated into the definition of boundary conditions. Boundary conditions define the simulation model's inputs for flow velocity and volumetric flow rate, and they determine how the fluid enters or exits the model. Conditions for the heat transfer coefficient and heat flow are defined by the exchange of energy between the model and its surroundings. Thus, boundary conditions connect the simulation model with its environment, enabling development of the simulation process [Rimar 2022a,b, Rodriguez 2022].

The boundary conditions can be defined either as stationary conditions (i.e. steady state) or as transient conditions. The steady state conditions are remaining constant throughout the entire simulation, while the transient conditions are varying over time — typically with the crank angle (°CA) or with the engine speed — and they are used to simulate such processes as heat release or pressure rise during combustion. Initial conditions are active only at the beginning of the simulation process.

The thermodynamic model requires to know the geometrical parameters of engine, mainly the cylinder bore, piston stroke, compression ratio, and height of combustion chamber. The initial values of the engine temperature, in-cylinder pressure and mass fractions of the gases define the initial thermodynamic state in the combustion chamber. To evaluate heat transfer, the surface areas of the cylinder head and piston were used. For the combustion process, the Wiebe function parameter was applied to describe the evolution of combustion characteristics, with the combustion type specified accordingly.

4 EXPERIMENTAL RESULTS

Figure 1 illustrates the cylinder pressure course depending on the crank angle during combustion of air-gasoline mixture and also for combustion of hydrogen-air-gasoline mixture. The presented diagrams were obtained by averaging of 100 consecutive cycles. With the spark timing held constant, combustion of the gasoline-hydrogen mixture results in a significant increase in the pressure curves, in higher maximum pressure due to the higher combustion speed and also in higher calorific value of hydrogen compared to gasoline. Maximum pressure also occurs earlier within the working cycle, i.e. closer to the top dead centre of the main combustion phase, which may correspond to an improvement in isochoric combustion when using H_2.

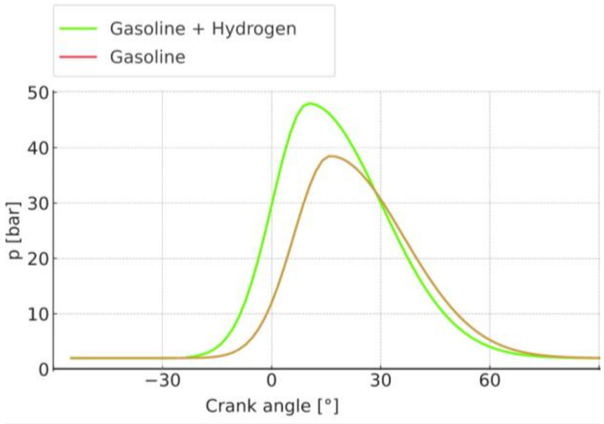

Figure 1. Cylinder Pressure Graphs

Based on the graphs that are illustrating the heat release rate (Figure 2), it is possible to state that the air-gasoline-hydrogen mixture is burning faster compared to the air-gasoline mixture and achieves higher heat release rate than in the case of gasoline combustion alone. With the use of hydrogen, the maximum heat release rate increased by more than 10%.

Since the amount of applied hydrogen was relatively low, the original engine settings were left unchanged. At the same time, it can be observed that the initial phase of combustion starts earlier. Likewise, due to higher burning rate of the air-hydrogen mixture, the overall duration of the combustion process was shortened.

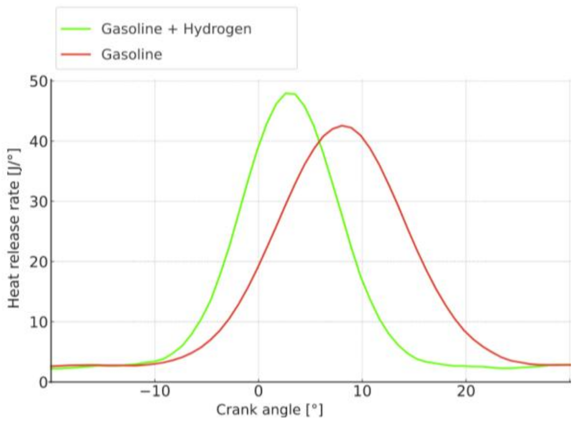

Figure 2. Graphs of Heat Release Rate

The use of hydrogen resulted in 14% reduction of unburned hydrocarbon (HC) emissions compared to combustion with pure gasoline only. The higher burning rate of homogeneous air-hydrogen-gasoline mixtures contributes to reduction of HC emissions. The wider flammability limits and higher burning rate of the air-hydrogen mixture reduce the likelihood of incomplete combustion and flame extinction in the gas phase or near the combustion chamber walls, which has a positive effect on lowering of HC emissions.

The level of carbon monoxide (CO) emissions decreased by 10.2% with the use of hydrogen compared to gasoline (Figure 3). When hydrogen is used, the faster combustion of the air-fuel mixture, together with shorter combustion duration, can contribute to reduction in carbon monoxide formation due to dissociation reactions. Additionally, the carbon content in the fuel mixture is reduced by replacing part of the gasoline with hydrogen, which also leads to lower CO generation.

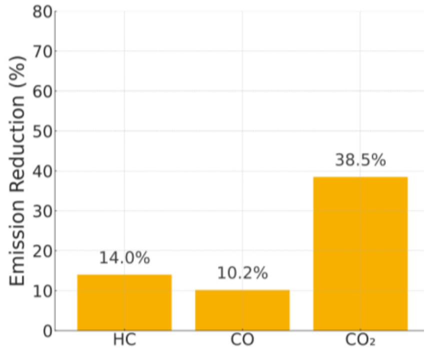

Figure 3. Percentage Reduction of Emissions with Hydrogen

Reduction of carbon content in the engine cylinder when using hydrogen also affected CO_2 emissions. The level of carbon dioxide emissions decreased by 38.5% with the use of hydrogen compared to gasoline. This reduction can be attributed to the lower carbon content in the air-fuel mixture when hydrogen is used.

5 THEORETICAL ANALYSIS RESULTS

The diagrams of in-cylinder pressure values, resulting from the theoretical study, are compared with the diagrams of the experimentally obtained pressures in Figure 4.

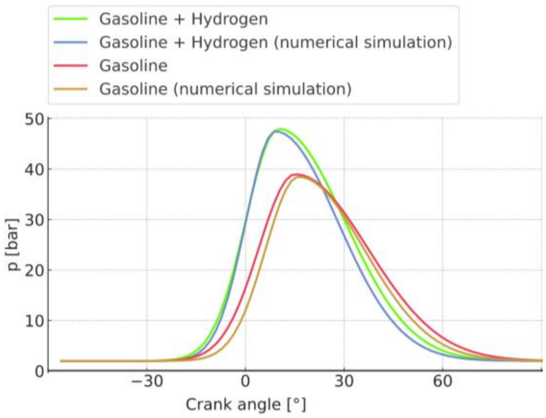

Figure 4. Theoretical and Experimental Cylinder Pressure Graphs for Gasoline and Gasoline-Hydrogen Combustion

The performed analysis shows that combustion with hydrogen addition leads to an increase in the maximum pressure compared to combustion with gasoline alone, both in the theoretical and experimental study. This increase is caused by the higher calorific value of hydrogen compared to gasoline.

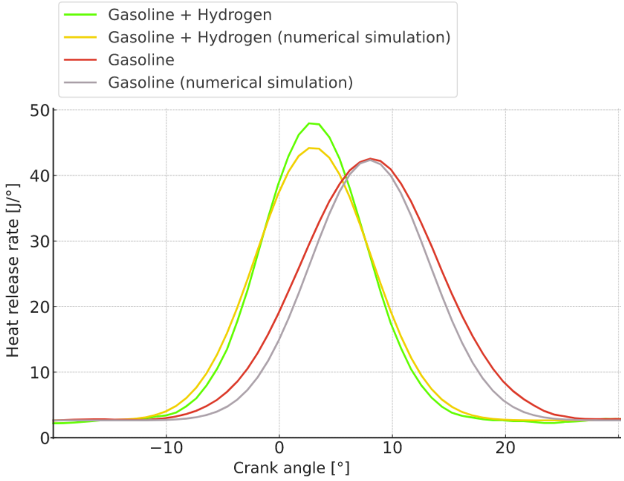

Figure 5. Heat Release Rate Diagrams from Theoretical and Experimental Studies of Gasoline and Gasoline-Hydrogen Combustion

The duration of the combustion process was shortened in the presence of hydrogen, as shown in Figure 5. The analysis of heat release rate indicates that combustion starts 2 °CA earlier when hydrogen is used. The initial phase of combustion was accelerated due to the wider flammability limits and lower minimum ignition energy of hydrogen compared to gasoline. The experimental study confirmed that the overall combustion duration was significantly reduced. This shortening of the combustion duration led to an increase in the maximum pressure and to the maximum rate of pressure rise.

6 CONCLUSION

The utilisation of hydrogen as an additional fuel in the spark-ignition engine resulted in an increase of the maximum cylinder pressure value. At the same time, the rate of pressure rise also increased, which was related to the improved combustion characteristics of hydrogen. However, these changes were controlled by limiting the amount of hydrogen added, in order to maintain reliability of engine operation and to prevent engine knocking.

Another statement in conclusion is that maximum heat release rate increased, with combustion starting earlier and the overall duration of the combustion process being shortened. These characteristics were also confirmed by the results obtained from the theoretical model. The emissions of unburned hydrocarbons (HC) were reduced due to higher combustion rate of homogeneous air-hydrogen-gasoline mixtures, which decreases the likelihood of incomplete combustion. The carbon monoxide (CO) emissions were reduced thanks to a more efficient combustion process. The lower carbon content was resulting from partial replacement of gasoline with hydrogen, and also due to shorter combustion duration. The carbon dioxide (CO_2) emissions decreased due to reduced carbon content in the air-fuel mixture when hydrogen was used.

It is also necessary to say that utilisation of pure hydrogen as a fuel is not yet practically applicable in the automotive industry due to its low density and demanding storage requirements. A promising trend for further research is application of higher portions of hydrogen at different engine loads, especially in the case of lean mixtures, together with optimization of engine settings.

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REFERENCES

[Chitragar 2021] Chitragar, S., Bhat, T., Yadav, A. Performance and Emission Analysis of a SI Engine Fueled with Gasoline–Hydrogen Blends. Materials Today: Proceedings, 2021, Vol. 46, pp. 7917-7923. DOI: 10.1016/j.matpr.2020.10.449.

[Hosseini 2023] Hosseini, V., Raji, A., Shabani, B. Reduction of Carbon-Based Emissions in Diesel Engines Using Hydrogen as Supplementary Fuel. Internat. J. of Hydrogen Energy, 2023, Vol. 48, No. 7, pp. 2940-2951. DOI: 10.1016/j.ijhydene.2022.11.076.

[Ling-Chin 2020] Ling-Chin, J., Ma, Z., Roskilly, A.P. Techno-Economic and Environmental Assessment of Hydrogen Infrastructure for Land Transport. Energy Conversion and Management, 2020, Vol. 203, 112244. DOI: 10.1016/j.enconman.2019.112244.

[Molina 2023] Molina, S., Lopez, A., Carreras, C. Experimental Analysis of Port Fuel Injection vs. Direct Injection of Hydrogen in a SI Engine. Internat. J. of Hydrogen Energy, 2023, Vol. 48, No. 2, pp. 1722-1732. DOI: 10.1016/j.ijhydene.2022.10.156.

[Niu 2022] Niu, J., Li, Y., Wang, D., Zhao, H. Effects of Hydrogen Addition on Combustion and Emissions of a SI Engine under Different Excess Air Ratios. Applied Thermal Engineering, 2022, Vol. 210, 118328. DOI: 10.1016/j.applthermaleng.2022.118328.

[Ozyalcin 2021] Ozyalcin, O., Kilic, M. Experimental Study of NOx Emissions Reduction in a Hydrogen-Fueled SI Engine Using SCR Technology. Internat. J. of Hydrogen Energy, 2021, Vol. 46, No. 10, pp. 7478-7488. DOI: 10.1016/j.ijhydene.2020.12.215.

[Pana 2023] Pana, C., Cernat, A., Lupu, R. Thermodynamic Modeling of Hydrogen Combustion in SI Engines: Kinetics and Emission Analysis. Internat. J. of Automotive Technology, 2023, Vol. 24, No. 1, pp. 129-138. DOI: 10.1007/s12239-023-0018-7.

[Park 2021] Park, S. Performance and Emission Characteristics of a Hydrogen-Fueled SI Engine Using a Direct Injection System. Internat. J. of Hydrogen Energy, 2021, Vol. 46, No. 58, pp. 29845-29855. DOI: 10.1016/j.ijhydene.2021.06.165.

[Purayil 2023] Purayil, A.H., Pillai, M., Paulose, J. A Review on Hydrogen Dual-Fuel Combustion in SI Engines: Advantages and Challenges. Fuel, 2023, Vol. 334, 126541. DOI: 10.1016/j.fuel.2022.126541.

[Puskar 2010] Puskar, M., Bigos, P. Output Performance Increase of Two-stroke Combustion Engine with Detonation Combustion Optimization. Strojarstvo, 2010, Vol. 52, No. 5, pp. 577-587.

[Puskar 2012] Puskar, M., Bigos, P., Balazikova, M., Petkova, V. Measuring method for feedback compensation in engine test-bench. Measurement, 2013, Vol. 46. DOI: 10.1016/j.measurement.2012.08.002.

[Puskar 2017] Puskar, M., Fabian, M., Kadarova, J., Blistan, P., Kopas, M. Autonomous vehicle with internal combustion drive based on the homogeneous charge compression ignition technology. Internat. J. Adv. Robotic Systems, 2017, Vol. 14, No. 5. DOI: 10.1177/1729881417736896.

[Puskar 2022] Puskar, M., Kopas, M., Soltesova, M., Tarbajovsky, P. Simulation Model of Advanced System for Application of Sustainable Fuels. Internat. J. of Simulation Modelling, 2022, Vol. 21, No. 2, pp. 308-319. DOI: 10.2507/ijsimm21-2-611.

[Rimar 2022a] Rimar, M., et al. Method of Sequential Approximation in Modelling the Processes of Heat Transfer and Gas Dynamics in Combustion Equipment. Applied Sciences, 2022, Vol. 12, 11948. https://doi.org/10.3390/app122311948.

[Rimar 2022b] Rimar, M., et al. Study of Selected Burner Parameters on the Gas-Air Mixture Combustion. MM Science J., 2022, Vol. Dec., pp. 6251-6256. DOI: 10.17973/MMSJ.2022_12_2022158.

[Rodriguez 2022] Rodriguez, C.G., Lamas, M.I., Rodriguez, J.D., Abbas, A. Possibilities of Ammonia as Both Fuel and NOx Reductant in Marine Engines: A Numerical Study. J. Marine Sci. and Engineering, 2022, Vol. 10, No. 1. DOI: 10.3390/jmse10010043.

[Shi 2022] Shi, J., Tang, Z., Chen, M. Investigation on NOx Emissions in a Hydrogen-Enriched Gasoline SI Engine. Fuel, 2022, Vol. 313, 122685. DOI: 10.1016/j.fuel.2021.122685.

[Teoh 2023] Teoh, C.M., Chan, S.H., Ho, W.S. Comparative Review on Hydrogen Internal Combustion Engine and Hydrogen Fuel Cell Technologies. Energy Reports, 2023, Vol. 9, pp. 129-145. DOI: 10.1016/j.egyr.2022.11.020.

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