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Development prospects of the rotary combustion engine as a car power unit

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The article briefly describes the main advantages and disadvantages of a rotary combustion engine as a car power unit and considers the option of improving the engine performance specifications due to the use of hydrogen as a fuel. Analyzing the researches, it was established the possibility of hydrogen rotary combustion engines safe work and improvement of the fuel mixture combustion indicators. Hydrogen rotary engines have been found to have low emissions. A scheme for integrating the hydrogen injection system into the design of a rotary internal engine is proposed. The operation of the apex seal between the rotor and the engine block was studied by modeling. It is reasonable to assume that rotary engines equipped to run on hydrogen fuel in the future can potentially be used as car power units, but today their design still needs further technological improvement.

Keywords: combustion, emission, fuel injection, hydrogen, rotary engine.

Перспективи розвитку роторного двигуна як рушія автомобіля

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У статті коротко описані основні переваги та недоліки роторного ДВЗ як рушія автомобіля та розглянуто варіант поліпшення характеристик двигуна за рахунок використання водню як палива. Аналізуючи багаторічні дослідження щодо застосування водневого палива для живлення роторного двигуна, встановлено можливість безаварійної роботи даних водневих ДВЗ за рахунок особливостей їх конструкції. Також з'ясовано, що заміна робочого палива фактично нівелює недоліки пов'язані з поганим згоранням бензино-повітряної суміші та викидами її недогорілих частин у атмосферу. Наведено опис основних характеристик водню (межі займистості, швидкість поширення полум'я, температура самозаймання та ін.) та його переваги в порівнянні з бензиновим паливом при застосуванні в роторному ДВЗ. Встановлено, що водневі роторні двигуни мають низький рівень викидів у порівнянні з бензиновими версіями, також для них доцільно застосувати системи рециркуляції вихлопних газів (EGR) для додаткового зниження рівня шкідливих речовин та одночасно з тим збільшення теплової ефективності. Запропоновано схему можливої інтеграції водневої системи живлення в конструкцію роторного ДВЗ, що складається з форсунок безпосереднього впорскування та форсунок зовнішнього впорскування, та коротко описано її роботу. Розглянуто вирішення проблеми слабкого крутного моменту роторного двигуна в діапазоні низьких обертів. Наведено дані 2022 року стосовно виробництва та застосування в автомобільному транспорті водневих роторних двигунів. Досліджено шляхом моделювання роботу верхівкового ущільнення між ротором і поверхнею корпусу двигуна з метою визначення обсягів витоків робочих газів та доведено, що вони не будуть чинити критичний вплив на ефективність двигуна. Обґрунтовано, що обладнані для роботи на водневому паливі роторні двигуни в майбутньому, потенційно, можуть використовуватися як рушії транспортних засобів, проте на сьогоднішній день дана силова установка не досягла свого найкращого рівня розвитку, її конструкція все ще потребує подальшого технологічного вдосконалення.

Ключові слова: згорання, викиди, система живлення двигуна, водень, роторний двигун.

Introduction

In the last years the use of hydrogen as an alternative to fossil fuels for powering traditional internal combustion engines is one of the promising directions for the further road transport development. After all, the main advantages of hydrogen fuel are high combustion efficiency, high thermal efficiency and extended ignition bounds, and its combustion produces sufficiently clean energy. It is also important that there is a possibility of generating this fuel from renewable energy sources.

In addition, hydrogen internal combustion engines (HICE) require less investment to set up serial production compared to hydrogen fuel cells (HFC) due to the complexity of the manufacturing technology and the high cost of their components, which contain precious metals.

However, nowadays the wide implementation of piston engines equipped to work on hydrogen fuel in automobile transport is hindered by problems related to the risk of abnormal fuel combustion. But unlike piston internal combustion engines, the rotary engine can be converted to operate on hydrogen fuel without the risk of emergency modes. And it can be thanks to its design features. In addition, it will make it possible to get rid of some shortcomings those arise when using gasoline fuel.

Review of research sources and publications

The first studies on the possibility of using hydrogen as a fuel for a rotary engine began in the mid-70s of the last century. In the early 1980s, German companies Audi and FEV conducted research on the suitability of hydrogen for rotary engines. It was determined that with a light modification of the rotary engine, it is possible to use hydrogen as a fuel. At the same time, the specific power of a rotary engine can remain as high as that has a conventional gasoline piston engine [1].

Mazda Motor Corporation as a automotive manufacturer has been researching the technology of using hydrogen fuel in rotary combustion engines for many years. In 1992, the company experimentally proved that a rotary hydrogen engine with preliminary mixture formation reaches a power of up to 63% of similar indicators when working on gasoline, while a piston hydrogen engine with preliminary mixture formation reaches only 50%. Also, in the case of a rotary engine, the injection cycle can be easily implemented with an output power at the level of 75% of the gasoline engine characteristics [2].

In 2011, scientists from the Kyushu University Engineering Faculty (Japan) together with Mazda engineers focused on optimizing the combustion process of hydrogen fuel in a rotary engine by increasing the combustion speed, increasing turbulence and changing the place of combustion. The effectiveness of the turbulence formation in the lower part of the combustion chamber, which was created with the help of a protrusion located in the depression of the rotor side wall, was proven, as it increased the flame propagation speed [3].

Among the latest scientific works on the use of hydrogen in engines, it is possible to highlight the study of the abnormal combustion problem for this fuel in a rotary engine and in a piston engine with reciprocating piston movement (2022) [4].

Comparing a hydrogen rotary engine and a hydrogen piston engine, the researchers found that the first one can provide more power per chamber unit volume while maintaining roughly the same efficiency. It was also established that thanks to the physical and chemical properties of hydrogen, it is possible to significantly reduce the emissions and improve the thermal efficiency of the engine [5].

Definition of unsolved aspects of the problem

To fully realize the potential of the rotary mechanism for the car engine, it is necessary to eliminate the main shortcomings of its design. In the future, this will provide him with the opportunity to become one of the promising power units in road transport.

Problem statement

The goal of our research is to analyze the possibility of eliminating some shortcomings of the rotary engine and improving its operational characteristics due to the use of hydrogen as fuel. Assess the current situation with the production and use of hydrogen rotary engines.

Basic material and results

We will take the design of a Wankel rotary engine as a basis for the research. It is an internal combustion engine and produces power similar to a conventional piston engine. The engine block parts form an insulated space around the rotor and function similar to the cylinders in a reciprocating piston engine. So the rotor rotates and simultaneously performs the work that the piston, connecting rod and valves do together. A cross-sectional view of the engine rotor mechanism is presented in fig. 1.

The rotor does not just rotate, but rolls with its internal toothed crown around the fixed gear, thus forming three combustion chambers in which cycles of injection, compression, ignition and emission take place sequentially.

All the functions of the valve train in this engine are performed by the intake and exhaust ports in the engine block side walls and the rotor itself, which opens and closes them in rotating movement.

Let's consider the advantages and shortcomings of the design of gasoline rotary engines compared to piston internal combustion engines.

Advantages:

1. Compactness and higher power-to-weight ratio than a similar piston engine.
2. Ensuring the smoothness of the torque change thanks to a short interval between working strokes.
3. More time for gas exchange (intake and exhaust) – provides more torque at high revs.
4. Low vibration and noise.
5. Less weight of the engine.

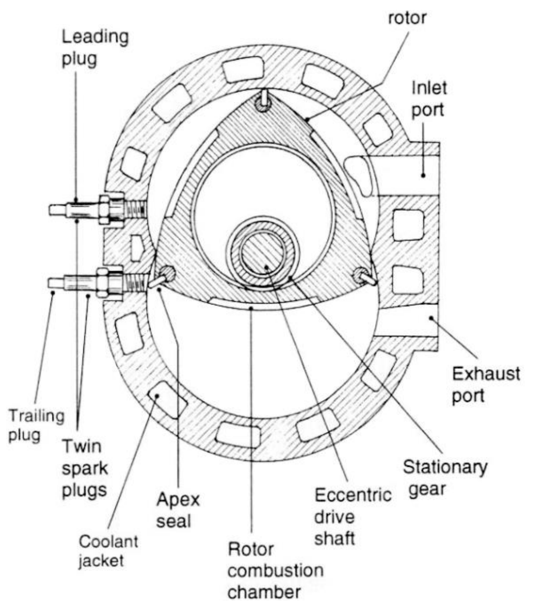


Figure 1 – Cross-sectional view scheme of the engine rotor mechanism

6. Extended range of rotation frequency.
7. Serial production of engines has lower cost.
8. The engine is well suited for working on hydrogen.

Shortcomings:

1. The problem of working gases leaks between the rotor apex seals and the engine block.
2. The need to control the level and condition of the lubricant in the engine (under operating conditions, part of the lubricant is burned together with the fuel).
3. The problem of uneven thermal load on the engine body parts within the working chamber of the rotor.
4. Low torque in the low revs range.
5. Slow combustion of the working mixture.
6. Low fuel economy.
7. High emissions.

As can be seen from the above shortcomings, the classic gasoline rotary engine, despite its compactness and universal design, is difficult to compete with gasoline piston internal combustion engines in terms of fuel efficiency, while complying with today's strict environmental standards. Thus, in 2012, due to non-compliance with the Euro 5 environmental standard, serial production of the Mazda RX-8 car, which was equipped with the most advanced version of the gasoline rotary engine at the time, was completed [6].

However, since the design of the rotary engine is well adapted to work on different fuels, over the years of researches and experimentations, it has been found possible to eliminate the shortcomings associated with poor combustion of the gasoline-air mixture and emissions. This was realized by converting the engine to burn hydrogen.

Hydrogen, as a fuel, has unique properties that ensure stable combustion processes, even for highly diluted mixtures. As a result, the combustion rate of the hydrogen-air working mixture increases and the overall engine fuel efficiency improves [7].

Also, the hydrogen diffusivity not only ensures high-quality mixture formation, but also in the leak event, hydrogen quickly disperses in the air, preventing the occurrence of dangerous situations. A comparison of the hydrogen and gasoline fuel properties is shown in Table 1 [8].

Table 1 – Basic properties of hydrogen and gasoline fuel

<table>
<tr><th colspan="2">Properties</th><th>Gasoline</th><th>Hydrogen</th></tr>
<tr><td colspan="2">Molar mass, [kg/kmol]</td><td>114</td><td>2.016</td></tr>
<tr><td colspan="2">Theoretical ratio of air to fuel, [kg/kg]</td><td>14.5</td><td>34.32</td></tr>
<tr><td colspan="2">Density at 0°C and 760 mmHg, [kg/m³]</td><td>0.735-0.760</td><td>0.0899</td></tr>
<tr><td rowspan="2">Ignition bounds in air at 20°C and 760 mmHg</td><td>% mas.</td><td>1.48-2.3</td><td>4.1-75.6</td></tr>
<tr><td>air ratio, λ</td><td>1.1-0.709</td><td>10.12-0.136</td></tr>
<tr><td colspan="2">Flame propagation speed in air (λ=1) at 20°C and 760 mmHg, [m/s]</td><td>0.12</td><td>2.37</td></tr>
<tr><td colspan="2">Octane rating</td><td>90-98</td><td>>130</td></tr>
<tr><td colspan="2">Min. ignition energy in air , [mJ]</td><td>0.2-0.3</td><td>0.018</td></tr>
<tr><td colspan="2">Auto-ignition temperature, [K]</td><td>753-823</td><td>848-853</td></tr>
<tr><td rowspan="2">Lower heating value (gas at 0°C and 760mmHg);</td><td>Stoichiometric fuel-air mixture, [kJ/m³]</td><td>3661</td><td>3178</td></tr>
<tr><td>[kJ/kg]</td><td>42690</td><td>119600</td></tr>
</table>

Below is a description of the main characteristics hydrogen and their advantages in comparison with gasoline fuel when used in a rotary combustion engine.

Extended ignition bounds. Hydrogen has an extended ignition bounds in air, which allows the use of enriched or depleted mixtures. This property in combination with high turbulence in the combustion chamber expands the rotary engine using possibilities. Thus, lean fuel-air mixture operation results in better fuel economy due to more complete fuel combustion and lower NO_X emissions due to lower combustion temperatures.

Shorter extinguishing distance. Extinguishing distance is the distance between the cylinder wall or block wall in the case of a rotary engine and the point where the flame is extinguished. Hydrogen fuel has an extinguishing distance of 0.6 mm, while gasoline has an extinguishing distance of 2 mm.

High flame propagation speed. The hydrogen engine has an almost ideal thermodynamic cycle due to the high flame propagation speed when stoichiometric conditions are ensured. Thanks to the rapid combustion of hydrogen, the engine can operate at high revs, which leads to an increase in power, but at the same time, its economy decreases.

Minimum ignition energy. It is defined as the minimum energy required to initiate fuel combustion. A hydrogen-air mixture requires a smaller energy by ignition source compared to a gasoline-air mixture. The minimum ignition energy of a hydrogen-air mixture is 0.02 mJ, while a gasoline-air mixture requires 0.24 mJ.

High auto-ignition temperature. The minimum temperature at which the fuel ignites without the use of an external ignition source is determined by the auto-ignition temperature. For hydrogen, it is higher than for other fuels, and is about 585 °C. Because of this, it is difficult to initiate the combustion of hydrogen only due to an increase in temperature, so an external ignition source is necessary. Due to the high auto-ignition temperature, a higher compression ratio can be used for a hydrogen-powered engine compared to a gasoline engine.

Regarding the emissions situation, the hydrogen rotary engine produces very low emissions compared to gasoline rotary engines [7]. And residual toxic substances in the exhaust gases, such as hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NO_X) are cleaned when passing through a catalytic converter.

Since in order to lubricate the rotor seals inside the combustion chamber, it is necessary to constantly add oil to the working mixture in small proportions. So a CO-neutral solution would be the use of bio-oils or synthetic materials.

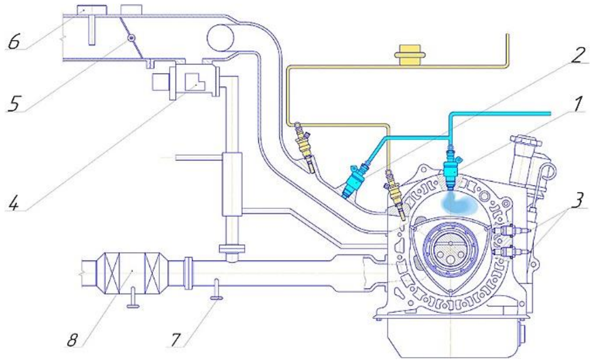
To overcome the problem of uneven thermal load on the engine block parts within the working chamber, the use of an exhaust gas recirculation system (EGR) is proposed in its working cycle. The thermal and dilution effects of the EGR system reduce the temperature of the rotor and block working surfaces inside the engine, thereby reducing the amount of nitrogen oxides (NO_X) produced by the combustion of hydrogen. The EGR system is also an effective factor in increasing thermal efficiency and output power while simultaneously reducing the emissions of harmful substances [9-11].

Separately, it can be noted that unlike piston engines, a rotary combustion engine has separate low-temperature intake zones and high-temperature combustion chambers, and it also have no exhaust valves, which are a potential hot zone too. Accordingly, in a rotary engine running on hydrogen, there is no risk of pre-ignition in the part of the operating cycle when hydrogen is injected. This makes engines more resistant to interruptions in operation [4].

Also, the physical separation of the intake and combustion zones allows for direct hydrogen injection, as a safe temperature is provided for the rubber seals of the hydrogen injectors. Thus, injectors can be installed in the engine block next to the intake chambers for direct injection [12].

Below in fig. 2, a scheme of the possible hydrogen power system integration into the design of the rotary combustion engine is proposed.

Figure 2 – The main elements of the fuel injection



system and the exhaust system of a rotary engine equipped to work on hydrogen:
1 – hydrogen injector (direct injection);
2 – hydrogen injector (external injection); 3 – spark plugs; 4 – EGR system valve; 5 – electric throttle; 6 – mass air flow sensor; 7 – lambda sensor; 8 – catalytic converter

This scheme (fig. 2) shows that direct hydrogen injectors are mounted in the upper part of the engine block (one for each rotor) and inject fuel directly into the working chamber.

This design assumes that air from the intake manifold is sucked through a port in the engine block side into the working chamber, where it mixes with atomized gaseous hydrogen. And an additional external injection system is installed on the intake manifold body in order to ensure a higher quality working mixture at high revs.

To overcome the problem of low torque in the low revs range, it is recommended to install one or more auxiliary electric motors. The electric motor will increase the torque, which is low for initial acceleration, until the engine revs up.

Such a solution was tested by Mazda engineers on one of the experimental cars with rotary engine [13].

The hydrogen rotary engines advantages of the serial production lower cost and the high efficiency of their use can be made even more significant by conducting research in this direction.

For example, Mazda company experimented with various hydrogen injection systems for rotary engines. And at the beginning of the 2000s, several batches of experimental RX-8 Hydrogen RE cars (Fig. 3) were produced on the basis of the RX-8 sports car, which were successfully operated by Japanese government departments [14, 15].

The automotive manufacturer also demonstrated other vehicle prototypes with hydrogen rotary engines, but nowadays their production, at least in small series, has not been realized.

In addition to Mazda, the German company Wankel Supertec, which specializes in the production of multi-fuel rotary engines for aviation and ground vehicles, is engaged in the development of a hydrogen rotary engine as a motor for cars [16]. Since 2019, the enterprise has established production several models of hydrogen rotary power plants in small quantity. The future hydrogen hybrid drive concept by Wankel Supertec is presented in fig. 4. Among its main components is a rotary combustion engine.

Figure 3 – Experimental RX-8 Hydrogen RE car

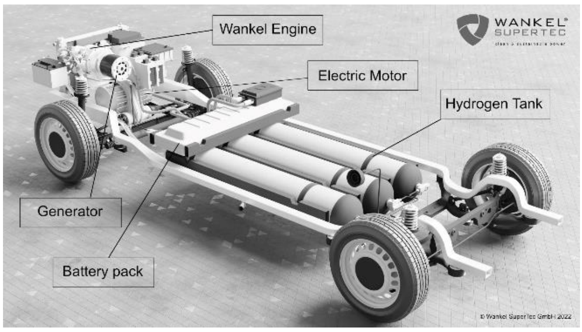


Figure 4 – The future hydrogen hybrid drive concept by Wankel Supertec

As of the end of 2022, the company was working on a project of a light truck equipped with a hydrogen rotary engine. Over time, it is planned to present it on the market under its own brand [17].

The analysis of shortcomings in the rotary engine operation showed that one of the main affecting factors its efficiency is the problem of working gases leaks between the rotor apex seals and the engine block. Accordingly, gas leaks between the working chambers directly depend on the contact area between the apex seal on the triangular rotor and the engine block surface.

And since the engine performance as a whole depends on the sealing efficiency, it is important to study their influence on the volumetric efficiency in the engine. Therefore, it was decided to conduct a study of the internal gas flow characteristics using Computational Fluid Dynamics (CFD) instruments for the Mazda RX-8 Hydrogen RE engine.

To carry out the research using CFD, a rotary engine CAD model was previously designed. To simplify construction, the top seals are integral with the rotor, and the intake and exhaust ports are located on the engine block.

Modeling was performed using the SolidWorks. In this study, a gas flow simulation was built based on the conservation of mass and momentum using the finite volume method.

The initial data and boundary conditions for the gas flow are as follows. For the convenience of modeling, air was taken as internal working gas with a density of 1.29 kg/m^3 and a viscosity of 1.8E-05 kg/m·s. The inlet pressure is equal to twice the atmospheric pressure of 202.6 kPa; the output pressure is equal to atmospheric amount 101.3 kPa; the rotational frequency of the engine eccentric shaft is 2000 rpm.

Also, for the correct simulation of the gas flow, it is assumed that the gas flow is built on the basis of a turbulent model; the flow of gases is uneven, turbulent and under pressure; the influence of accompanying heat exchange and radiation is not taken into account; the flow is initially stationary, two-dimensional.

As it is known, a rotary engine during operation is affected by unbalanced gas pressure and centrifugal forces of rotation, changing the contact conditions with the apex seal, causing its vertical displacements. As a result, there is a small gap between the end seal and the engine block surface, which can lead to leakage problems. Based on this, for the convenience of building the model, we assume that the set gap is 0.15 mm. After conducting a computer simulation, consider the situation with gas leaks between the working chambers of a rotary engine (fig. 5). Assuming the presence of a defined gap between the engine block surface and the rotor apex seal, the leakage condition is represented by the trajectory lines of the gas flows. It demonstrates that the flow occurs from a zone with high pressure to a zone with low pressure.

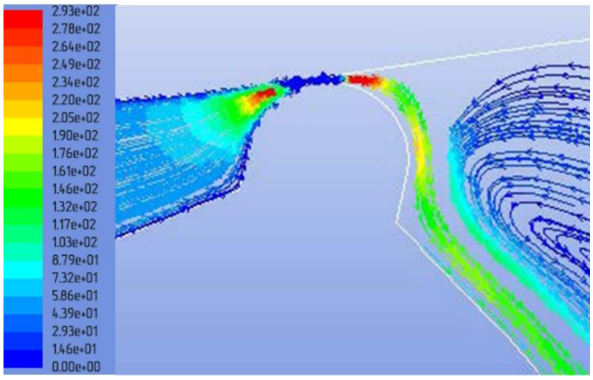


Figure 5 – Leaks simulation in apex seal

Trajectory lines are colored according to the speed value diagram (m/s) that is situated on the left side of fig. 5.

As it can be seen from the simulation, the leakage zone is concentrated in the gap, and the flow speed reaches up to 290 m/s in this gap. Under the specified research conditions, a volume of the gas mixture that will not exceed 4.35E-05 m^3 will pass through the apex seal gap in one revolution of the engine rotor. And this corresponds to the engine volume efficiency of 96.7%. So we can conclude that such an indicator is not critical and will ensure the rotary engine efficiency, will allow it to be competitive on the market.

Conclusions

Many years of research and testing by various organizations from around the world testify to the promising design of the rotary engine for operation on hydrogen fuel (hydrogen rotary engine – HRE).

Due to the high turbulence of internal flows and a long operating cycle, the homogeneity of the hydrogen and air mixture is ensured, which causes high efficiency of hydrogen combustion. The short extinguishing distance and high hydrogen ignition speed ensure complete fuel combustion without residues in the exhaust, as happens when using gasoline fuel. And, therefore, a correctly adjusted rotary engine running on hydrogen can even surpass a gasoline piston engine in terms of specific power.

The compact dimensions and low noise level provide the possibility of using these engines in hybrid vehicles as a mileage extender.

Accordingly, hydrogen rotary combustion engines, potentially, in the future, can be used to drive environmentally friendly vehicles. However, nowadays this engine has not yet reached its best level of development and needs further improvement and refinements to optimize fuel economy, durability and reduce the cost of production. There are also other shortcomings of the design that have not been fully resolved, among which is the problem of working gases leaks between the rotor apex seals and the engine block, which requires separate thorough studies with the help of CFD and other innovative computer modeling methods, the introduction of new materials types into use.

Also important for the effective use of hydrogen engines is the general state of infrastructure development for the production, transportation and distribution of hydrogen as fuel for cars. After all, without solving these issues, it is impossible to achieve proper competitive cars with a rotary engine on hydrogen fuel.

References

1. Stutzenberger H., Boestfleisch V., Pischinger F. (1983). The suitability of rotary engines for hydrogen operation. *Mtz mot zeitschrift*, 44, 1-25
2. Morimoto K., Teramoto T., Takamori Y. (1992). Combustion Characteristics in Hydrogen Fueled Rotary Engine. *SAE Technical Paper*, 920302, 1-9
3. Jaber N., Mukai M., Kagawa R., Nakakura H., Moriue O., Murase E. (2012). Amelioration of Combustion of Hydrogen Rotary Engine. *International Journal of Automotive Engineering*, 3, 81-88
4. Meng H., Ji C.;Wang D., Xin G., Chang K., Yang J., Wang S. (2022). Research on the load control of hydrogen-fueled Wankel rotary engine. *Int. J. Hydrogen Energy*, 47, 16665–16675 https://doi.org/10.1016/j.ijhydene.2022.03.118
5. Gao J., Tian G., Ma C., Balasubramanian D., Xing S., Jenner P. (2020). Numerical investigations of combustion and emissions characteristics of a novel small scale opposed rotary piston engine fuelled with hydrogen at wide open throttle and stoichiometric conditions. *Energy Convers. Manag*, 221, 113-178 https://doi.org/10.1016/j.enconman.2020.113178
6. Mazda stops RX-8 production. *Autoblog.com:* веб-сайт. URL: https://www.autoblog.com/2011/08/22/mazda-stops-rx-8-production/ (дата звернення: 22.04.2023)
7. Meng H., Ji C., Yang J., Wang S., Chang K., Xin G. (2021). Experimental study of the effects of excess air ratio on combustion and emission characteristics of the hydrogen-fueled rotary engine. *Int. J. Hydrogen Energy*, 46, 32261–32272 https://doi.org/10.1016/j.ijhydene.2021.06.208
8. Negurescu N., Pana C., Cernat A. (2012). Aspects of using hydrogen in SI engine. *U.P.B. Sci. Bull. Series D*, Vol. 74, Iss. 1. 1-10
9. Gong C., Si X., Liu F. (2021). Combustion and emissions behaviors of a stoichiometric GDI engine with simulated EGR (CO_2) at low load and different spark timings. *Fuel*, 295, 120-614 https://doi.org/10.1016/j.fuel.2021.120614
10. Verhelst S., Maesschalck P., Rombaut N., Sierens R. (2009). Increasing the power output of hydrogen internal combustion engines by means of supercharging and exhaust gas recirculation. *Int. J. Hydrogen Energy*, 34, 4406–4412 https://doi.org/10.1016/j.ijhydene.2009.03.037
11. Fontana G., Galloni E. (2010). Experimental analysis of a spark-ignition engine using exhaust gas recycle at WOT operation. *Appl. Energy*, 87, 2187–2193

1. Stutzenberger H., Boestfleisch V., Pischinger F. (1983). The suitability of rotary engines for hydrogen operation. *Mtz mot zeitschrift*, 44, 1-25
2. Morimoto K., Teramoto T., Takamori Y. (1992). Combustion Characteristics in Hydrogen Fueled Rotary Engine. *SAE Technical Paper*, 920302, 1-9
3. Jaber N., Mukai M., Kagawa R., Nakakura H., Moriue O., Murase E. (2012). Amelioration of Combustion of Hydrogen Rotary Engine. *International Journal of Automotive Engineering*, 3, 81-88
4. Meng H., Ji C.;Wang D., Xin G., Chang K., Yang J., Wang S. (2022). Research on the load control of hydrogen-fueled Wankel rotary engine. *Int. J. Hydrogen Energy*, 47, 16665–16675 https://doi.org/10.1016/j.ijhydene.2022.03.118
5. Gao J., Tian G., Ma C., Balasubramanian D., Xing S., Jenner P. (2020). Numerical investigations of combustion and emissions characteristics of a novel small scale opposed rotary piston engine fuelled with hydrogen at wide open throttle and stoichiometric conditions. *Energy Convers. Manag*, 221, 113-178 https://doi.org/10.1016/j.enconman.2020.113178
6. Mazda stops RX-8 production. *Autoblog.com:* веб-сайт. URL: https://www.autoblog.com/2011/08/22/mazda-stops-rx-8-production/ (дата звернення: 22.04.2023)
7. Meng H., Ji C., Yang J., Wang S., Chang K., Xin G. (2021). Experimental study of the effects of excess air ratio on combustion and emission characteristics of the hydrogen-fueled rotary engine. *Int. J. Hydrogen Energy*, 46, 32261–32272 https://doi.org/10.1016/j.ijhydene.2021.06.208
8. Negurescu N., Pana C., Cernat A. (2012). Aspects of using hydrogen in SI engine. *U.P.B. Sci. Bull. Series D*, Vol. 74, Iss. 1. 1-10
9. Gong C., Si X., Liu F. (2021). Combustion and emissions behaviors of a stoichiometric GDI engine with simulated EGR (CO_2) at low load and different spark timings. *Fuel*, 295, 120-614 https://doi.org/10.1016/j.fuel.2021.120614
10. Verhelst S., Maesschalck P., Rombaut N., Sierens R. (2009). Increasing the power output of hydrogen internal combustion engines by means of supercharging and exhaust gas recirculation. *Int. J. Hydrogen Energy*, 34, 4406–4412 https://doi.org/10.1016/j.ijhydene.2009.03.037
11. Fontana G., Galloni E. (2010). Experimental analysis of a spark-ignition engine using exhaust gas recycle at WOT operation. *Appl. Energy*, 87, 2187–2193

https://doi.org/10.1016/j.apenergy.2009.11.022

12. Yip H.L., Srna A., Yuen A.C.Y., Kook S. (2019) A Review of Hydrogen Direct Injection for Internal Combustion Engines: Towards Carbon-Free Combustion *Appl. Sci. 2019*, 9(22), 42-48

13. Tokyo Motor Show: Mazda Premacy Hydrogen RE hybrid. *Autoblog.com:* веб-сайт. URL: https://www.autoblog.com/2007/10/24/tokyo-motor-show-mazda-premacy-hydrogen-re-hybrid/ (дата звернення: 22.04.2023)

14. Mazda Hydrogen Rotary Now Street Legal. *newsroom.mazda.com:* веб-сайт. URL: https://newsroom.mazda.com/en/publicity/release/2004/200410/1027e.html (дата звернення: 22.04.2023)

15. Mazda Delivers Two Rotary Hydrogen Vehicles to Hiroshima Government Authorities. *newsroom.mazda.com:* веб-сайт. URL: https://newsroom.mazda.com/en/publicity/release/2006/200604/060421.html (дата звернення: 22.04.2023)

16. Wankel supertec. *wankelsupertec.de:* веб-сайт. URL: https://www.wankelsupertec.de/en/ (дата звернення: 22.04.2023)

17. Wankel Super Tec – Success Story: Die Energie der Zukunft soll emissionsfrei und nachhaltig sein. *www.fundernation.eu:* веб-сайт. URL: https://www.fundernation.eu/blog/wankel-super-tec-success-story-die-energie-der-zukunft-soll-emissionsfrei-und-nachhaltig-sein/ (дата звернення: 22.04.2023)

18. Abdalla A.M., Hossain S., Nisfindy O.B., Azad A.T., Dawood M., Azad A.K. (2018). Hydrogen production, storage, transportation and key challenges with applications: A review. *Energy Convers. Manag*, 165, 602–627

19. Srinivasan C., Subramanian R. (2014). Hydrogen as a spark ignition engine fuel: technical review. *Int J Mech Mechatron Eng*; 14, 7-111

https://doi.org/10.2298/HEMIND0206256K

20. Salvi B.L., Subramanian K.A. (2016). Experimental investigation on effects of compression ratio and exhaust gas recirculation on backfire, performance and emission characteristics in a hydrogen fueled spark ignition engine. *Int J Hydrogen Energy*; 41, 5842-5855

https://doi.org/10.1016/j.ijhydene.2016.02.026

https://doi.org/10.1016/j.apenergy.2009.11.022

12. Yip H.L., Srna A., Yuen A.C.Y., Kook S. (2019) A Review of Hydrogen Direct Injection for Internal Combustion Engines: Towards Carbon-Free Combustion *Appl. Sci. 2019*, 9(22), 42-48

13. Tokyo Motor Show: Mazda Premacy Hydrogen RE hybrid. *Autoblog.com:* веб-сайт. URL: https://www.autoblog.com/2007/10/24/tokyo-motor-show-mazda-premacy-hydrogen-re-hybrid/ (date of application: 22.04.2023)

14. Mazda Hydrogen Rotary Now Street Legal. *newsroom.mazda.com:* веб-сайт. URL: https://newsroom.mazda.com/en/publicity/release/2004/200410/1027e.html (date of application: 22.04.2023)

15. Mazda Delivers Two Rotary Hydrogen Vehicles to Hiroshima Government Authorities. *newsroom.mazda.com:* веб-сайт. URL: https://newsroom.mazda.com/en/publicity/release/2006/200604/060421.html (date of application: 22.04.2023)

16. Wankel supertec. *wankelsupertec.de:* веб-сайт. URL: https://www.wankelsupertec.de/en/ (date of application: 22.04.2023)

17. Wankel Super Tec – Success Story: Die Energie der Zukunft soll emissionsfrei und nachhaltig sein. *www.fundernation.eu:* веб-сайт. URL: https://www.fundernation.eu/blog/wankel-super-tec-success-story-die-energie-der-zukunft-soll-emissionsfrei-und-nachhaltig-sein/ (дата звернення: 22.04.2023)

18. Abdalla A.M., Hossain S., Nisfindy O.B., Azad A.T., Dawood M., Azad A.K. (2018). Hydrogen production, storage, transportation and key challenges with applications: A review. *Energy Convers. Manag*, 165, 602–627

19. Srinivasan C., Subramanian R. (2014). Hydrogen as a spark ignition engine fuel: technical review. *Int J Mech Mechatron Eng*; 14, 7-111

https://doi.org/10.2298/HEMIND0206256K

20. Salvi B.L., Subramanian K.A. (2016). Experimental investigation on effects of compression ratio and exhaust gas recirculation on backfire, performance and emission characteristics in a hydrogen fueled spark ignition engine. *Int J Hydrogen Energy*; 41, 5842-5855

https://doi.org/10.1016/j.ijhydene.2016.02.026